# Advancing the Fundamental Sciences

## Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004

## Volume 1


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Cover:
Backprint–A creek in the Tushar Mountains, Fishlake National Forest, central Utah. Photo by Bert Lowry.

Top left–Waterfall on Fridley Run, near Harrisonburg, Virginia, on the George Washington and Jefferson National Forest. Photo by Mike Land.

Bottom left–The Dolores River just outside the Grand Mesa, Uncompahgre, and Gunnison National Forests, western Colorado. Photo by Jerry Freeouf.

Top right–Island Lake and Fremont Peak, Wind River Range, Bridger-Teton National Forest, Wyoming. Photo by Scott Clemons.

Middle right–Terminus of Hubbard Glacier, Tongass National Forest, southeast Alaska. Photo by J. Lott.

Bottom right–Quartz Creek, North Fork Clearwater River, Clearwater National Forest, Idaho. Photo by Richard Jones.

Title page: Powder River, Wallowa-Whitman National Forest, northeast Oregon. Photo by Bruce McCammon.

## Preface

Bruce McCammon and Bonnie Ilhardt

It is a great pleasure for us to present the proceedings of the Advancing Fundamental Sciences conference held in San Diego, California, in October 2004. This conference was attended by nearly 450 Forest Service earth scientists representing hydrology, soil science, geology, and air. In addition to active members of the earth science professions, many retired scientists also attended and participated in the week's events. Even though it rained much of the week, attendees maintained a high level of enthusiasm and participated actively.

The week was filled with memorable, but transient, events. A variety of keynote speakers reminded us of our history, challenged us with new thoughts, and reaffirmed our responsibility for proper stewardship of the unique physical resources on Forest Service lands. Panel discussions allowed the pioneers of the physical science disciplines to be recognized for their careers and acknowledged for their contributions. Speakers took the opportunity to present new work and interact with their peers. Poster displays gave many people an opportunity to present their work and explain its importance. Everyone who attended will remember the three-part play "The Life and Times of Forrest Stump." The play presented a snapshot of a hypothetical physical scientist's career beginning when physical scientists were new to the agency and ending when he retired after a long and distinguished career. The skit struck close to home for many and left the crowd howling with laughter and asking for more. Conference critiques showed clearly that the variety of events during the week led to the success of the conference.

These proceedings are the durable product of the conference and come to you only as the result of hard work by authors, reviewers, and editors. These proceedings include 60 technical papers that have been through a series of peer and editorial reviews. Fifty-six people participated as reviewers of the technical papers. Each paper was improved through incorporation of two sets of peer-review comments. Our thanks go to each of the people who volunteered to be a reviewer. Special thanks go to Michael Furniss, Caty Clifton and Kathryn Ronnenberg for coordinating the reviews, providing a high level of editorial consistency, and for preparing this proceedings.

We hope that these proceedings will serve as a valuable reference for your work in the future.

Bruce McCammon
Retired, Pacific Northwest Region
Conference Chair

Bonnie Ilhardt
Eastern Region
Conference Co-chair

## Editors' Note

Michael J. Furniss, Catherine F. Clifton, and Kathryn L. Ronnenberg

Most earth scientists like rain. We know it is the source of much we hold dear, sustaining the systems we study and love, necessary for flowers to grow and flourish and bloom. But… rain for a week? In San Diego? It was an unusual deluge that greeted us in southern California, but fitting. It accompanied an unprecedented gathering of more than 400 Forest Service earth scientists for a first-ever national conference. It was a landmark event. Good times, along with the precipitation, were in abundance. The weather lifted rather than dampened the mood as we ran through downpours, arriving soaked and excited for the next encounter.

Many attendees expressed surprise that "there are so many of us." We have a lot in common through our work, but until that week, we'd never seen so many soil scientists, geologists, hydrologists, and air specialists together in one place. There was a strong sense of a "community of practice": of shared goals, common experience and participation that reached across the Nation.

We were, perhaps, the largest such collection of public lands earth scientists on Earth. The conference was a celebration and expansion of our collective knowledge, experience, identity, history, and a glimpse of our future potential. We commend the conference organizers for this extraordinary, multidisciplinary conference, for their recognition that knowledge from one branch is unable to advance without knowledge from another, and that together we are a stronger, more sustainable community.

Two thousand four was also the year of the Forest Service Centennial celebration. The sense of history was in the air, as retirees mixed with newer hires. We took stock of the five or six decades that earth scientists have contributed to the Forest Service, the ways times have changed, and the many ways we have advanced the agency and the conservation of earth resources.

The conference program offered a broad diversity of plenary and themed sessions, workshops, and field trips, and received rave reviews throughout the week. The book you hold contains submitted technical papers from the themed sessions. These 60 peer-reviewed papers represent a wide spectrum of earth science investigation, experience, research, and innovation in the Forest Service. Take the time to read and enjoy them, but don't stop there. You are encouraged to give an author a call or email to discuss what you read and how it relates to your work. Load up the CD in the back and review the keynote talks. Check the intranet web site for more memories and resources.

Let this collection be a portal into the rich pool of expertise, engagement, and collaboration that is our community of practice. The bonds formed and strengthened in San Diego can help sustain us in the decades to come. Our community was in full bloom that week, but it exists between conferences. Just as flora (and maybe conferences) need rain, communities of practice need cultivation to flourish. We have many ways to connect across forests, regions, and stations, to inform and support each other. In so doing, each of us can help nurture our community of practice.

We encourage you to call or email someone from another region. Email someone you know but haven't seen since San Diego. Create and participate in informal events that connect people. Convene discussions on common challenges, both remote and in person. Share experiences, successes, and failures. We each have the ability to cultivate and sustain our community of practice. Everything works when we participate and contribute. There is no better time than now.

# Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004

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**About the Advancing the Fundamental Sciences Portable Electronic Presentation CD**

The CD in the inside back cover is an interactive learning resource that presents many of the conference plenary talks and two of the workshops in an electronic format. The format provides for interactive access: you may watch them start to finish, or just the parts that most interest you.

A help screen is available from the home page to assist you with navigating the presentations.

The CD runs on both Windows and Macintosh-compatible machines. This CD content can also be found online at *http://www.stream.fs.fed.us/afsc*

See page 577 for a preview of the introductory screen.

# I. Concurrent Session Papers

## Section 1. Applied Science and Technology

### Part 1. Fire and Smoke

Overleaf:
The view northwestward across Lake Pend Oreille towards Blacktail and Grouse Mountains on the Idaho Panhandle National Forests, northern Idaho, summer 2004. Photo by Preston Hiatt.

# Erosion Risk Management Tool (ERMiT)–A Probability-Based Erosion Prediction Model

Peter R. Robichaud
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After wildfires, land managers must assess the potential for increased flooding, erosion, and sedimentation, and the increased threat these effects may pose to people, structures, and valued resources. A Web-based Erosion Risk Management Tool (ERMiT) has been developed to predict surface erosion from postfire hillslopes, and to evaluate the potential effectiveness of various erosion mitigation practices. The model uses a probabilistic approach that incorporates temporal and spatial variability in weather, soil properties, and burn severity for forests, rangeland, and chaparral hillslopes. Using multiple runs of the Water Erosion Prediction Project (WEPP) model, ERMiT provides event-based erosion rate probabilities-with and without treatments-for five post-fire years.

Keywords: *post-fire modeling, erosion prediction, resource management, erosion control, BAER treatments, straw mulch, contour-felled logs, seeding*

Post-fire rehabilitation efforts continue to be a major land management activity due to the increase in the number, size, and intensity of wildfires in the western United States during the past decade. The threat of future wildfire damage to resources and property is creating a demand for effective erosion mitigation strategies as well as improved modeling tools on which to base treatment decisions. Post-fire rehabilitation treatments cannot prevent erosion, but they can reduce overland flow amounts, site soil loss, and sedimentation for some rainfall events. Thus the risk of postfire damage to water quality, habitat, roads, and other structures cannot be eliminated, but it can be reduced. It is useful to do risk assessments-balancing the increased risk of erosion, flooding, and other hazards against the risk reduction expected from specific treatments-when making postfire treatment decisions. The Erosion Risk Management Tool (ERMiT) (Robichaud et al. 2006, 2007; Robichaud et al. [in press]) has been developed to provide a risk assessment (i.e., probability-based) approach to post-disturbance erosion modeling and rehabilitation treatment effectiveness.

ERMiT provides probabilistic estimates of single-storm postfire hillslope erosion by incorporating variability in rainfall characteristics, soil burn severity, and soil characteristics into each prediction. ERMiT uses WEPP technology as the runoff and erosion calculation engine. WEPP simulates both inter-rill and rill erosion processes and incorporates the processes of evapo-transpiration, infiltration, runoff, soil detachment, sediment transport, and sediment deposition to predict runoff and erosion at the hillslope scale (Flanagan and Livingston 1995). Through the ERMiT interface, stochastic weather files generated by CLImate GENerator (CLIGEN) (Nicks et al. 1995) are selected for use in WEPP. Users may customize climate parameter files using the integrated Rock:Clime web interface (Scheele et al. 2001).

ERMiT users specify: 1. climate parameters based on location with adjustments made through Rock:Clime (Elliot 2004); 2. vegetation type – forest, range, chaparral; 3. soil type – clay loam, silt loam, sandy loam, loam-and rock content; 4. topography – slope length and gradient; and 5. soil burn severity class – low, moderate, high. These input choices are similar to other WEPP-based interfaces (Elliot 2004) (Figure 1). However, the incorporation of variability in these parameters and the probability-based output are unique to ERMiT.

The general process by which ERMiT incorporates parameter variability is to: 1) determine the range of possible parameter values; 2) select representative values from the range; and 3) assign an "occurrence probability" to each selected value such that the sum of assigned occurrence probabilities adds to 100 percent. Thus, all possible parameter values are represented in the model by the four to five selected values. The specific processes are:

***Climate variability***: Using a 100-year climate record generated by CLIGEN, WEPP is run for 100 years and the rain events with the greatest runoff from each year are rank ordered by runoff amount. The years and rain events with the 5th, 10th, 20th, 50th, and 75th ranked runoff amounts are selected for further analysis (Figure 2). Occurrence probabilities for the five rain events associated with the selected runoff events are 7.5, 7.5, 20, 27.5, and 37.5 percent, respectively.

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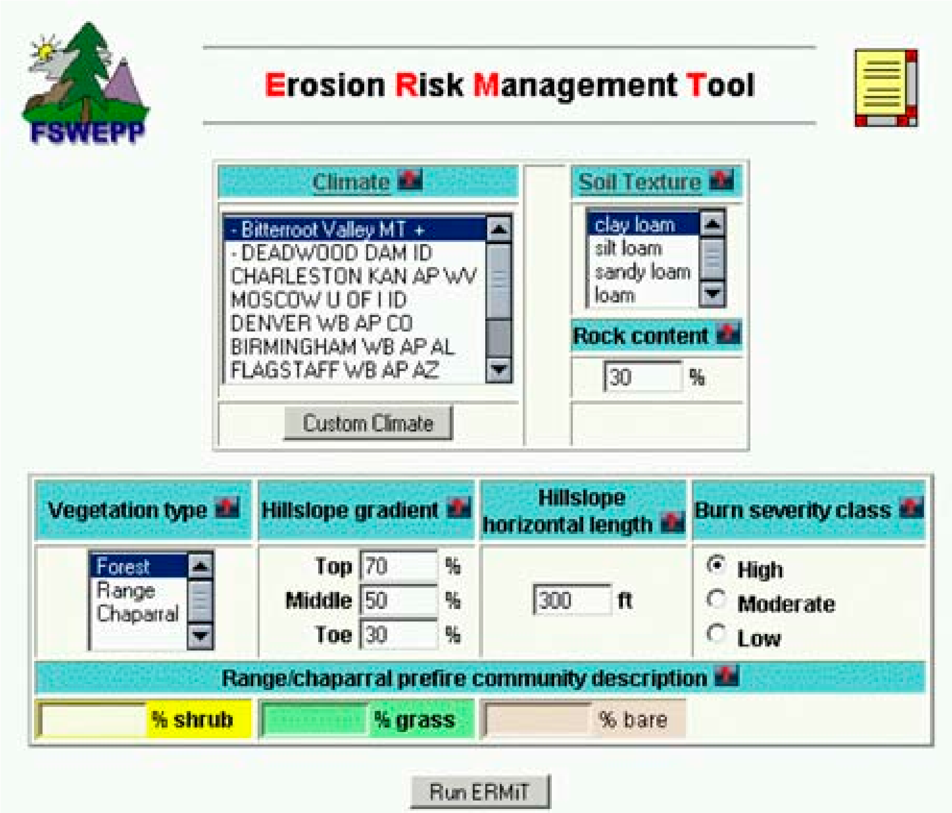



*Figure 1. Example Erosion Risk Management Tool (ERMiT) user input screen accessed at http://forest.moscowfsl.wsu.edu/fswepp/.*

***Soil parameter variability***: The variable effects of postfire ground cover, soil water repellency, and soil erodibility are modeled by variability in inter-rill erodibility, rill erodibility, effective hydraulic conductivity, and critical shear. Selected values, which vary by soil texture and soil burn severity, are grouped in five soil parameter sets from least erodible to most erodible. Thus, there are ten soil parameter sets for each soil texture-five for high soil burn severity and five for low soil burn severity. The five soil parameter sets (Soil 1, Soil 2, Soil 3, Soil 4, and Soil 5) are assigned occurrence probabilities of 10, 20, 40, 20, and 10 percent, respectively.

***Soil burn severity spatial variability***: WEPP models each hillslope in three sections, and in ERMiT each hillslope section can be either High or Low. Based on the user-designated soil burn severity input (high, moderate, or low), four spatial arrangements of High (H) and Low (L) sections, each with an assigned occurrence probability, are used. For example, a user designation of high soil burn severity will use four spatial arrangements of H and L for the three sections of hillslope (HHH, LHH, HLH, and HHL), which are assigned occurrence probabilities of 10, 30, 30, and 30 percent respectively.

***Temporal variability***: The changes in soil parameter values over time, due to recovery, are modeled by increasing the assigned occurrence probabilities of the lower erosion soil parameter sets and decreasing the occurrence probabilities of the higher erosion soil parameter sets. Also, the four spatial arrangements of hillslope sections are adjusted to include fewer high soil burn severity soil sets and more low soil burn severity soil sets with each year of recovery.

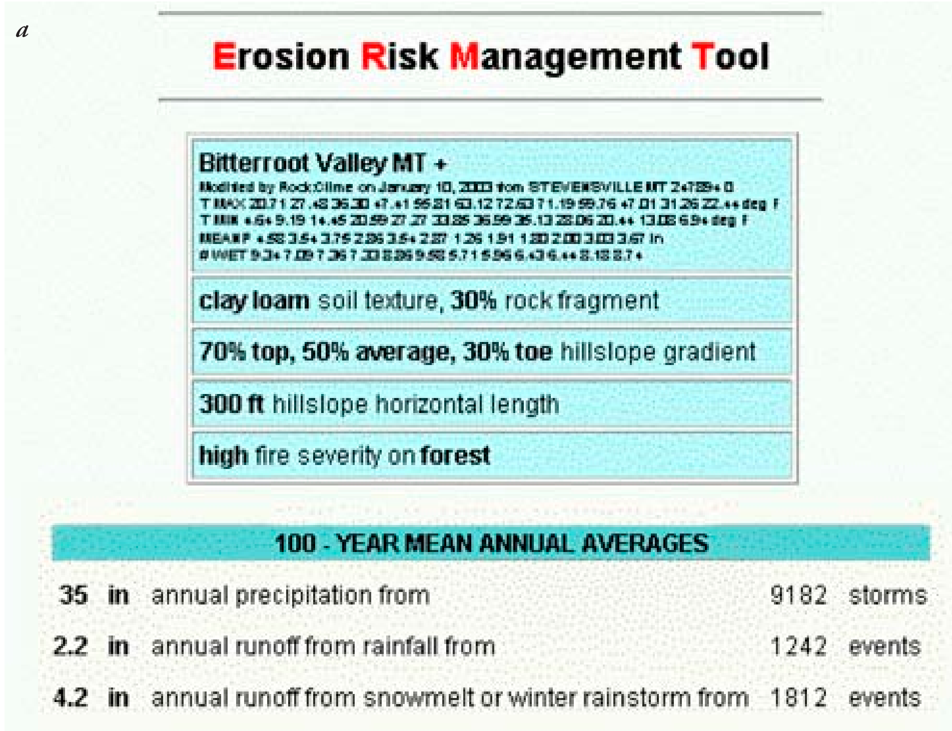
Through ERMiT, WEPP is run for each permutation of input parameters. Thus, every combination of the five selected rainfall events, five soil parameter sets, and four soil burn severity spatial arrangements is run to produce 100 event sediment delivery predictions. For each permutation, the product of the three component occurrence probabilities is the occurrence probability attached to the sediment delivery prediction. The probable erosion prediction output can be viewed in graphical (Figure 3) or tabular (Figure 4) form, with output data available for import into spreadsheets.

The interactive box in the tabular output screen allows users to delineate the level of risk (probability of exceedence) for potential erosion and then compare the relative effectiveness of various treatments to non-treatment as well as to one another (Figure 4).

ERMiT can also provide probabilistic estimates of the erosion reduction to be expected for three treatments-seeding, straw mulching, and contour-felled log or straw wattle erosion barriers. Data from rain simulation, sediment fence, and paired catchment studies are being used to calibrate the erosion reduction and sediment trapping

*Figure 2. Example ERMiT climate output screens. (a) Generated precipitation and runoff information for input parameters. (b) Selected rainfall events used for the ERMiT erosion predictions.*

a




b

| Ranking of event (return interval) | Storm Runoff (in) | Storm Precipitation (in) | Storm Duration (h) | tp (fraction) | ip (ratio) | 10-min peak intensity (in $h^{-1}$) | 30-min peak intensity (in $h^{-1}$) | Storm date |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.50 | 0.29 | 2.06 | 0.07 | 8.77 | 0.89 | 0.51 | April 5 year 46 |
| 5 (20-year) | 1.81 | 1.26 | 7.05 | 0.03 | 29.96 | 3.84 | 2.22 | March 27 year 44 |
| 10 (10-year) | 1.38 | 0.00 | 0.00 | 0.01 | 0.00 | N/A | N/A | April 5 year 42 |
| 20 (5- year) | 1.13 | 1.37 | 1.98 | 0.07 | 3.55 | 2.14 | 1.65 | June 21 year 4 |
| 50 (2- year) | 0.81 | 1.06 | 1.91 | 0.03 | 1.01 | 0.56 | 0.56 | October 18 year 43 |

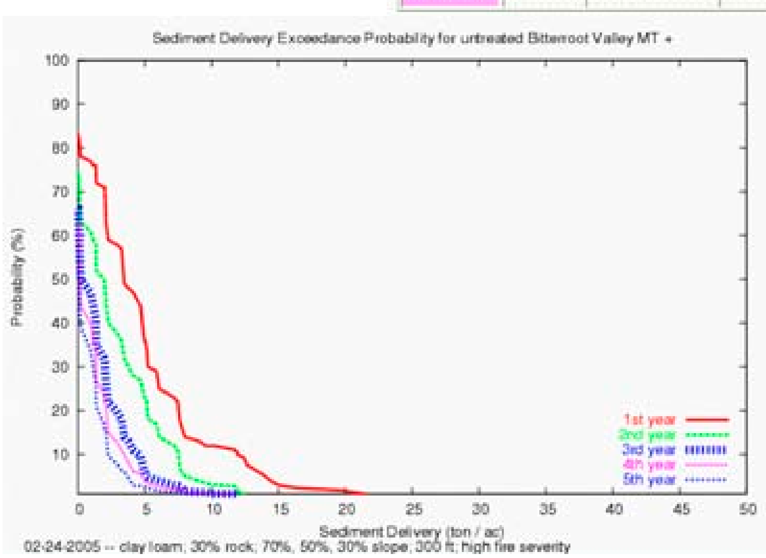



*Figure 3. Example ERMiT graphical output for sediment delivery exceedence probability for five postfire years in the area being modeled.*

| Target chance event sediment delivery will be exceeded 10 % go | Event sediment delivery (ton ac$^{-1}$) | | | | |
|---|---|---|---|---|---|
| | Year following fire | | | | |
| | 1st year | 2nd year | 3rd year | 4th year | 5th year |
| Untreated | 11.98 | 7.51 | 4.51 | 3.45 | 2.25 |
| Seeding | 11.98 | 4.51 | 3.45 | 2.25 | 2.25 |
| Mulch rate 0.2 ton ac$^{-1}$ | 5.9 | 4.93 | 4.51 | 3.45 | 2.25 |
| Mulch rate 0.4 ton ac$^{-1}$ | 3.27 | 3.78 | 4.51 | 3.45 | 2.25 |
| Mulch rate 0.7 ton ac$^{-1}$ | 2.24 | 3.66 | 4.51 | 3.45 | 2.25 |
| Mulch rate 0.9 ton ac$^{-1}$ | 1.7 | 3.27 | 4.51 | 3.45 | 2.25 |
| Logs & Wattles go Dia. 1 Sp. 10 | xxx | xxx | xxx | xxx | xxx |

*Figure 4. Example ERMiT tabular output with predicted sediment delivery (ton ac$^{-1}$) for untreated, as well as seed, mulch (four rates provided), and erosion barrier (barrier specifications are determined by the user) treated hillslopes. Predictions for five postfire years are included.*

efficiency (sediment stored by a contour-felled log divided by the sediment leaving the hillslope) of these treatments. Based on these data, straw mulch lowers predicted first-year erosion rates due to increased ground cover, more than the other treatments. Predicted erosion rates for erosion barriers vary by rainfall intensity (less erosion reduction occurs with high-intensity rainfall events) as well as estimated sediment storage capacity already filled.

Validation of ERMiT predictions by various users is ongoing. New data from treatment effectiveness studies and postfire erosion measurements will expand and refine the number of postfire rehabilitation treatments that can be modeled in ERMiT. Land managers who have used the model find the probability-based erosion predictions particularly useful when applied to risk-based management decisions, such as where to apply postfire rehabilitation treatments to get the most benefit for the cost.

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# Hillslope Erosion Rates in Areas With Volcanic Parent Materials and the Effects of Prescribed Fires in the Blue Mountains of Eastern Oregon and Washington, USA

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Prescribed fire is often proposed as a treatment for restoring forest health and reducing long-term risk of wildfires. It is generally assumed that wildfires and wildfire-related erosion pose greater threats to water quality and fish habitat than prescribed fires. However, limited empirical data are available for quantifying background erosion rates and the influence of prescribed fire on those rates. This study in the Blue Mountains of northeastern Oregon and southeastern Washington was designed to quantify background erosion rates and to examine the effects of prescribed fire on hillslope erosion and stream sedimentation. Two study areas were selected on the Umatilla National Forest. The first was a paired-watershed study at Skookum Creek in Oregon where stream discharge and sediment yield have been recorded continuously since the watersheds were gaged in 1992. Measurements within the watersheds were augmented with hillslope erosion plots in 2002. Hillslope erosion plots were also established in 2002 in the Red Fir prescribed burn project in Washington. Preliminary results from the Skookum paired-watershed study showed large differences between hillslope erosion rates measured from plots and watershed sediment yields, suggesting that episodic processes dominated sediment production and transport and therefore controlled watershed-scale sediment budgets. Preliminary analyses of all hillslope erosion data combined indicated that erosion rates were significantly related to aspect and amount of bare ground, but were not influenced by prescribed fire.

Keywords: *fuel treatment, prescribed fire, sediment yield, silt fence, streamflow, surface erosion, water quality*

## Introduction

Changes in forest composition and the mortality of forests in the interior West over the last century are often characterized as forest health problems (Everett et al. 1994; Hessburg et al. 1994; Quigley and Arbelbide 1997). Forest health has been targeted by recent legislation, administrative procedures, and management strategies with the aim of reducing long-term risks to forests from wildfire, drought, insects and disease (USDA FS and USDI 2001; USDA FS 2002, 2003). These management strategies emphasize using prescribed fire and other fuel reduction techniques to reduce wildfire risk, and are often motivated by concerns for protecting water supplies and species listed as threatened or endangered. Implied in the widespread use of prescribed fire as a management tool to reduce the risk of stand-replacing wildfires is the assumption that the direct effects of wildfires, as well as wildfire-related erosion and sedimentation of streams, are greater threats to water quality and fish habitat than are the effects of fuels treatments.

Most previous watershed studies of the impact of fire were focused on the effects of stand-replacing wildfires, salvage logging after fire, or prescribed fire associated with timber harvesting and slash control (McIver and Starr 2000). Despite the existing body of literature that describes the effects of fire and other land-management activities on erosion, sediment, and water quality, there remain significant knowledge gaps specific to effects of prescribed fire and fuels treatments. Few published studies have been conducted in areas with volcanic parent materials or volcanic-ash-derived soils – the soil types most common in central and eastern Oregon and southeastern Washington. Data are lacking on hillslope transport and redistribution of eroded sediment and the delivery of sediment to streams. At the local level, limited data are available to validate planning and assessment tools currently being used. Consequently, analyses rely on results from studies

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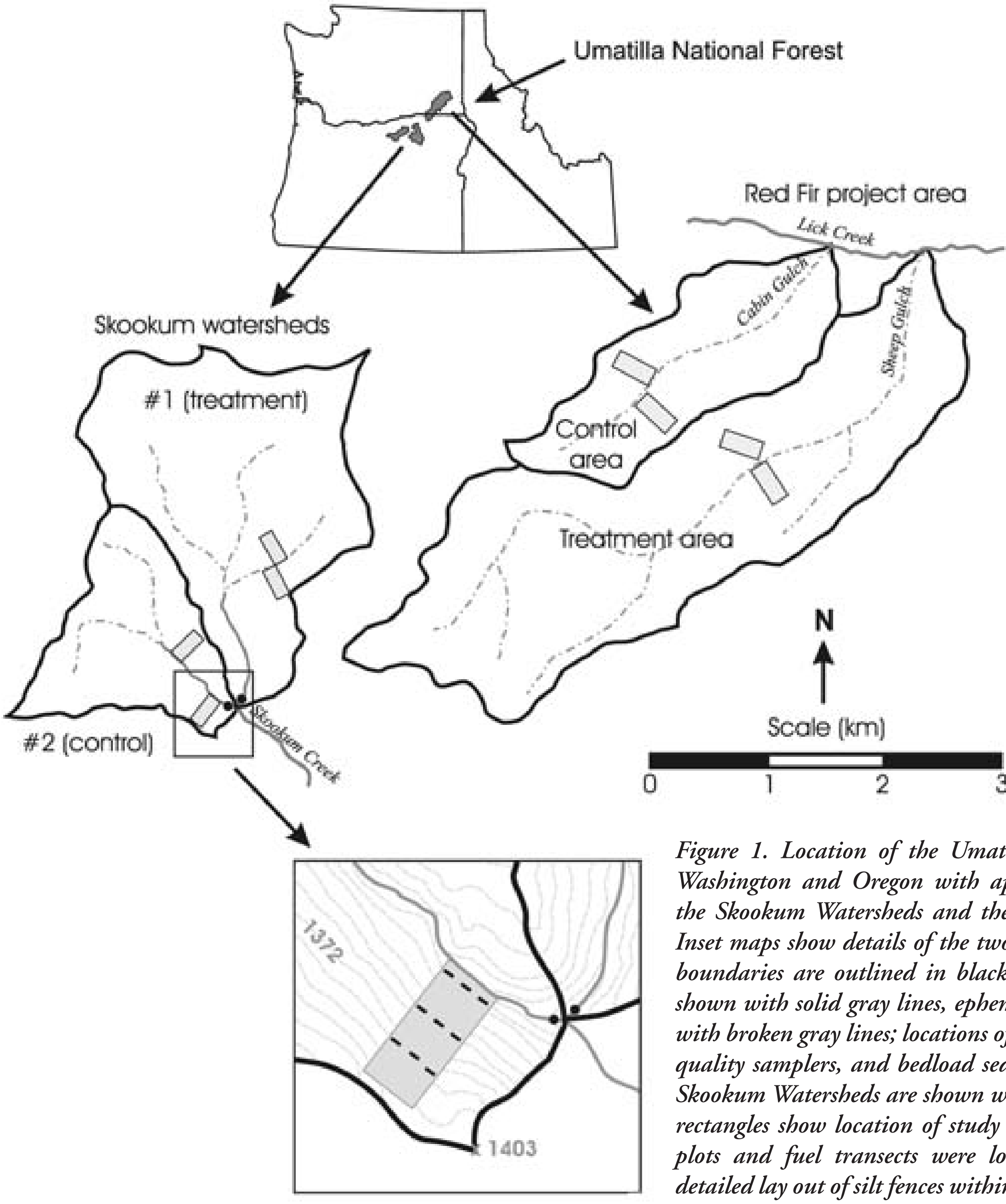


*Figure 1. Location of the Umatilla National Forest in Washington and Oregon with approximate locations of the Skookum Watersheds and the Red Fir project areas. Inset maps show details of the two study areas: watershed boundaries are outlined in black, perennial streams are shown with solid gray lines, ephemeral streams are shown with broken gray lines; locations of the gaging weirs, water quality samplers, and bedload sediment boxes within the Skookum Watersheds are shown with filled circles. Shaded rectangles show location of study hillslopes where erosion plots and fuel transects were located. Inset box shows detailed lay out of silt fences within a single study hillslope, dashed lines are topographic contours (contour interval 12 m), dark lines within the study plot denote locations of silt fences. There are three fences each, at upper-, mid-, and toe-slope positions.*

conducted in other regions, and from studies of wildfire, logging, and road building practices. Empirically derived data are needed to support revision of National Forest management plans and to plan fuels reduction treatments, particularly in the wildland-urban interface and in watersheds with Endangered Species Act-listed salmon.

This study is designed to collect data on background erosion rates and to examine the effects of prescribed fire on hillslope soil erosion and stream sedimentation. We report 11 years of background discharge and sediment yield data, and two years of background hillslope erosion data, from the Skookum paired-watershed study. We also present preliminary results from two years of post-treatment data from the Red Fir prescribed burn project.

## Study Area

The project areas are located in the northern Blue Mountains of the interior Columbia River basin in a region characterized by uplifted, dissected volcanic plateaus. The Skookum paired watersheds are located in the John Day River basin in northeast Oregon. The Red Fir prescribed

*Table 1. Skookum, Red Fir, and Lick Creek study area descriptions.*

| | Skookum Project | Red Fir Project | Lick Creek Project |
|---|---|---|---|
| **Area (km²)** | 8 | 6.8 | 6.3 |
| **Elevation range (m)** | 1,220 - 1,730 | 915 - 1,370 | 1,250 - 1,555 |
| **Average precipitation (cm)** | 56 | 38 | 89 |
| **Aspect** | north and south | north and south | north |
| **Treatment date** | Deferred | October 2002 | October 2004 |

burn project is located on a tributary of the Asotin River in the Lower Snake River basin in southeast Washington (Figure 1, Table 1). Forest conditions are similar at both project areas. Dry south- and west-facing slopes are characterized by open stands of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*). Hillslope hollows with deeper soils typically have mixed dominance, with abundant western larch (*Larix occidentalis*) and lodgepole pine (*Pinus contorta*). Ridge-tops, north, and east slopes have denser, mixed stands of larch, lodgepole pine, and grand fir (*Abies grandis*). Historically, fire regimes were mixed, with areas of low, moderate, and high-severity fires (Arno 2000), but none of the project areas have experienced a stand-replacing fire in recent times. Fuel loadings on dry south-facing slopes appear to have changed little from historical conditions. In contrast, fuel loadings have changed dramatically in wetter and cooler sites where fire exclusion led to increased density of shade tolerant conifers (Franklin and Agee 2003). In the Skookum watershed, ridge tops and north-facing slopes that previously supported dense stands suffered high mortality in the most recent (1990) spruce budworm (*Choristoneura* spp.) outbreak. Since then, many dead trees have fallen, and loadings of downed woody fuels have reached 224 tonnes/ha in some areas. Grasses and forbs now grow densely within stands of dead timber, especially on north-facing slopes, and a variety of coniferous species are establishing in these areas.

The Skookum project area, about 8 km$^2$ in size, is located in the headwaters of Skookum Creek (lat 45°5'N, long 119°28'W), a tributary to the North Fork John Day River near the town of Monument, Oregon (Figure 1). Elevations in the project area range from 1220 to 1730 meters. The watershed is within a designated roadless area and is relatively unaffected by past timber management. Two adjacent tributaries (control and planned treatment) were instrumented for a paired catchment study in 1992. The watersheds were fenced to exclude domestic livestock at that time. The larger watershed, Skookum #1 (5 km$^2$) was designated as the planned treatment watershed and the smaller watershed, Skookum #2 (3 km$^2$) was designated as the control. In 2002, monitoring in both watersheds was expanded with the installation of erosion plots to measure rates of hillslope erosion, down slope transport, and delivery of sediment to stream channels. A 1998 prescribed burn plan called for controlled burning in the treatment watershed and adjoining areas, leaving the control watershed untreated. By spring of 2004, planned treatments had not been implemented in large part because of weather and fuel conditions, and the existing plan was deemed out of date.

The Red Fir prescribed burn project is located in southeast Washington in tributaries to the North Fork Asotin River (lat 46°15'N, long 117°25'W) in the lower Snake River drainage, near the town of Pomeroy, Washington (Figure 1). Elevations range from 915 to 1555 meters. Treatment hillslopes include both south and north-facing slopes. Control plots were established on hillslopes with similar aspects in an adjacent drainage approximately 1 km away. These control hillslopes had been treated with prescribed fire in 1999 but the effects of this earlier prescribed burn are unlikely to influence erosion rates measured in this study because ground cover vegetation appeared to have recovered completely by 2002. The Red Fir project, implemented in 2002, was a Forest Service district prescribed burn designed to reduce fuel loading.

## Methods

The study was designed to take advantage of the existing Skookum paired-watershed study and fuels reductions treatments already planned by the USFS. The Skookum watersheds, with 11 years of pre-treatment data, provided a rare opportunity to examine erosion budgets at multiple scales and within the context of longer-term water and sediment yield. Thus we augmented existing measurements with silt-fence erosion plots to measure hillsope erosion rates within both of the Skookum watersheds. We recognized the possibility that the watersheds would not be treated as planned due to their large size, lack of roads, heavy fuel accumulations, and the fact that they are contiguous with a large roadless area. The risks and consequences of an escaped prescribed fire would be substantial. Therefore we considered other planned prescribed fire projects within the Blue Mountains. The Red Fir prescribed burn project, which had a high probability of taking place as planned, had relatively easy access, and contained planar hillslopes with nearby controls, was selected to measure hillslope erosion and down-slope transport of sediment. This site was not located within gaged, experimental watersheds and therefore lacks the long period of pre-treatment monitoring available at the Skookum watersheds. Also, because of the timing of the treatments, no pre-treatment data could be collected and analyses focus on comparison between treatment and control sites only, without reference to background conditions.

**Hillslope Erosion Plots**

Variable-area erosion plots were used to measure hillslope erosion rate in both project areas. In the Skookum project area, plots were established at both the control and proposed treatment watersheds in July 2002. At the Red Fir site, erosion plots were established in the control in July 2002, and one week after the sites were burned in October 2002. Erosion plots on the treated hillslopes at the Red Fir site were located and staked with steel fence posts at the time that the control plots were established to avoid unintentionally biasing plot placement to sample areas of greater (or lesser) burn intensity.

Sediment fences were located on planar hillslopes (neither concave nor convex across the contour) so that calculated erosion rates would not be confounded by convergent or divergent patterns of overland flow. Fences were laid out in transects consisting of three replicates, spaced 30 m apart, with transects located at upper-, mid-, and toe-slope positions along the length of the hillslope. Sediment fences were designed following the methods described by Robichaud and Brown (2002), and were made from black silt-fence fabric supported with light-weight metal fence posts (Figure 2). Each fence is 5 m wide and oriented perpendicular to the hillslope (or parallel to the contour). Two features of our design differ from the design described by Robichaud and Brown (2002). First, we used 1.83-m-wide fabric, using the excess width to form a contiguous apron, covering the soil surface and extending 0.5 to 0.8 m upslope of the actual sediment fence, to allow collection of small amounts of sediment without accidentally collecting any of the underlying soil. Secondly, all plots are "unbounded" so the contributing area of each plot is defined by a variable area of hillslope that contributes runoff, surface erosion and dry ravel over the period of measurement. We used unbounded plots because they provided an estimate of cumulative erosion rates along the length of the hillslope so that differences between transects can be used to calculate net erosion and deposition rates along the length of the hillslope. If net downslope transport of eroded sediment occurred, it should be evident in a downslope increase in the amount of sediment collected. The amount of sediment collected in the toe-slope transects, alone, measured the gross delivery of sediment to the valley floor.

Sediment in the fences was collected in late spring (after snowmelt) and again in the fall. Additional collections were planned following all intense summer rainstorms that generated significant overland flow; however, such storms have not occurred in the study areas to date. To collect the accumulated sediment, all large branches, sticks and cones were first removed and discarded. Large accumulations of dirt were collected with a trowel, and the fence apron was then swept with a whisk-broom and fine sediment was collected with a dust pan. Collected materials were labeled, bagged, and transported to the laboratory. In the laboratory, larger organic debris was separated by hand and discarded. The remaining sample was sieved into size-fractions, oven dried (96 hr at 55ºC), and weighed. The oven-dried samples were combusted in a muffle furnace (10 hr at 600ºC) to burn off residual organic matter and

*Figure 2. Example of a sediment fence. The fence is 5 meters wide, 0.5 m tall, with a 0.8 m long apron. The upslope edge of the apron is buried in a shallow trench. See Robichaud and Brown (2002) for installation details.*

then re-weighed. The weight of the remaining sample was corrected for the residual mineral content from the combusted organic materials, assuming that the mineral content of organic matter averaged 5.05 percent (Wondzell, unpublished data).

A variety of additional measurements were collected to characterize conditions at each erosion plot. These measurements were taken in a plot measuring 10 m wide, starting at the sediment fence and extending upslope for 10 m. Slope and aspect of the plot were recorded. Duff thickness was measured at 0.5-m intervals along the length of the upslope, vertical face of the 0.1-m-wide trench into which the upslope end of the silt-fence material was buried. Visual estimates of the percent cover of ash, charcoal, bare ground, gravel, rock, duff, wood, and vegetation were made. These estimates focused on the ground surface exposed to direct raindrop impact so that the sum cannot exceed 100%. Further visual estimates of vegetation cover were made to break total canopy cover into the following growth forms: grasses, forbs, sub-shrubs, shrubs, and trees. These measurements were collected from both control and treatment plots during the summer prior to the prescribed burn, directly after the burn, and every summer after treatment. Photographs of the plots were taken from the plot perimeters: from the mid-point of the silt fence and from the mid-points of the upper and side boundary lines of each plot (Figure 3 and 4). Fuel load transects were established at each hillslope in the Skookum project area. Four, 15.24-m fuel load transects were spaced across each hillslope position, alternating with the silt fences, for a total of 12 fuel load transects per hillslope. Data were collected following methods described by Brown (1974).

**Paired, Small-Watershed Study**

The Skookum Experimental Watershed Study was established 1992. Measurements collected within the Skookum study area include stream discharge, suspended sediment, annual bedload sediment yields, water and air temperatures, and precipitation. Annual summaries of total yields are made on a water-year basis – from 1 October through 30 September of the following year. The control and treatment watersheds are instrumented with 120 degree V-notch weirs. Stream stage is measured at the gaging stations by float sensors in stilling wells. From 1992 to 2001, stage was recorded on punch tapes at 15-minute intervals using a Fisher-Porter[1] analog to digital recorder. Stage data were converted to discharge using the program HYDRA and the rating equation for a 120-degree V-notch

*Figure 3. Red Fir project area, Sheep Gulch South, plot #3, a south-facing plot in an upper slope position. The photograph was taken looking across the erosion plot on 14 August 2002, before the prescribed fire.*

*Figure 4. Red Fir project area, Sheep Gulch south, plot #3 photographed on 28 October 2002, immediately after the prescribed fire from almost the same location as Figure 3. Much of the large log visible in the foreground of Figure 3 was consumed by the fire. Loss of some shrub cover exposed logs not visible in Figure 3.*

weir (Rantz et al. 1982). In 2001, the Fisher-Porters were upgraded to Design Analysis H-510 digital recorders.

Stream water samples were collected using battery-operated pumping samplers with intakes positioned in the deepest part of the channel, approximately 15 cm above the streambed. Samplers were programmed to collect a daily composite sample consisting of four samples drawn at six hour intervals (midnight, 6:00 AM, noon, 6:00 PM). The samples were analyzed for total suspended solids at the Umatilla National Forest water laboratory in Pendleton, Oregon.

Bedload was collected using in-channel bedload boxes, measuring approximately 1.5 m long, 0.7 m wide, and

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

0.7 m deep, with plywood sides and bottom, set into the stream channel with the upstream lip set flush with the streambed. The bedload boxes spanned the full width of the active stream channel. Boxes were emptied once a year by diverting the stream, draining the box, and shoveling the collected sediment into a bucket. The total volume of collected sediment was measured in "buckets" and later converted to a dry weight. In both 2002 and 2004 a sub-sample of the bedload sediment was collected from Skookum #1; only small amounts of sediment had accumulated in the bedload box of Skookum #2 in these years so the entire amount was collected. Wet volumes of the collected sediment were measured in a graduated beaker and then oven dried at 55ºC until successive weighings had stabilized, indicating that all water was evaporated from the sample. Samples were sieved into particle-size fractions and weighed. In all cases, samples contained large but variable amounts of water, which had a substantial effect on estimated conversion factors from wet volume to dry weight (mean = 0.55 kg dry sediment per liter wet bedload sample; SD = 0.25). We combined data from both watersheds, weighted by the wet volume of each sample, to estimate a conversion factor, 0.60 kg dry sediment per liter wet bedload sample, that most closely approximated the volumes measured as the bedload traps were emptied.

Water and air temperatures were recorded at hourly intervals using an Onset HOBO[1] temperature logger. From 1992 to 2003, precipitation was measured using a Fisher-Porter punch tape weighing precipitation gage equipped with an antifreeze and methanol reservoir to capture snow precipitation. Measurements were logged at 15-minute intervals. In 2003, a tipping bucket raingauge equipped with a snow conversion kit was installed to replace the Fisher-Porter raingauge.

**Data Analysis**

A hierarchically nested sampling design was used to study erosion across scales, from the plot scale up to the whole watershed scale. Individual plots provided point estimates of erosion rates, differences between transects in different hillslope positions traced the transport and redistribution of sediment along hillslopes, the toe-slope transect of sediment fences measured the amount of sediment delivered to valley floors. At the Skookum Watersheds, the automated water samplers and bedload boxes quantified the amount of sediment leaving the watershed.

***Hillslope Erosion Plots:*** Erosion rates among blocks of erosion plots were examined for significant differences ($\alpha = 0.05$) using analysis of variance (ANOVA). Data were first natural-log transformed because raw erosion data were highly skewed (many small values and few large values). Because this project is in progress, analyses of the sediment collections completed to date are complicated by an unbalanced number of sampling periods – with three sample collections completed (spring 2003, fall 2003, and spring 2004). Preliminary analyses showed that erosion rates were not significantly different between season (spring 2003, fall 2003) or year (spring 2003, spring 2004), consequently, the amounts of sediment collected from each plot were summed across all measurement dates and divided by the 1.66 years for which the sediment fences have been in place, thereby converting mass of sediment collected to an annual erosion rate. Separate analyses were conducted for each project area. The Skookum project has not been treated, but allows investigation of background erosion rates and the influence of aspect and slope position on these rates. The Red Fir project was treated with prescribed fire and thereby allows investigation of prescribed fire effects on erosion rates.

The first step in the analyses for each project area was to examine the effect of slope position against the hypothesized relation that would be expected if eroded sediment was transported the length of the hillslope resulting in a net, down-slope accumulation of eroded sediment. Separate ANOVA analyses were conducted for each project area. ANOVA analyses showing a significant affect of slope position ($\alpha = 0.05$) were further examined using Tukey means comparisons tests to identify hillslope positions with significant differences. These analyses were conducted by combining plots from all hillslopes within a project area (aspect and treatment combined); by examining plots divided into analysis blocks by aspect (proposed treatments combined); and finally, by examining plots divided into analysis blocks for each individual hillslope. The relatively small number of erosion plots (three within a single transect at a given slope position) and the high variability between plots suggested that this test would have little power to detect small differences. Consequently, we also examined the data looking for non-significant differences that followed the hypothesized trend. If there was no evidence that erosion rates measured within a single hillslope were dependent upon slope position (i.e., lack of significant differences in the means comparison tests; lack of hypothesized trend) we dropped slope position as a categorical variable and treated each plot as an independent replicate in all subsequent analyses.

To examine the effect of aspect on annual erosion rates, all nine erosion plots on a single hillslope were treated as independent replicates, grouped into a single block within the ANOVA. As before, project areas were analyzed separately. Data from treated hillslopes within the Red

Fir project area were not used in this analysis because the results could have been confounded by unbalanced treatment effects. ANOVA analyses showing a significant effect of aspect ($\alpha = 0.05$) were further examined using a Tukey means comparison test to further identify specific differences in annual erosion rates related to aspect.

Erosion rates measured on the Red Fir erosion plots were examined for significant differences ($\alpha = 0.05$) resulting from the prescribed fire treatment using ANOVA. Separate analyses were conducted for north-facing and south-facing hillslopes. These analyses were confounded by an unbalanced treatment effect (despite a balanced experimental design). The prescribed fires were set at ridge top and upper slope positions and allowed to spread downhill, but failed to reach toe-slope transects on the south facing slopes and both toe-slope and mid-slope transects on the north facing slope. Because erosion plots were treated as independent replicates, unburned plots were grouped with control plots, resulting in 6 burned plots and 12 control plots with southerly aspect and 3 burned plots and 15 control plots with northerly aspect. Treatment sample sizes were very small so the data need to be interpreted with caution.

To further clarify the relation between hillslope erosion rates and the factors typically related to surface erosion, a regression analysis was conducted using the continuously distributed variables: slope, average duff thickness, and the natural-log transformed average of bare ground plus ash. A backward, stepwise procedure was used to eliminate non-significant variables ($\alpha = 0.05$). Relating the average annual rate of observed hillslope erosion to the amount of bare ground plus ash was complicated by the fact that ground cover estimates were repeated each summer. Relatively little change was observed, through time, on control plots, but large changes in the amount of bare ground and ash were apparent on the treated plots. Consequently, use of the time-averaged bare ground plus ash in the regression analysis might obscure results. Therefore, the regression analysis used the data from each collection date, expressed as an annualized rate (rather than the average of all three collections). We assumed that ground cover would change little over the winter, so that the bare ground estimates from summer 2002 were regressed against spring 2003 erosion rate; bare ground estimates from summer 2003 were regressed against fall 2003 and spring 2004 erosion rates.

***Watershed-scale Sediment Budgets:*** Data collected from the Skookum Experimental Watersheds provides a time-series of precipitation inputs and water and sediment yield over the 11 pre-treatment years of study. Runoff ratios (total annual precipitation divided by total annual water yield) were calculated from these data. Annual runoff ratios and yields from the two watersheds were analyzed to see if differences between watershed means (the 11-year mean annual unit-area runoff ratios and yields of water, suspended sediment, and bedload sediment) were significantly different than zero ($\alpha = 0.05$). Finally, average annual yields were calculated by averaging total annual yield over the 11 complete years of measurement data currently available (1993 through 2003, inclusive).

## Results

### Skookum Experimental Watersheds

Precipitation and water yield in the Skookum watershed during the pre-treatment period showed high inter-annual variability with large differences in unit area water yields between catchments (Figure 5). The 20-year average precipitation measured at Madison Butte Lookout, a Natural Resource Conservation Service SNOTEL site located at the headwaters of the Skookum watersheds was about 56 cm per year. Of pre-treatment years sampled, six had below average precipitation, while four years were above average. Unit area water yields from Skookum #1 (proposed treatment watershed) were significantly higher than yields from Skookum #2 (control watershed) ($p = 0.013$). Runoff ratios were also significantly higher in Skookum #1, where annual runoff was 19 percent of precipitation inputs compared to 14 percent of precipitation inputs in Skookum #2 ($p = 0.006$).

Suspended and bedload sediment yields showed high inter-annual variability in both watersheds (Figure 5). Unit area suspended sediment yields were significantly higher in Skookum #1 than in Skookum #2 ($p = 0.037$), even though the two catchments have similar geology, soils and vegetation. Suspended sediment yields from Skookum #1 peaked in 1995 and 1996, and decreased dramatically the following year, 1997, the year with the highest water yield observed over the period of record. Similarly, unit area bedload yields are significantly higher in Skookum #1 than in Skookum #2 ($p = 0.006$). Bedload yields from Skookum #1 peaked in 1995 and decreased gradually thereafter. Suspended sediment comprises more than 99% of the total sediment yield from both watersheds.

There were no significant differences in hillslope erosion rates within the Skookum watersheds among upper-, mid-, and toe-slope positions when the data from all plots was combined or when analyzing north-and south-facing plots separately. Examining the four hillslopes individually resulted in one case where erosion rate varied significantly with slope position ($p = 0.009$). The means comparison test, however, showed that the rate measured at mid slope (50.18 g/m hillslope width) was significantly higher than

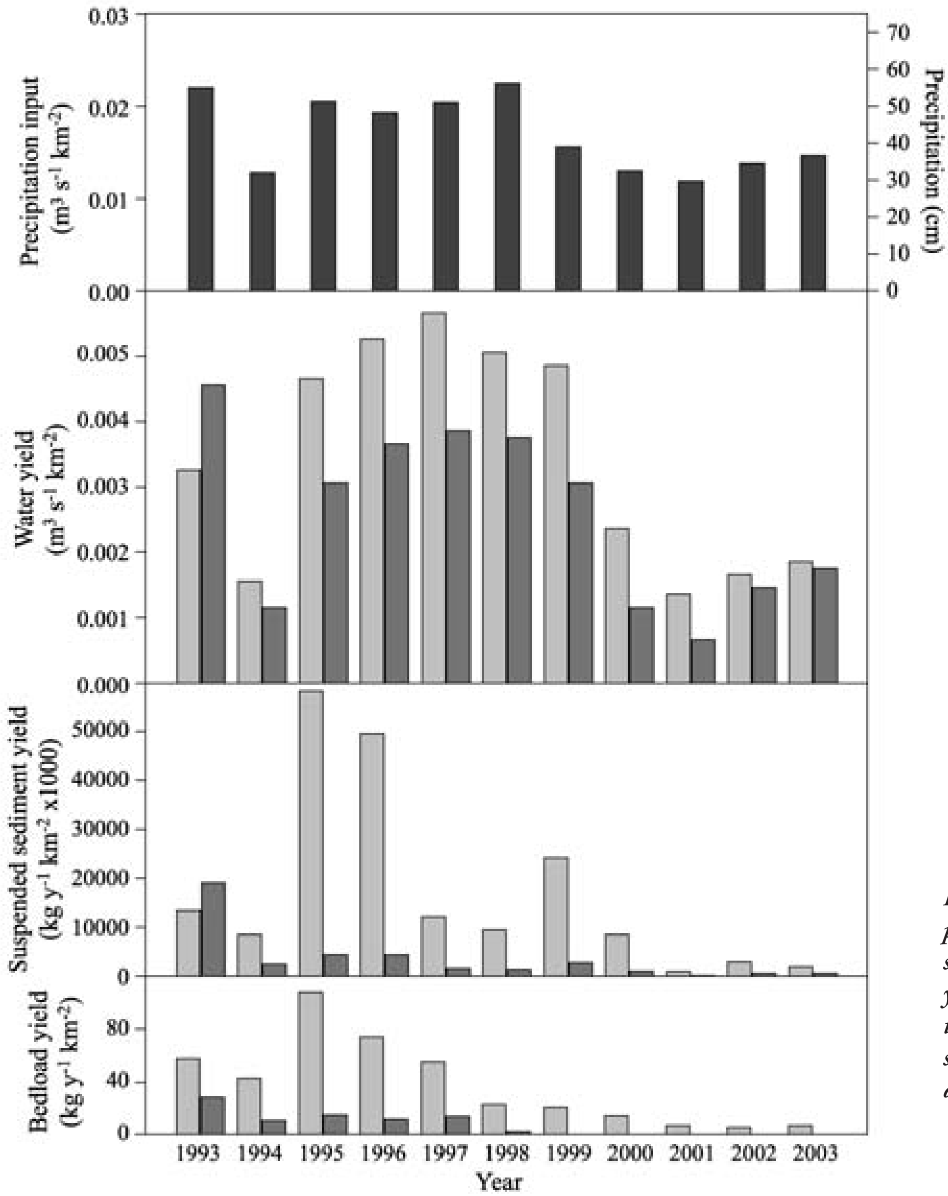


*Figure 5. Skookum project area annual precipitation, water yield, suspended sediment yield, and bedload sediment yield from 1993 through 2003. In the lower three panels, Skookum #1 is shown in light gray, Skookum #2 in dark gray.*

at either the upper slope (9.04 g/m) or the toe slope (8.08 g/m). In no case did the observed trends support our hypothesized relation of a net, down-slope accumulation of eroded sediment at the sediment fences caused by sediment erosion and subsequent transport along the length of the hillslope.

Annual hillslope erosion rates were strongly influenced by aspect, with significantly higher rates on south-facing hillslopes than north-facing hillslopes (Figure 6). Soils on south-facing slopes were more exposed, with less cover of litter and duff than on north-facing slopes. We observed frequent signs that animal burrowing activity on the south-facing aspects was contributing local sediment to the sediment fences. We did not observe signs of burrowing activity and sediment loading of the fences on the north-facing aspects.

**Treatment Effects**

At the Red Fir site, there was no significant difference between the burned and unburned plots in the annual hillslope erosion rate averaged from the three collection dates (Figure 7). On the north-facing treatment hillslope, the prescribed fire burned only the upper three plots, leaving six of the plots (middle and lower) unburned. On the south-facing treatment hillslope, the prescribed fire burned the upper and middle plots, leaving the three lower plots unburned. In our analysis, the unburned erosion plots in the planned treatment block were grouped with the control plots. The resulting data structure was highly unbalanced, and had little statistical power to resolve the small differences observed between the burned and unburned plots (Figure 7). At the Red Fir site, elk are

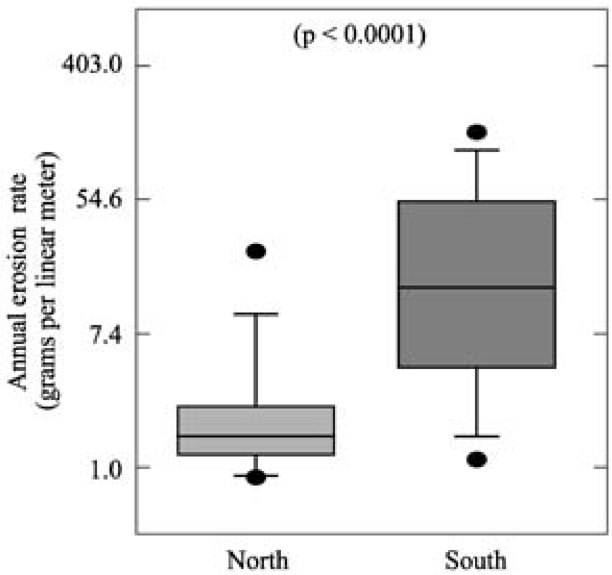


*Figure 6. Comparisons of annual erosion rates between north- and south-facing hillslopes in the Skookum project area during the pre-treatment phase of the project (n = 18 for each box). Box and whisker diagrams show median values (fine line in the filled box), 25th and 75th percentiles (box), 10th and 90th percentiles (whiskers) and individual observations beyond the 10th and 90th percentiles.*

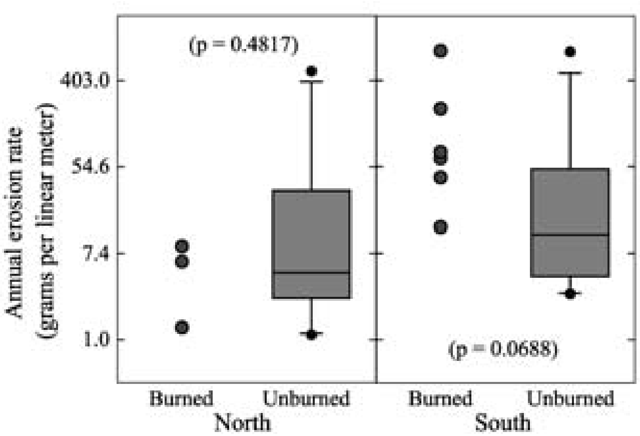


*Figure 7. Comparison of annual erosion rates between burned and unburned plots on north and south aspects at the Red Fir project area (north, unburned, n = 15; south, unburned, n = 12). Box and whisker diagrams show median values (fine line in the filled box), 25th and 75th percentiles (box), 10th and 90th percentiles (whiskers) and individual observations beyond the 10th and 90th percentiles.*

*Figure 8. Red Fir project area, Cabin Gulch south, plot #6, a south-facing mid slope plot. Note the obvious bioturbation caused by elk walking above the sediment fence when the ground was wet, accumulation of sediment, short delivery distances, and damage to the sediment fence.*

attracted to the erosion plot silt fences, and there is evidence of damage to the plots, especially on the south-facing control hillslope (Figure 8). Much of the erosion measured in these locations appears to be caused by elk trampling above the silt fence.

Exploratory data analysis suggested that the amount of bare ground was positively correlated with the observed annual erosion rates. Backwards, stepwise regression analyses showed that natural-log transformed sum of bare ground plus ash was more highly correlated to erosion than were either slope angle or duff thickness. The relation between the area of bare ground and erosion also appears to vary with aspect, with an equivalent bare ground area supporting higher erosion rates on south-facing aspects than on north-facing aspects (Figure 9). The amount of bare ground plus ash was usually higher in burned plots than in unburned plots, and on south-facing aspects, burned plots had among the highest observed erosion rates. Burning leads to substantially reduced ground cover and increased areas of the soil surface covered by ash in the time immediately after the fire. However, this cannot be linked to the treatment effects in the statistical analysis

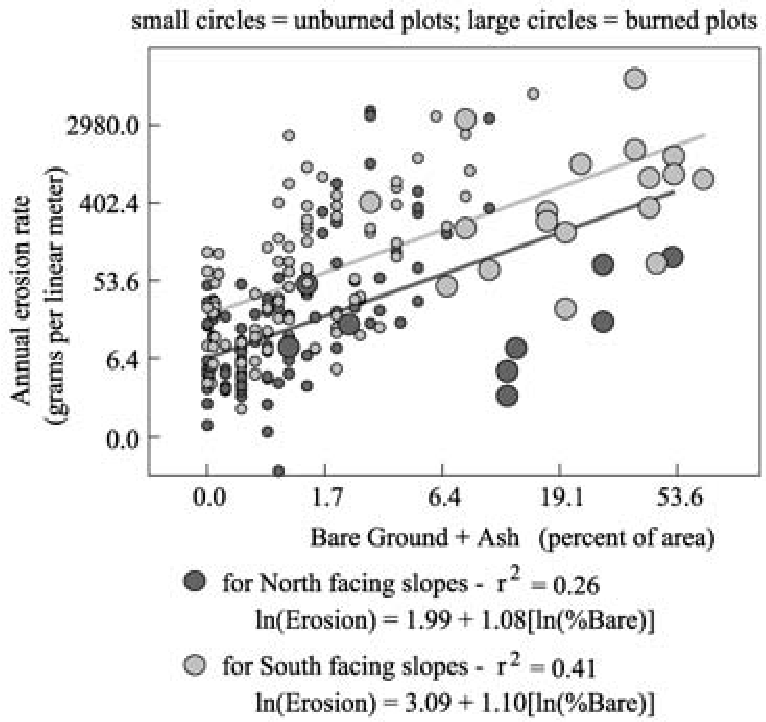


*Figure 9. Skookum and Red Fir project areas bare ground plus ash percent of plot area vs. annual erosion rate. Burned plots are denoted with large filled circles; unburned plots with small filled circles.*

because of the small number of burned plots and the highly unbalanced sample design.

## Discussion

### Background Natural Disturbance – The Spruce Budworm Outbreak

The Skookum Experimental Watersheds are a paired watershed study with 11 years of pre-treatment data on discharge, suspended sediment, bedload sediment, and water temperature. Our study design called for establishing erosion plots one full year before implementing the prescribed burn which would allow a "Before-After/Treatment-Control" study design to examine changes in sediment budgets at scales ranging from the plot, to the hillslope, to the whole watershed. For a variety of reasons, however, the Skookum watersheds were not treated, turning this into a study of background erosion rates. The study remains valuable because it provides information on baseline erosion rates from watersheds with volcanic parent materials within the Blue Mountain physiographic province. These results will be useful in the design and evaluation of future projects for purposes of improving erosion estimates, understanding the range of natural variability, and calibrating predictive models.

The degree to which the extensive forest mortality resulting from the spruce budworm outbreak in the early 1990s contributed to the changes in water and sediment yields observed over the period of record is an intriguing question. Suspended sediment yield peaks in 1995 and 1996 may be related to the forest mortality from the spruce budworm outbreak. Loss of the forest canopy would have exposed the soil surface to direct impact of raindrops and decreased transpirational losses might have led to increased runoff, both of which could contribute increased amounts of sediment to channels and help transport this sediment out of the watersheds. Residual live trees remaining in areas where most trees had died would have been more exposed to wind, and were probably more likely to be toppled during windstorms in the years immediately following the catastrophic die off of the canopy. Root wads from toppled trees provided exposed, easily detached soil that was available for erosion. Eroded sediment from root wads in toe-slope, riparian, and stream-bank positions may have contributed to the peak yields of suspended and bedload sediment observed in 1995 and 1996.

Understory vegetation is now dense, especially on northwesterly through easterly aspects because loss of the forest canopy has increased the amount of light available to forest floor vegetation. Further, as root systems and boles of insect-killed trees began to rot away, the trees would have been much less wind-firm, falling under the forces of gravity, snow loading, and wind. Dense vegetative cover now protects the soil from erosion and increased downed logs now provide an abundance of sediment storage locations on the hillslopes. Further, transpiration from the dense understory has probably reduced water yields from the watersheds. A combination of all these processes could explain the reduced water and sediment yield since 2000. However, annual precipitation has also been below average since 1999, which may also contribute to decreased sediment yields in recent years. Without pre-budworm outbreak data, however, the identification of causal mechanism is speculative. Overall, large differences in sediment yields between watersheds, high inter-annual variability, and confounding affects from extensive forest mortality would likely make it difficult to discern prescribed fire effects on watershed-scale sediment yields unless these were very large.

**Hillslope-scale Erosion and Sediment Transport**

Infiltration-excess overland flow is a major driver of erosion in the intermountain west, especially following fire [see reviews by Wondzell and King (2003)]. While there is little direct research on the influence of prescribed fire on erosion, research following wildfire suggests that the potential to increase erosion rates is correlated to fire severity. Large, stand-replacing wildfires have the greatest impact on soil properties that influence erosion. Most prescribed fires are set when weather and fuel conditions make large, high severity fires unlikely. Even if prescribed fires did increase potential hillslope erosion rates, without large storms to generate overland flow in the year or two after the burn, significant erosion is unlikely.

We never observed evidence of overland flow that would have driven surface erosion and downslope transport of eroded sediment at any of our study sites over the course of this study. Without major storm events to drive extensive overland flow, the physical mechanism that would drive erosion and down-slope sediment transport is lacking. Under these conditions it is not surprising that observed patterns of erosion did not support the hypothesized relation of a net, down-slope accumulation of eroded sediment at the sediment fences. Rather, observations made while emptying the erosion fences suggested that the hillslope area contributing sediment to the erosion fences was very small, perhaps extending no more than a meter upslope of the fence apron. In the most part, erosion resulted from bioturbation. Clods of dirt appeared to have been kicked onto the fence aprons, judging from the deep footprints elk left in wet soil immediately above the fences in several locations. Similarly, small mammals digging immediately above the plots send small amounts of dirt into the fences. All these facts combined suggest that each sediment fence functioned as an independent sample unit under the conditions during which these study was conducted.

**Watershed-scale Sediment Budgets**

The design of this study allowed estimation of both total sediment delivery to the stream channel and net sediment yield from the watershed. The difference between these two values was the net channel erosion rate, where positive values represented channel aggradation and negative values represented bank erosion or channel incision.

Preliminary estimates of background hillslope erosion rates suggested that low amounts of sediment are delivered to valley floors within each catchment, as measured with the silt fences located in toe-slope positions. A simple, watershed-scale budget of sediment delivery was made by estimating the length of mainstem channel, and clearly defined tributary channels within each watershed and multiplying by a sediment delivery rate. We assumed that the sediment delivery to each meter of valley-floor length equaled two-times the overall average hillslope erosion rate measured from all 32 hillslope erosion plots within the Skookum watersheds (i.e., one side of the valley floor receiving sediment inputs at the rate measured on south-aspect hillslopes; the other side receiving sediment inputs at the rate measured on north-aspect hillslopes). Skookum #1 had 3.40 km of mainstem channel and 5.33 km of tributary channel; Skookum #2 had 2.29 km of mainstem channel and 1.96 km of tributary channel. The calculations showed that, on average, 52 kg of sediment were delivered to the valley floor of Skookum #1, while valley floors in Skookum #2 received an average of 25 kg/y.

Watershed-scale estimates of sediment yield derived from water samples collected at the outlet streams suggest sediment losses hundreds of times greater than sediment delivery rates to the valley floors (12,000 kg/y from Skookum #1 and 3,000 kg/y from Skookum #2). Assuming that the dry bulk density of suspended sediment is 1.7 g $cm^{-3}$ and assuming an average wetted perimeter of 0.70 m for mainstem channels and 0.35 m for tributary channels, and assuming that sediment is eroded evenly from the entire channel network, annual sediment yields could be accounted for by 3 to 12 mm of streambed and streambank erosion. Most of the annual sediment yield is comprised of suspended sediment, and most of this is removed from the watershed by peak flows during spring snowmelt. Our calculations probably overestimate the degree of stream erosion needed to supply annual sediment yields because the calculations do not include sediment eroded from hillslope hollows lacking obvious channels that are connected to the stream network during snowmelt. Because sediment may be stored on valley floors for long periods of time, continued erosion of stored sediment may maintain elevated sediment loads in streams, even when little erosion is occurring on upland sites. The results of both the hillslope- and watershed-scale erosion patterns highlight the influence of episodic hillslope erosion events, sediment storage on floodplains, and minor amounts channel erosion on watershed-scale sediment budgets.

## Concerns and Issues for Management

Requirements for species protection under the Endangered Species Act have caused many changes in project design. In general, riparian protection requirements limit the scope of management activities in these areas. To date, prescribed fire treatments are generally designed to have no measurable effect on streams and riparian areas for consultation purposes under the Endangered Species Act. Design criteria include not burning within the riparian conservation area (riparian and buffer zone) and limiting total area in bare soil in the project area. Results presented in this paper validate the design of treatments for no effect to aquatics under "normal" weather conditions. Avoiding active treatment within riparian areas may, over the short term, prevent direct effects of sedimentation to streams but riparian conditions, including fuel loading, may or may not be at desired levels in a project area. Further, at the landscape scale, effective fuels treatments to reduce uncharacteristic wildfire risk may in some cases conflict with riparian protection management standards (generally interpreted as no active treatment). Active riparian treatment using prescribed fire may be desired in certain circumstances for purposes of improving riparian conditions and reducing landscape-scale wildfire severity.

## Future Work

Sampling of erosion plots will begin at a third fuels treatment project, the Lick Creek site, in June 2005. Fuel conditions forest wide are increasingly complex, and managers are turning to combined treatments of mechanical thinning and burning to reduce fuel loads. These types of treatments will be more common in the future, and the Lick Creek project will provide data on combined treatment effects on hillslope erosion rates. Additional study plans include: 1) analyzing Skookum fuel load measurements; 2) comparing hillslope erosion to changes in channel morphology using stream reference reaches; 3) comparing pre- and post-burn fuel load measurements for Lick Creek; 4) comparing results with FSWEPP modeled results; 5) sharing data with FSWEPP developers for local model calibration; 6) sharing study results with local managers for use in developing project effects analysis; and 7) archiving data in the Pacific Northwest Forest Science Databank.

## Summary

Challenges faced in this study include the uncertainty of treatments being implemented and short timeframes during which measurable effects were likely. Successful implementation of planned prescribed fire projects was often uncertain because of stringent requirements for burning, availability of resource personnel, and competing priorities. Once implemented, timeframes in which to measure potential effects were limited by relatively rapid recovery of understory vegetation and the likelihood of significant storms occurring during this period was relatively low. As a result, responses under more extreme weather conditions such as winter rain-on-snow events or intense summer convective storms were difficult to capture.

The preliminary data reported here showed that background hillslope erosion rates varied significantly by aspect and were generally higher on south-facing slopes. At the watershed scale, annual sediment yields were highly variable. Watershed sediment budgets showed that episodic erosion events most likely control sediment delivery to streams but that sediment storage in valley floors and subsequent removal via bank erosion influences annual sediment yields over the long term. Without large storm events in the first two years after prescribed fire, there was no significant difference in hillslope erosion between burned and unburned plots. The significant relationship between bare ground and erosion rates demonstrated the role of soil cover in controlling surface erosion.

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# Long-Term Ecological Changes With Postfire Emergency Seeding

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Post-fire emergency response treatments are developed to immediately protect life, property and watershed related values. However, many treatments have long-term effects on the soil and vegetation of the ecosystem. This study compares treated and non-treated vegetative composition eight years following post-fire emergency restoration efforts. The long term effects of seeding native grasses with two types of soil disturbances were evaluated. The use of native grass species for emergency rehabilitation was shown to decrease overall species diversity and prohibit the establishment of several native plant species following fire. Seeding of native grass species was shown to be successful only with treatments that included surface soil disturbance. The long-term implications of emergency restoration seeding and recommendations for its use are discussed.

Keywords: *soil, fire, vegetation, succession, rehabilitation, seeding, native*

## Introduction

The Burned Area Emergency Response (BAER) program has been with the Forest Service since 1975 (USDA FS 2001). The program has evolved from watershed emergency stabilization to a program of emergency protection of identified values at risk. The values at risk under today's BAER program can range from the original watershed emphasis to listed species habitat, cultural resources, and infrastructure (USDA FS 2001). The objectives of the Forest Service BAER program are found in the Forest Service Manual (FSM) 2523 (USDA FS 2004). The objectives are: "To determine the need for and to prescribe and implement emergency treatments to minimize threats to life or property or to stabilize and prevent unacceptable degradation to natural and cultural resources resulting from the effects of a fire". Many types of treatments are prescribed and implemented to reduce the threats to the identified values at risk. The use and necessity of emergency treatments have been questioned as to the success and ecological consequences of treatments (Dellasala et al. 2004). Various monitoring efforts are being conducted to determine the applicability of many treatments to meeting the intended objectives.

One of the most common treatments for the past 30 years has been the use of grass seed to provide a vegetative cover on burned lands to reduce the rain drop impact and runoff energy associated with post-fire rain events. More recently, native grass seeding has been used to reduce the potential for invasive plants. The effectiveness of seeding burned areas, particularly by broadcast aerial or ground methods has been reviewed by Robichaud et al. (2000) and Byers (2004). Reviews of past monitoring information has showed that there is very little quantified data on the effectiveness of seeding burned areas to meet emergency restoration objectives. There is also very little data on long term (5+ years) effects of BAER seeding treatments on the ecological succession of burned areas.

Recently there has been an emphasis on the use of native species for all restoration and rehabilitation treatments. Executive Order 13112, Forest Service policy FSM 2081 (USDA FS 2004), and several Forest Service Regional policies direct the agencies land managers to use native species for any planting or seeding operations whenever possible. The direction to use native species is firm and BAER teams often use native species mixes when seeding treatments are prescribed for post-fire emergency protection. The Forest Service BAER program (FSM 2523) emphasizes natural recovery first and second the use of native species that originate from genetically local sources. Further down in preference is the use of non-native species that are non-persistent and not likely to spread beyond the treatment area.

The effectiveness and ecological effects of seeding are often not quantified during BAER implementation nor post BAER operations. The BAER program provides for funding to determine qualitatively if treatments are installed properly and/or if they are effective at meeting emergency objectives. However, the BAER program cannot fund the validation of treatment types, quantified measurements, nor the effects of treatments beyond the emergency period (FSM 2523). The effects of native species seeding to the post fire ecosystem processes may be much longer than the initial emergency period. There is very little information available on the long term (5+ years) effects of emergency

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seeding of native species in wildfire areas. This study quantitatively looks at the long term effects of native grass seeding as part of a BAER program.

## Study Area

The study was conducted in August 2004 within the 12,000-acre (4860-ha) Buffalo Creek Fire that occurred in May 1996. The fire area is located adjacent to the town of Buffalo Creek, CO and is approximately 50 miles (80 km) southwest of Denver, CO. The pre-fire vegetation was predominantly continuous canopies of Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). A depauperate understory existed under the closed canopies of the conifer species. Soils of the area are derived from the Pikes Peak Batholith (USDA NRCS 1992). The soils are referred to as decomposed granite (DG) soils. The soils are coarse textured with very little soil structure. The clay content is low and the water holding capacity is low. The soils are easily eroded when surface cover is removed. They also have a high potential to produce hydrophobic conditions following fire due to the high amount of coniferous litter and high volume of macro pore space. The elevation of the area is 2300 to 2600 m. Precipitation averages 40-46 cm per year. Severe thunderstorms are common during the summer months.

The human-caused Buffalo Creek Fire was a very complete fire, leaving very few unburned islands of vegetation within the fire area. Approximately 3038 ha of the 4860 ha burn area was mapped as high fire severity (USDA FS 1996a). Hydrophobic soil conditions were reported in the fire area for several years. Infiltration rates were significantly reduced due to the hydrophobic soil conditions (Moody and Martin 2001a). Natural regeneration in the first few years following the fire was poor. There were very few pre-fire herbaceous understory plants or shrubs, and many seeds were consumed during the fire event.

Several major runoff events occurred in the first two years following the fire. These events caused losses to homes, lives, roads, water supply to the city of Denver, and other natural resources. The events removed surface horizons and moved sediment stored in drainages throughout the fire area. (Moody and Martin 2001b)

### BAER Treatments

Emergency BAER treatments were installed in 1996, 1997, and 1998. Treatments varied as to type and location. Restoration measures were prescribed and implemented to protect lives and property, protect water quality, and protect long-term soil productivity. Some of the treatments implemented were grass seeding (aerial and ground), contour felling, contour trenching, dozer ripping, Rotoclear[1] mulching, bank stabilization, channel modification, and water source protective barriers. Grass seeding treatments included broadcast aerial and ground seeding. Species used in the treatments ranged from mixes of non-persistent grains to native grass species. A summary of the grass seeding operations is shown in Table 1.

Ground seeding was done on ground disturbing treatments including dozer ripping and Rotoclear chipping. The dozer ripping treatment included the use of shallow ripper teeth pulled behind a small dozer perpendicular to the slope. A broadcast seeder was mounted on the back of the dozer and seed was spread on the ripped path and outside of the ripped path more than twice the width of the ripped path. The ripped paths were spaced 12-15 m apart. The Rotoclear treatment included the use of a rotating, toothed drum that mulched materials passing beneath it (Figures 1 and 2). The Rotoclear was pulled behind a large Caterpillar D8 dozer. The dozer would

***Figure 1. Rotoclear machine showing rotating drum.***

***Figure 2. Rotoclear machine with dozer.***

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

*Table 1. Summary of seeding treatments for the Buffalo Creek Fire restoration.*

| Treatment | Species in Mix | Percent of Species in Mix by Weight | Estimated Total Pure Live Seeds per square meter | Hectares Seeded | Dates of Seeding |
|---|---|---|---|---|---|
| **Aerial Seeding** | white oats (*Avena sativa*) | 100 | 110 | 2,025 | June 1996 |
| **Aerial Seeding** | white oats | 50 estimated | 210 | 2,025 | March 1997 |
| | slender wheatgrass (*Elymus trachycaulus*) | 25 estimated | | | |
| | Canby bluegrass (*Poa canbyi*) | 25 estimated | | | |
| **Rotoclear** | slender wheatgrass | 23.41 | 430-530 | 405 | August - December 1996 |
| | thickspike wheatgrass (*E. macrourus*) | 25.65 | | | |
| | streambank wheatgrass (*E. lanceolatus*) | 14.05 | | | |
| | green needlegrass (*Nassella viridula*) | 14.49 | | | |
| | mountain brome (*Bromus marginatus*) | 9.87 | | | |
| | Canby bluegrass | 5.05 | | | |
| | Idaho fescue (*Festuca idahoensis*) | 3.75 | | | |
| | Arizona fescue (*F. arizonica*) | 1.01 | | | |
| **Dozer Ripping** | slender wheatgrass | 23.41 | 430-530 | 608 | April - May 1997 |
| | thickspike wheatgrass | 25.65 | | | |
| | streambank wheatgrass | 14.05 | | | |
| | green needlegrass | 14.49 | | | |
| | mountain brome | 9.87 | | | |
| | Canby bluegrass | 5.05 | | | |
| | Idaho fescue | 3.75 | | | |
| | Arizona fescue | 1.01 | | | |

push burned trees over and the Rotoclear mulched the tree into 8- to 13-cm chips and incorporated some of the woody material into the soil surface. The Rotoclear was pulled along the contour perpendicular to the slope. Two 4-meter-wide Rotoclear paths were created, spaced 12 to 15m apart. Grass seed was broadcast over the paths and outside the paths to more than twice the width of the path.

In general, the two aerial seedings did not provide adequate plant establishment. Neither were effective in controlling surface runoff and erosion (Bruggink et al 1998). Most of the seed did not germinate, was lost to overland flow, or was consumed by animals. The Rotoclear and dozer ripping treatments did show some effectiveness in controlling runoff and erosion (Bruggink et al. 1998), however, the effectiveness appeared to be related to the soil disturbance and addition of organic matter that allowed increased infiltration. The native seeding that was included in the treatments did germinate successfully in the areas with some soil disturbance within the first two years of seeding, but the contribution to reducing runoff was not evident (Bruggink et al. 1998). Ground based broadcast seed that fell adjacent to the disturbed soils had similar results to the aerial seeding.

In summer 2003 (seven years after the burn), the burn area was visited by the author. At that time there were visual differences in the type and amount of vegetative species on both the dozer ripped and Rotoclear treatment areas compared to areas that were seeded without soil disturbance and areas that were not treated. There was a noticeable difference in species composition, species cover, and the amount of bare ground between areas treated with ground disturbance treatments and those with no soil disturbance. The areas that received broadcast seeding without any soil disturbance appeared similar in species composition and diversity to areas that were not treated.

*Table 2. Cover class mid-points used in calculations.*

| Data Sheet Code | Canopy Cover Range (percent foliar cover) | Canopy Cover Midpoint used in calculations (percent foliar cover) |
|---|---|---|
| T | 0-1.0 | 0.5 |
| 1 | 1.1-5.0 | 3.0 |
| 2 | 5.1-25.0 | 15.0 |
| 3 | 25.1-50.0 | 37.5 |
| 4 | 50.1-75.0 | 62.5 |
| 5 | 75.1-95.0 | 85.0 |
| 6 | 95.1-100.0 | 97.5 |

In summer 2004, the vegetation was sampled on the Rotoclear, dozer ripped, aerial seeded, ground seeded without soil disturbance, untreated, and unburned sites. The sampling was intended to determine the long term successional effects of seeding burn areas, to determine the difference in seeding with soil disturbance compared to seeding without soil disturbance, and to determine the long term effects of BAER treatments in reducing erosion.

## Methods

Sampling sites were stratified by the type of treatment. The aerial seeding was dropped from the list of treatments due to the following reasons.

1. The first aerial seeding included only a non-persistent cereal grain (white oats, *Avena sativa*) that was not successful according to the 1998 monitoring report.
2. The second aerial seeding was also reported as having very poor success in the 1998 monitoring report. This mix did include two native species; however these species were also included in the dozer ripping and Rotoclear treatments where seed was spread both on disturbed and non-disturbed soils. An assumption was made that the ground broadcast seeding between the dozer ripped and Rotoclear paths would represent all broadcast seeding (aerial and ground) where no soil disturbance was used. These areas became the controls for the soil disturbance and seeded applications.
3. Very little to no visual difference could be detected between non-seeded areas and areas that received broadcast seeding with no soil disturbance.

A total of four sites were sampled. Vegetation data at each of the sites were collected. The vegetation sampling method followed USDA Forest Service Region 2 Rangeland Handbook (USDA FS 1996b) protocols for cover-frequency transects. The transects included 30.48 m transects with 20 Daubenmire (Daubenmire 1959) 20-cm x 50-cm frames (subplots) along each transect to determine percent cover by species. Six cover classes were used plus a trace class. The class midpoints shown in Table 2 were used in calculations for cover data. Data for each frame included life form, species, and cover class. Ground cover type and it's cover class were also collected for each frame. Species frequency was determined for each species by transect and average species canopy cover. Three transects were completed for each treatment type as well as for each control. The only exception was the control for the dozer ripping, where only two transects were completed (Table 3). The Rotoclear and dozer ripped sites had both transects along the soil disturbance paths that were seeded, and also between the paths that were seeded but had no soil disturbance.

### Analysis

General averages of vegetation and ground cover by treatment typ, and Student's t-tests (Steel and Torrie 1980) (two-tailed, unequal variances) for significant ($p < 0.05$ and $p < 0.01$) species differences within treatment types were calculated. Sample size for treatments was $n = 60$ except for the dozer ripping treatment where $n = 40$. The general summaries by treatment type included total species richness (total species counts), cover percents of seeded species (mean percent cover), total number of unique species (total species counts unique to treatment type), and percent effective ground cover (mean percent ground cover). Selected species were compared between soil disturbed seeding and non-soil disturbance seeding for

*Table 3. Summary of sites and replications.*

| | Site 1 - Dozer Ripping | | Site 2 - Rotoclear | | Site 3 - Control | Site 4 |
|---|---|---|---|---|---|---|
| | Soil Disturbance | No Soil Disturbance (control) | Soil Disturbance | No Soil Disturbance (control) | Untreated | Unburned |
| **Number of Transects** | 3 | 2 | 3 | 3 | 3 | 3 |
| **Average Slope Percent** | 20 | 20 | 10 | 8 | 25 | 10 |
| **Average Aspect (degrees)** | 275 | 275 | 30 | 35 | 276 | 280 |
| **Date Sampled** | 16 Aug. 2004 | 16 Aug. 2004 | 17 Aug. 2004 | 17 Aug. 2004 | 16 Aug. 2004 | 17 Aug. 2004 |

*Table 4. Average effective ground cover eight years post-treatment.*

| | Average Percent Effective Ground Cover |
|---|---|
| **Rotoclear Seeded** | 76 bd |
| **Non-Rotoclear Control, Seeded** | 52 be |
| **Dozer Ripping Seeded** | 84 a |
| **Non-Dozer-Ripping Control, Seeded** | 88 c |
| **Burn Control, Unseeded** | 65 acde |
| **Unburned Control** | 96 abc |

*a, b, c, e, f - significant difference at p < 0.01 level*
*d - significant difference at p < 0.05 level*

*Table 5. Average foliar cover eight years post-treatment. *The unburned control includes only foliar cover from vegetation less than 3.7 m in height.*

| | Average Percent Foliar Cover |
|---|---|
| **Rotoclear Seeded** | 65 a |
| **Non-Rotoclear Control, Seeded** | 44 a |
| **Dozer Ripping Seeded** | 41 c |
| **Non-Dozer-Ripping Control, Seeded** | 51 b |
| **Burn Control, Unseeded** | 39 ab |
| **Unburned Control** | 24* abc |

*a, b, c - significant difference at p < 0.01 level*

significant ($p < 0.05$ and $p < 0.01$) differences of foliar cover. All summary statistics and t-test of significance were performed using Microsoft Excel (2002) software.

## Results

### Effective Ground Cover

One of the objectives of the study was to determine the long-term soil protection and stability of the dozer ripping and Rotoclear treatments. Total effective ground cover was used as an indicator to determine long-term soil protection from erosion and to determine long-term maintenance of soil productivity. Ground cover has beenshown to be a reliable, quantifiable and repeatable indicator for measuring soil health and stability (Beasley 1974; O'Brien et al. 2003; Pannkuk and Robichaud 2003). Ground cover in the form of coarse woody debris is also essential to maintaining long-term soil productivity (Graham et al. 1994). Effective ground cover for the study included living and dead vegetation on the soil surface, as well as rock greater than 1.9 cm in diameter (USDA FS 2003). There were significant differences in effective ground cover 8 years following treatment application both within and between treatments (Table 4). The Rotoclear seeded treatment had significantly higher ($p < 0.01$) effective ground cover than the area that was seeded but had no Rotoclear treatment. The dozer ripping and seeded treatment showed no difference in effective ground cover compared to the area that was seeded but received no dozer ripping. Only the Rotoclear seeded showed average differences within a site location compared to its control. This indicates that the Rotoclear seeded treatment 8 years post-fire has a significantly higher amount of effective ground cover compared to its control. However, much of the ground cover consisted of wood chips created from the mulching of trees by the Rotoclear. The dozer ripping and seeding treatment showed no difference compared to its control.

### Foliar Cover

Foliar cover is often used as a surrogate to determine production and to give an estimate of soil health and stability (Dadkhah and Gifford 1980; Meyer et al. 2001); however, foliar cover can vary significantly from year to year or by season, especially with grass and forb species, and it is not a good predictor of soil loss (Hardy 2002). In this study, foliar cover was used to verify the ground cover estimates and to determine productivity differences between treatments and their controls (Table 5). The results show a similar trend to effective ground cover when

*Table 6. Plant species richness across treatments and controls.*

| | Total Species | Total Forbs | Total Grasses | Total Shrubs | Total Trees | Unique Species |
|---|---|---|---|---|---|---|
| **Rotoclear Seeded** | 33 | 23 | 9 | 1 | 0 | 8, compared to control seeded |
| **Non-Rotoclear Control, Seeded** | 43 | 27 | 14 | 2 | 0 | 18, compared to Rotoclear seeded |
| **Dozer Ripping Seeded** | 32 | 18 | 13 | 1 | 0 | 9, compared to non-dozer ripping seeded |
| **Non-Dozer-Ripping Control, Seeded** | 36 | 24 | 10 | 1 | 0 | 13, compared to dozer ripping seeded |
| **Burn Control, Unseeded** | 38 | 28 | 7 | 3 | 0 | |
| **Unburned Control** | 25 | 15 | 5 | 3 | 2 | |

comparing the treatments to their controls. However, there was a jump in foliar cover for the Rotoclear treated transects. This indicates that the Rotoclear treated sites had a much higher plant production during the 2004 growing season. The increase in plant production may be due to the increase in soil carbon with the woody material, the increase in soil moisture due to the surface cover from the wood chips that may have reduced evaporation and drying the of the soil, or to both mechanisms.

### Species Richness

The total number of vegetative species found, grouped by each life form class, was determined for the treatments studied and their controls (Table 6). Based on total counts, the controls that had no soil disturbance had higher total number of plant species. The burned non-seeded control also had a higher total species richness than the seeded treatments with soil disturbance. The greatest differences by life form showed that more forbs were present in the controls without soil disturbance and more grasses in the soil disturbance treatments. The higher richness of grasses in the soil disturbance is due to the success of the native species that were seeded. The total number of unique species was higher in the treatment controls. The summary results point to a long term reduction in total species richness when native grass species are used for emergency fire restoration and successful establishment occurs.

### Species and Genera Differences

The Rotoclear seeded treatment was compared to its seeded control, and the dozer ripped and seeded treatment was compared to its control (Table 7 and Table 8). Some plants could be identified only to genus, while others displayed enough identifying characteristics to be classified to species level. The species and genera that showed significantly higher ($p < 0.01$) canopy cover in the non-Rotoclear control included three native forb species and genera, and one native *Carex* species (Table 7). The Rotoclear and seeded plots had significantly higher ($p < 0.05$ and $p < 0.01$) canopy cover for two seeded native grasses and one non-seeded native grass. There was also a higher ($p < 0.05$) canopy cover for an unidentified *Poa* species that is believed to be one of the seeded grasses, *Poa canbyi*. The Rotoclear treatment created conditions that provided favorable conditions for seeded native grasses. These grasses and the soil conditions created by the treatment prohibited the establishment of several native species that would likely have been present without the Rotoclear and seeding treatment.

Several species and genera showed significantly higher canopy cover for the dozer ripped and seeded treatment compared to the control (Table 8). The control had higher canopy cover for one native forb species ($p < 0.05$), one native family (Asteraceae) ($p < 0.05$), one native *Carex* species ($p < 0.05$), and one native grass species ($p < 0.01$). The dozer ripped and seeded showed significantly higher canopy cover for two of the native grasses ($p < 0.01$) that were seeded, and for one native forb species ($p < 0.05$). These results are similar to the Rotoclear treatment in that the soil disturbance with native seeding prohibited the establishment of several native species. The successional pathways and species composition eight years following the emergency rehabilitation treatments is dissimilar to the natural fire recovery of the area.

## Conclusions

This study has shown that soil disturbance was required for successful immediate establishment of native grass species following fire on decomposed granitic soils. Areas that were broadcast seeded without soil preparation showed no evidence of successful grass seed establishment. The total amount of effective ground cover only increased with the Rotoclear treatment or the treatment where woody material was distributed on the soil surface. Seeded native grasses competed with the native flora. Species diversity

***Table 7. Canopy cover differences by species and genera for Rotoclear seeded and non-Rotoclear control.***

| Control | Rotoclear Seeded |
|---|---|
| *Carex* species ** (*Carex* spp.) | Slender Wheatgrass ** (*Elymus trachycaulus*) |
| Dogbane ** (*Apocynum cannabinum*) | Arizona Fescue * (*Festuca arizonica*) |
| *Penstemon* species ** (*Penstemon angustifolius*) | Bluebunch Wheatgrass * (*Pseudoroegneria spicata* ssp. *spicata*) |
| *Potentilla* species ** (*Potentilla* spp.) | *Poa* species * (*Poa* sp.) |

****** Significance level $p < 0.05$; ** Significance level $p < 0.01$***

***Table 8. Canopy cover differences by species and genera for dozer ripped and seeded and non-dozer ripped control.***

| Control | Rotoclear Seeded |
|---|---|
| *Carex* species * (*Carex* sp.) | Slender Wheatgrass ** (*Elymus trachycaulus*) |
| *Poa* species ** (*Poa* sp.) | Idaho fescue ** (*Festuca idahoensis*) |
| *Aster* species * (Asteraceae Family) | Little Goldenrod * (*Solidago nana*) |
| *Potentilla* species * (*Potentilla* sp.) | |

****** Significance level $p < 0.05$; ** Significance level $p < 0.01$***

was reduced in areas where the native seeded grasses were established following emergency post-fire restoration activities. Where the native grass seed was successful, the emergency restoration activities have created a long term successional pattern that differs from the natural fire recovery successional pattern.

## Recommendations

Recommendations for future use of native grass species for emergency fire restoration on similar soil and pre fire vegetation types include:

1. Consider non-persistent or sterile species for immediate post-fire protection needs.
2. The use of native species for emergency protection post-fire must consider the long-term vegetation objectives. If there are no defined desired conditions for future vegetation composition, then it may be better to use only non-persistent species.
3. Soil preparation may be required for establishment of native grass species following fire on soil and pre-fire vegetation types similar to those in this study.

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# McNally Postfire Discharge and the Relationship of Sierra Nevada-Wide Flood Frequency Curves and Local Kern River Discharge Curves

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The analysis tool recommended to USDA Forest Service Burned Area Emergency Rehabilitation (BAER) team hydrologists to determine design flow in ungaged systems is defined in *Magnitude and frequency of floods in California* by Waananen and Crippen (1977). These authors provide discharge equations for the 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year recurrence interval storms for six regions in California based on 703 streamflow stations. Stream channel discharge relationships were developed from tributaries and USGS gage stations in the Kern River basin in response to the need to develop local hydro-physiographic discharge relationships for BAER assessment. Kern River hydro-physiographic channel geometry and discharge relationships versus drainage area were developed from this effort. This information was used to determine pre-fire stream design flow for the 2002 McNally fire. Comparison of discharge using local Kern River hydro-physiographic relationships and those derived from Waananen and Crippen (1977) yielded interesting results. With the exception of the 5-year recurrence interval, discharges derived from field measurements and local data are at least a magnitude of order higher for most of the recurrence intervals studied than those derived from Waananen and Crippen. Discharge relationships for the 5-year recurrence interval have the closest relationship using these two methods. Since the 2002 McNally fire, the response of fire-affected watersheds to winter and summer thunderstorm events has been studied. Rattlesnake Creek and Tobias Creek watersheds were surveyed in 2002 either prior to or immediately after the fire, and again in 2003 and 2004. Parameters measured include cross-sections, longitudinal profiles, bank stability, and particle distribution. Discharge estimates were calculated using resistance equations, which base discharge on bankfull depth, bankfull cross-sectional area, wetted perimeter, hydraulic radius bed material, and slope. The results of this study suggest that post-fire runoff may provide the means to estimate actual post-fire discharge by a watershed and thus be useful in validating adjusted design flows calculated during BAER assessment.

Keywords: *hydrology/water, watershed, hydrologic processes, hydrologic modeling, physiographic processes, streamflow*

## Introduction

Wildfires result in increased runoff commensurate with burn severity. Burned Area Emergency Rehabilitation (BAER) teams use burn severity to estimate runoff increases resulting from fires. This increase is calculated as adjusted design flow – the flow increase expected to occur as a result of decreased infiltration and interception following a wildfire. This discharge value is used to evaluate the need to increase the capacity of drainage structures such as culverts and bridges, and provides an estimate of flooding potential to nearby communities.

Before an adjusted design flow can be determined, the pre-fire design flow must be calculated. This is the flow expected to occur prior to the fire, responsible for forming present day channel conditions, and used to estimate proper performance of culverts and other drainage structures. BAER teams are directed to determine design flow from related storm duration and magnitude (design storm) estimates from U.S. Geological Survey data, or to calculate it from a regional analysis for an equivalent design recurrence interval (Forest Service Handbook 2509.13,40 [USDA FS 1993]). These estimates assume pre-fire ground infiltration and ground cover conditions. The analysis tool recommended to BAER team hydrologists to determine design flow in ungaged systems is defined in *Magnitude and frequency of floods in California* by Waananen and Crippen (1977).

Adjusted design flow is calculated using the same relationships as design flow; however, runoff response is estimated by assuming increased runoff commensurate with burn severity, in terms of recurrence interval. This recurrence interval estimates the response of the newly burnt landscape to an average annual storm. For example, a pre-fire landscape would respond with a discharge associated with a 1.5- to 2-year storm given an average rainfall event, while post-fire, the same landscape may

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

respond as if the discharge were associated with a 5- or 10-year event. The increased discharge associated with predicted recurrence interval is then prorated across the watershed by burn severity level to yield the post-fire discharge or the adjusted design flow. Watershed area above infrastructure and communities at risk from post-fire erosion-related damage (flooding, debris flows, culvert failures and washouts) often determines the size of watershed chosen for analysis.

This paper will demonstrate how *Magnitude and frequency of floods in California*, Waananen and Crippen (1977), the recommended method used to analyze both design and adjusted design flows, underestimates discharge for most rainfall response conditions when compared to discharge relationships determined from gaged and ungaged sites in the vicinity of the Kern River, in the southern Sierra Nevada. In addition, post-fire discharge calculations based on channel characteristics may provide hydrologists with a process to measure actual post-fire adjusted design flow and monitor BAER design flow predictions.

## Calculation Methods for Emergency Runoff Response

The most widely used publication for calculation of design flow in California is U.S. Geological Survey Water-Resources Investigation Report 77-21, *Magnitude and frequency of floods in California*, by A.O. Waananen and J.R. Crippen (1977). This investigation provides analysis of 703 stream flow stations across California, with records ranging in length from 5 to 85 years and provides a method for evaluating magnitude and frequency of floods at gaged and ungaged sites. Because climatic and topographic conditions create a variety of watershed responses to precipitation events, these authors have divided California into six regions: North Coast, Northeast, Sierra, Central Coast, South Coast, and South Lahontan-Colorado Desert regions. Each region has a set of discharge equations developed for the flows from a 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year storm event. Equations for the Sierra Region are as follows:

$$Q_2 = 0.24(A^{0.88})(P^{1.58})(H^{-0.80}) \quad (1)$$

$$Q_5 = 1.20(A^{0.82})(P^{1.37})(H^{-0.64}) \quad (2)$$

$$Q_{10} = 2.63(A^{0.80})(P^{1.25})(H^{-0.58}) \quad (3)$$

$$Q_{25} = 6.55(A^{0.79})(P^{1.12})(H^{-0.52}) \quad (4)$$

$$Q_{50} = 10.4(A^{0.78})(P^{1.06})(H^{-0.48}) \quad (5)$$

$$Q_{100} = 15.7(A^{0.77})(P^{1.02})(H^{-0.43}) \quad (6)$$

where Q = discharge, subscript indicates recurrence interval in years; A = drainage area in square miles; P = mean precipitation in inches; H = altitude index in thousands of feet. (Altitude index is computed as the average of the altitudes at points along the main channel of the stream 10 and 85 percent of the distance from the site to the basin divide as outlined on a topographic map.) These authors also provide references to water resource investigations for other areas within the United States.

The method set forth in Waananen and Crippen (1977) was initially applied to the 2002 McNally fire to determine design flow and adjusted design flow. The McNally fire affected roughly 150,000 acres (60,750 ha) on the Sequoia National Forest in the North Fork Kern River basin, which is located in the Sierra Region as defined by Waananen and Crippen (1977). Figure 1 shows the relationship of flows by recurrence interval to drainage area using the equations for the Sierra Region defined by these authors. The equations used drainage area, mean annual precipitation, and altitude values for the North Fork Kern watershed.

The North Fork Kern River is roughly an 1100-square mile (2820-$km^2$) watershed, as measured from north of Mount Whitney to Lake Isabella. The North Fork Kern River is located within the Kern River basin. The area defined as the Sierra Region by Waananen and Crippen (1977) ranges from Mt. Shasta to Bakersfield and encompasses roughly 47,000 square miles (122,000 $km^2$). Figure 2 shows the contrast in size between North Fork Kern and Sierra Region as well as gage stations located in the Kern River vicinity. The Sierra Region crosses numerous hydro-physiographic areas and is significantly larger than the North Fork Kern River watershed, which is located within a single hydro-physiographic area.

Design flows (pre-fire flows) for watersheds in the North Fork Kern River were calculated using the equation for the 2-year recurrence discharge from Waananen and Crippen (1977). Adjusted design flows (post-fire flows) were based on expected runoff response by burn severity. The McNally burn severity map was used to determine relative percentages of high, moderate, and low burn severity, and unburned areas in each watershed. Runoff response calculations used the 2-year recurrence discharge equation for unburned and low severity areas, the 20-year recurrence discharge equation for moderate severity areas, and the 50-year recurrence discharge equation for high severity burn areas (Figure 1).

## Development of Discharge Curves for the Kern River

During the summers of 2000, 2001, 2002, and 2003, stream channel geometry and flow relationships were developed using Kern River tributary streams and USGS

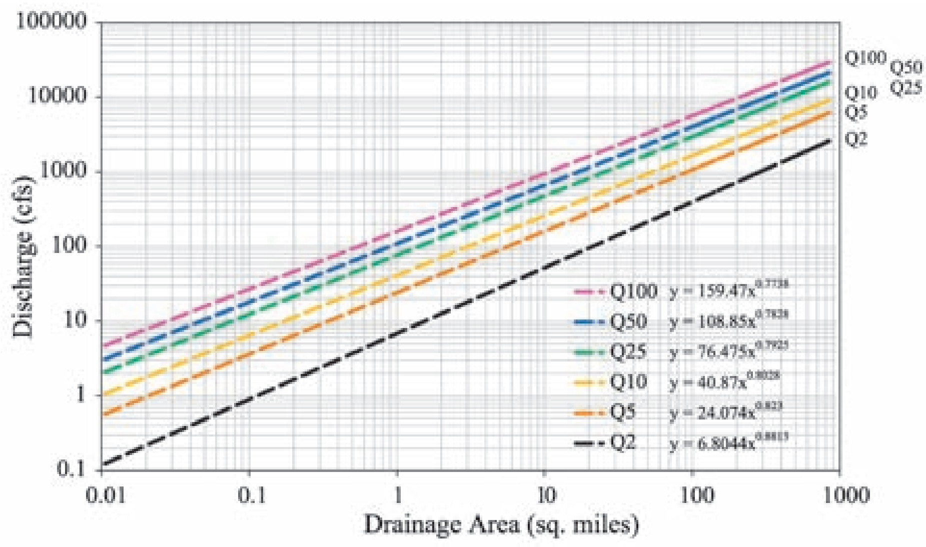
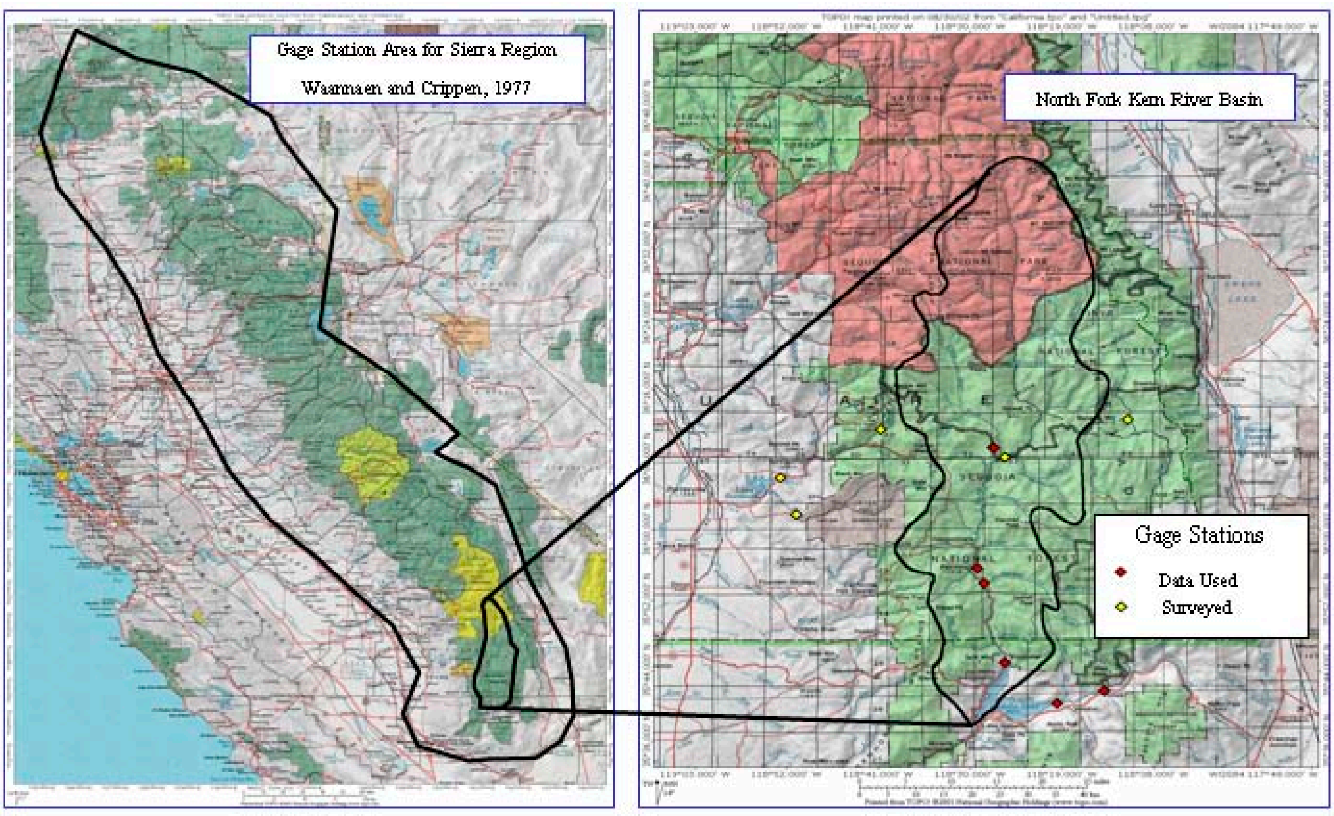



*Figure 1. Sierra Nevada Region flood frequency curves from Waananen and Crippen (1977) using drainage area, mean annual precipitation and altitude index values from the North Fork Kern River.*

*Figure 2. Contrast and location of the Sierra Region and the North Fork Kern River basin. (below)*




gage stations. Field crews collected data from cross sections, longitudinal profiles, and pebble counts following the protocol from Harrelson et al. (1994). Staff plate readings were taken at gage sites for bankfull discharge. Bankfull discharges were determined from station rating curves or USGS flow records. A protocol modified by McCandless and Everett (2002) was used for field surveys at gage stations. Modification of the protocol involved surveying only riffle habitats, and bed and bank material for most sites was characterized from reach-averaged pebble counts and riffle pebble counts. Stream bank material was not analyzed in this study.

Flow from most tributary streams was calculated using the Darcy-Weisbach with friction factor method after Hey (1979). Darcy-Weisbach uses hydraulic slope, cross-sectional area, mean depth, and the specific gravity of water in the following relationship:

$$U = \left(\frac{8gdS}{f}\right)^{1/2} \qquad (7)$$

where U = velocity, g = specific gravity of water, d = mean depth, S = hydraulic slope, and f is the friction factor defined by Hey (1979).

The friction factor, after Hey (1979), employs maximum depth, hydraulic radius and $D_{84}$ of the bed material as follows:

$$\frac{1}{\sqrt{f}} = 2.03\log\left(\frac{aR}{3.5D_{84}}\right) \qquad (8)$$

where f = friction factor, $D_{84}$ is the fraction of the bed material that 84% is finer than, R = hydraulic radius, and a is a function of channel cross section shape that varies between 11.1 and 13.46 and can be approximated as:

$$a = 1.11\left(\frac{R}{d_{max}}\right)^{-0.314} \qquad (9)$$

Manning's equation was used to calculate flow for channels with extremely low gradients and sand-size bottom material. Cross-sectional area, wetted perimeter, and slope were used to solve Manning's equation:

$$Q = \left(\frac{1.486}{n}\right)(A)(R^{2/3})(S^{1/2}) \qquad (10)$$

where: Q = discharge in cubic feet/second, A = cross-section area in square feet, R = hydrologic radius in feet (area/wetted perimeter), S = water surface slope, n = Manning's roughness coefficient.

For those tributary streams with low gradient (slope between 0.001 and 0.02) and sand-size bed material Jarrett's resistance equation (1984) was used to calculate Manning's 'n'. Manning's 'n' is calculated as a function of slope and hydraulic radius (area divided by wetted perimeter). Jarrett's equation for Manning's 'n' is:

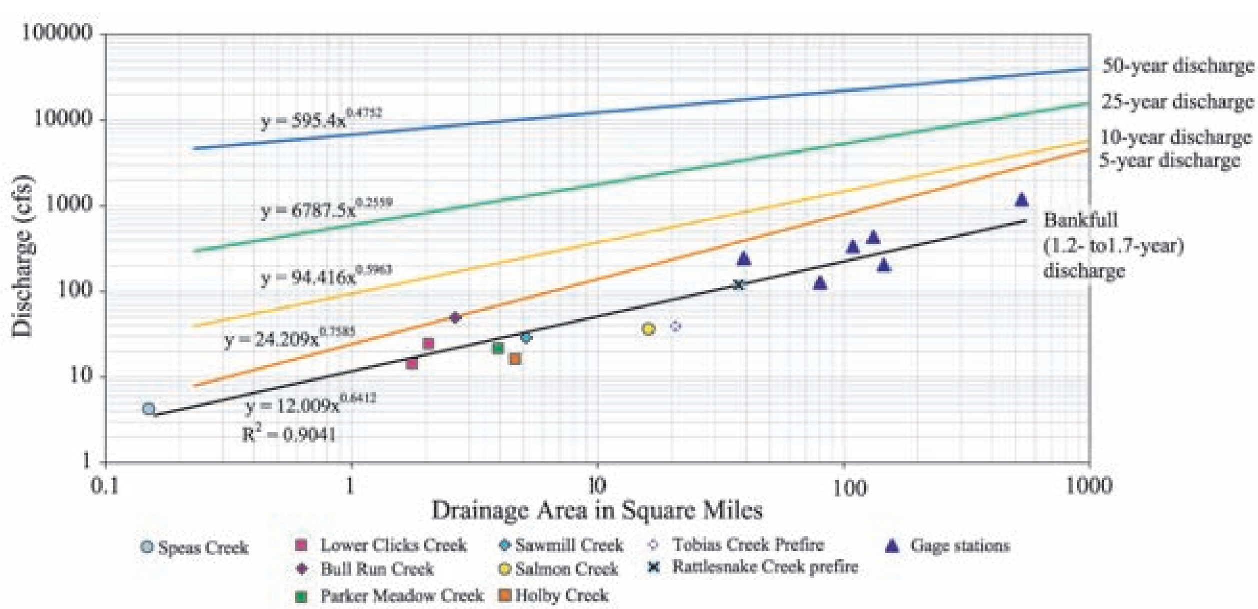
$$n = 0.39S^{0.38}R^{-0.16} \qquad (11)$$

where: n = Manning's n value, S = hydraulic gradient, and R = hydraulic radius.

Field surveys and discharge measurements within the Kern River provided data to develop discharge versus drainage area relationships with a 1.2 to 1.7-year flood frequency (the lower-most [black] line in Figure 3). Actual data points for surveyed stations are also shown. The recurrence interval of 1.2 to 1.7 years is derived from discharge measurements either calculated as described above, or measured at gage stations then compared to annual peak flow frequency analysis at gage stations. Frequency analysis for gage stations determined the 2-year, 5-year, 10-year, 25-year, and 50-year return interval curves (Figure 3).

Comparison of Sierra Region discharge curves using the relationships defined by Waananen and Crippen (1977) to local Kern River hydro-physiographic curves derived from field measurements provided surprising results. There is a large discrepancy between the sets of curves, even though many of the same gage stations evaluated in the Kern River were also used by Waananen and Crippen (1977). This is especially interesting since there is a very strong correlation between gage station sites and discharge data from non-gaged sites within the Kern River area, with an $R^2$ value of 0.9. Figure 4 displays the relationship of Sierra Region flood frequency curves to local Kern River hydro-physiographic discharge curves by recurrence calculated using Waananen and Crippen (1977). It is interesting

*Figure 3. Local Kern River hydrologic physiographic discharge relationships for bankfull, 5-year, 10-year, 25-year and 50-year recurrence interval. The 1.2- to 1.7-year discharge data were derived from field surveys; 5-, 10-, 25-, and 50-year discharges were acquired from USGS gage station discharge records.*



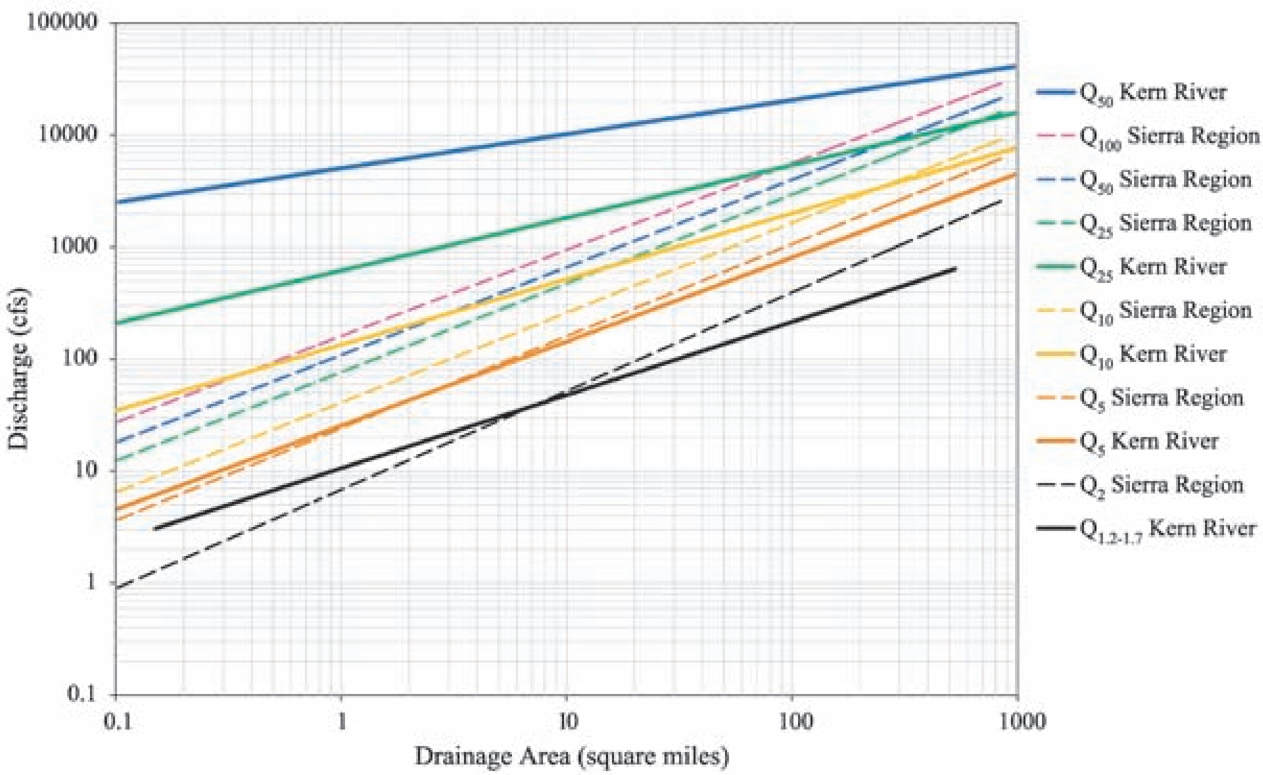



*Figure 4. Relationship of Sierra Region flood frequency curves after Waananen and Crippen (1977) to local Kern River hydrologic physiographic flood frequency curves.*

to note that for all frequency curves except the 5-year flood frequency curve there is an order of magnitude difference between locally calculated discharge and that calculated using Waananen and Crippen (1977). Discharge calculations using Waananen and Crippen (1977), for recurrence intervals greater than 5 years, are substantially lower than the measured discharge from the Kern River area. The 5-year flood frequency curve is reasonably similar to Kern River discharge relationships, while the 2-year flood frequency curve from Waananen and Crippen is lower for watersheds of roughly less than 5 square miles (13 $km^2$) and greater for watersheds greater than 10 square miles (26 $km^2$). This suggests that the Sierra Region equations provided by Waananen and Crippen (1977) provide reasonable estimates of discharge for 5-year recurrence interval estimates for any size watershed, and 2-year recurrence interval estimates for watersheds of roughly 5 to 10 square miles (13 to 26 $km^2$) within the Kern River area.

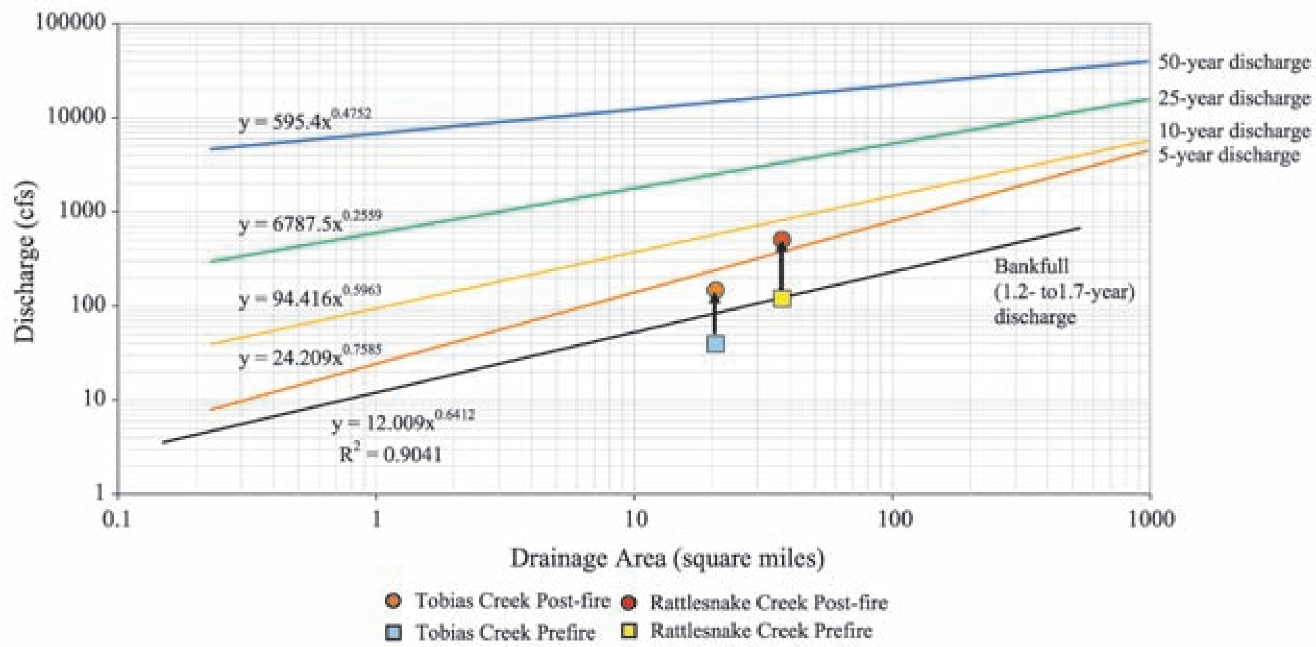
Just why this occurs could be related to application of state-wide gage station data across the Sierra Region to develop equations which were then applied to much smaller watersheds. The large variation in climate from north to south would be expected to account for some of the differences. Discharge relationships determined from local data (Figure 4) suggest that the equations from Waananen and Crippen grossly underestimate discharge for the North Fork Kern River, and it is clear that using data outside the immediate area provides substantially lower discharge for adjusted design flows. This could have serious implications in the case of BAER runoff determinations, which have the potential to affect life, property, and resources.

The data used to develop the Kern River hydro-physiographic discharge relationships (Figures 3, 4 and 5) are displayed in three groups (Appendix 1). The first group of figures represents field data collected at non-gaged sites along with discharge, velocity, and friction or n values used for resistance calculations. The second group is field data collected at gage stations and discharge information from station rating curves or USGS records. The third group is information used to develop discharge at the various recurrence intervals by watershed size derived from frequency analysis of peak flow data from the identified USGS gage stations.

## Monitoring of Predicted Adjusted Design Flows in the McNally Fire Area

The author is responsible for the selection of recurrence interval relative to burn severity and runoff rate estimates used in the McNally fire. Monitoring results suggest that

*Figure 5. Shift in post-fire discharge for Rattlesnake and Tobias Creeks as compared to local Kern River hydrologic physiographic discharge.*



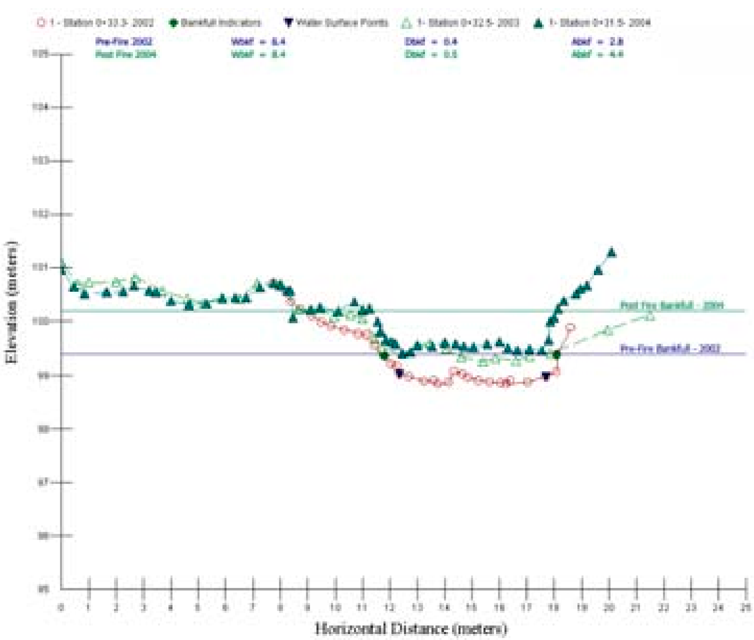



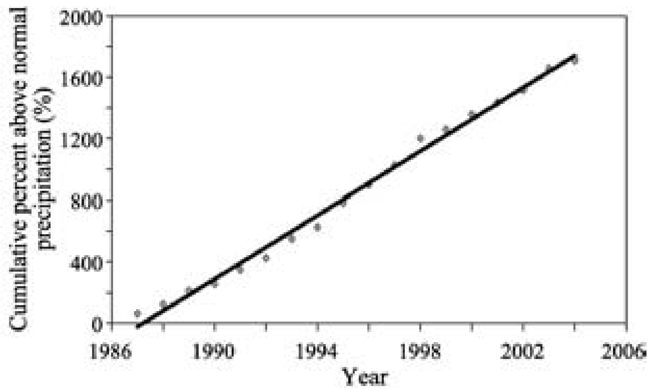

*Figure 6. Rattlesnake Creek cross section 0+31.5 (2000-2004).*

selected recurrence interval and discharge response for burn severity was grossly over-estimated, with the exception of those lands burned at low severity. This does not alleviate concern surrounding variance between Sierra Regional Flood Frequency curves versus local Kern River hydro-physiographic discharge curves. It only suggests that monitoring and follow up investigations of post-fire runoff rates is important so hydrologists can better estimate adjusted design flows in an emergency.

Monitoring of ungaged stream channels within the McNally fire area continued following the fire. And, serendipitously, the Tobias Creek watershed was surveyed just days prior to the fire. Rattlesnake Creek watershed was surveyed immediately after the fire prior to seasonal rains. These surveys were used in the creation of the bankfull hydro-physiographic discharge curves (Figure 3). Continued post-fire surveys have provided information on channel geometry following the wildfire.

Following the fire, channels of Tobias Creek and Rattlesnake Creek developed a new floodplain in response to increased runoff. Cross-sections and longitudinal profiles surveyed in 2003 and 2004 provided data on the channel geometry response to rainfall events. One of the cross sections taken on Rattlesnake Creek provides a good

*Figure 7. Cumulative percent above average precipitation in the vicinity of the McNally fire at KR3 Intake, 1986-2004. (below)*




example of floodplain development after the fire (Figure 6). Three years of data are overlaid in this figure. The newly formed floodplain provides bed and geometry information that was used to estimate discharge as previously discussed. When discharge values were plotted on Kern River hydro-physiographic discharge curves, they occurred between 5-year and 10-year recurrence curves. Rattlesnake Creek sustained higher burn severity and showed a higher recurrence than Tobias Creek. The post-fire discharge values have been plotted as circular points immediately above their square pre-fire points (Figure 5).

Rainfall events included the winter storm of November 2002 and numerous average annual thunderstorm events of July and August 2003. However, a study of 1987 to 2004 cumulative annual percent-above-normal rainfall by year did not show anomalous or unusually intense rainfall post-fire (Figure 7). This suggests that the increased runoff after the fire rather than an unusually high runoff season is responsible for the change in channel geometry. Furthermore, field investigations at Osa Meadow between August 2003 thunderstorms provide visual support that post-fire runoff is responsible for the creation of new floodplain in Rattlesnake and Tobias Creeks. Osa Meadow is located at the eastern edge of the McNally fire. The upstream section of the meadow was not affected by the fire; however the lower section of the meadow received increased runoff generated by a low severity burn in the headwaters of a tributary channel. The series of summer thunderstorms responsible for development of a new floodplain in Rattlesnake and Tobias Creeks was responsible for flooding in the lower portion of Osa Meadow. The portion of the meadow upstream where burning did not occur in tributary streams was unaffected by the storm. Figures 8a and 8b show Osa Meadow above and below the flooding caused by the McNally fire. The distribution of organic material defining the high water in upper Osa Creek meadow has a width of roughly three feet

*Figure 8. (a) Osa Meadow upstream of fire effects. (b) Osa Meadow downstream of fire effects.*



(0.9 m) commensurate with bankfull width, suggesting a storm responsible for a discharge of 1.2 to 1.7 years. The lower meadow had an accumulated flood width of roughly thirty-three feet (10 m) resulting from the same storm event. As evidenced in these two photos, the two sections of creek responded differently to the same event. These two areas are no more than 200 feet (61 m) apart.

## Summary

The results of this study suggest that local flow relationships provide the basis for design and adjusted design flow for emergency evaluations. However, when local information is unavailable the use of the 5-year flood frequency equation from Waananen and Crippen (1977) provides reasonably good estimates for watersheds of all sizes, while the 2-year flood frequency curves provide reasonable estimates of discharge for watersheds of roughly two to ten square miles (5 to 26 km$^2$) within the Kern

River area. Other recurrence interval discharge equations from Waananen and Crippen (1977) grossly underestimate discharge for the North Fork Kern River area. This could have serious consequences in the case of BAER runoff determinations which have the potential to affect life, property, and resources.

Comparison of post-fire effects to predicted adjusted design flow may provide managers with a way to predict discharge following fire, based on channel geometry. Currently there are only two locations with data available, so the concept is based on professional judgment and limited data. With additional study it may be possible to develop a dataset based on local fires and their effect on post-fire channel discharge. This study suggests that post-fire channel geometry may provide information on runoff rates following wildfires when compared to a set of recurrence interval discharge curves developed for the physiographic region associated with the wildfire event.

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I would also like to thank the Pacific Northwest Region of the Forest Service who supported the funding of Channel Geometry and Discharge curve development in the Southern Sierra Nevada. Without this funding this study would never have taken place. Very special thanks go to Dr. Dave Rosgen whose intensive review improved the quality of this document and Dr. Dan Tormey who spent many hours asking the right questions and providing sound suggestions. Additional thanks go to the two reviewers provided by the conference review team, Valdon Hancock and Mike McNamara.

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*Appendix 1. Data used for development of local hydrologic physiographic relationships.*

| Ungaged Creeks | Drainage Area (mi$^2$) | X-Sectional Area (ft$^2$) | Discharge (cfs) | Velocity (ft s$^{-1}$) | Friction factor *or "n" value | Resistance Equation Used |
|---|---|---|---|---|---|---|
| Speas | 0.15 | 1.20 | 4.24 | 2.97 | 0.39 | Darcy-Weisbach |
| Lower Clicks Creek | 1.76 | 8.60 | 14.32 | 1.53 | 0.07* | Jarrett |
| Lower Clicks Creek | 2.06 | 11.80 | 24.49 | 2.21 | 0.06* | Jarrett |
| Bull Run Creek | 2.64 | 10.66 | 49.63 | 4.44 | 0.03 | Darcy-Weisbach |
| Parker Meadow Creek | 3.95 | 7.21 | 21.7 | 2.04 | 0.16 | Darcy-Weisbach |
| Holby Creek | 4.62 | 10.76 | 16.25 | 1.15 | 0.02* | Jarrett |
| Sawmill Creek | 5.13 | 8.50 | 29.02 | 2.87 | 0.08 | Darcy-Weisbach |
| Salmon Creek | 16.10 | 13.99 | 36.62 | 3.73 | 0.12 | Darcy-Weisbach |
| Tobias Creek 2002 Pre-fire | 20.70 | 26.91 | 39.5 | 1.46 | 3.50 | Darcy-Weisbach |
| Tobias 2003 Post-fire | 20.70 | 39.83 | 146.34 | 3.75 | 0.44 | Darcy-Weisbach |
| Rattlesnake 2002 Pre-fire | 37.42 | 23.36 | 119.5 | 5.99 | 0.24 | Darcy-Weisbach |
| Rattlesnake 2003 Post-fire | 37.42 | 77.50 | 503 | 6.55 | 0.22 | Darcy-Weisbach |

| Gage Stations | | | | | |
|---|---|---|---|---|---|
| Name | Number | Drainage Area (mi$^2$) | X-Sectional Area (ft$^2$) | Bankfull Discharge | Bankfull Return Interval in Years |
| Wishon Fork Tule River | 11202000 | 39 | 37 | 243.7 | 1.69 |
| Tule River Near Springville | 11204000 | 80 | 60.7 | 127.15 | 1.2 |
| South Fork Tule River | 11204500 | 109 | 63.2 | 337 | 1.31 |
| Little Kern River Near Quaking Aspen Camp | 11185400 | 132 | 74.00 | 435.00 | 1.53 |
| SF Kern River Near Olancha | 11188200 | 146 | 50.00 | 205.00 | 1.55 |
| Kern River Near Quaking Aspen Camp | 11185350 | 530 | 230.00 | 1186.00 | 1.21 |

| Gage Stations | | | Discharge Values at Associated Return Intervals from Gage Records | | | |
|---|---|---|---|---|---|---|
| Name | Number | Drainage Area (mi$^2$) | 5-Year | 10-Year | 25-Year | 50-Year |
| Salmon Creek | 11186380 | 0.23 | 7.00 | 50 | 300 | 3000 |
| Salmon Creek | 11186360 | 0.30 | 12.00 | 90 | 700 | 7000 |
| Salmon Creek | 11186340 | 0.45 | 10.00 | 40 | 175 | 1000 |
| Wishon Fork Tule River | 11202000 | 39 | 1548 | 5333 | 11530 | 15049 |
| Tule River Near Springville | 11204000 | 80 | 1360 | 2280 | not available | not available |
| South Fork Tule River | 11204500 | 109 | 3084 | 4466 | 6857 | 12075 |
| Little Kern River Near Quaking Aspen Camp | 11185400 | 132 | 2010 | 7370 | 14000 | 57200 |
| SF Kern River Near Olancha | 11188200 | 146 | 1000 | 1314 | 3500 | 20000 |
| Kern River Near Quaking Aspen Camp | 11185350 | 530 | 4053 | 7867 | 15000 | 30000 |
| Kern River Near Onyx | 11189500 | 530 | 2389 | 3576 | 6784 | 17196 |
| Kern River near Kernville river only | 11186000 | 846 | 5241 | 10533 | 27076 | 46510 |
| Kern River at Isabella | 11190000 | 982 | 1788 | 3612 | 10000 | 40000 |

# The Effects of Selected Postfire Emergency Rehabilitation Techniques on Small Watershed Sediment Yields in Southern California

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Forest Service Research has quantified the effects of selected Burned Area Emergency Response (BAER) treatments on sediment yields from small watershed by constructing dams to impound runoff and measure debris from several burn sites in southern California. In this paper, we cite examples from three studies to demonstrate the effectiveness of these treatments. In 1999 the Mixing Fire burned over 1200 hectares of mixed pine/oak forest with a brush understory on granitic terrain in the San Bernardino National Forest. A 1-hectare watershed treated with log erosion barriers (LEBs) was compared to a nearby untreated burned catchment. Results indicate that, although the LEBs retained considerable sediment, unforeseen differences in site characteristics masked any differences in treatment effectiveness. The 2002 Williams Fire burned over 15,000 hectares of chaparral on largely metamorphic terrain on the Angeles National Forest. Seven different 1- to 2-hectare watersheds were used to compare the effects of the soil flocculent polyacrylamide (PAM) or prefabricated small-diameter log structures as channel check dams against nearby untreated watersheds. Results indicate that PAM had no effect but that the channel check dams significantly reduced sediment yield. In 2003, the Cedar Fire burned about 117,000 hectares of brush on granitic terrain in the Cleveland National Forest. Three 2- to 3-hectare watersheds were used to compare two levels of an aerial hydromulch treatment (100 percent treated and 50 percent contour strips) to a nearby untreated watershed. Preliminary results indicate that the 50 percent treatment produced more sediment than the untreated but the 100 percent treatment generated less than half the sediment of the untreated watershed. Rigorous testing needs to continue before these erosion control treatments become standard practice.

Keywords: *fire, post-fire erosion, erosion control, monitoring, debris basins, sediment yield, BAER treatments*

## Introduction

In fire-prone ecosystems of the southwestern United States, it has been well documented that wildfire can dramatically alter the erosion response of upland landscapes (Kraebel 1934; Wells 1981; Heede et al. 1988), primarily by removing the protective vegetation canopy and ground surface organic material. In addition, the combustion of soil organic matter can create a subsurface water-repellent layer that restricts infiltration and promotes overland flow (DeBano 1981), thereby enhancing sediment production (Hamilton et al. 1954; Hibbert 1985). In southern California, first-year post-fire sediment yield is 35 times greater on average than annual levels in comparable unburned areas (Rowe et al. 1954).

Accelerated post-fire erosion and sedimentation can threaten life, property, and infrastructure at the southern California wildland/urban interface, where growing population centers meet the adjacent steep mountain fronts. Moreover, post-fire environmental degradation can adversely affect habitat and populations of endangered species along sensitive riparian corridors. To mitigate these undesirable post-fire consequences, federal land managers have developed a Burned Area Emergency Response (BAER) program of hillslope and stream channel rehabilitation treatments for the purpose of erosion control. The goal of these treatments is to cost-effectively protect both the onsite and downstream values at risk until the native vegetation community can recover to the point that the watershed functions normally again.

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Landscape level post-fire erosion control treatments attempt to reduce and delay the accelerated erosion and sedimentation that typically follows wildfires. Although many types of treatments have been used over the years, they can be grouped into three different classes: 1) ground covers (mulch, seeding) to reduce the erosive power of rainsplash and overland flow; 2) mechanical barriers (log erosion barriers, straw wattles) to retain debris; and 3) chemical sprays (wetting or flocculating agents) to promote infiltration, thereby reducing overland flow. Unfortunately, the benefits of many of these erosion control measures have yet to be quantitatively demonstrated in rigorous field studies (Robichaud et al. 2000).

Forest Service Research has quantified the effects of selected BAER treatments on small watershed sediment yields from several burn sites in southern California. The purpose of this research is to evaluate the effectiveness of these rehabilitation efforts as erosion control practices, as well as to document the post-fire sediment yield response from a variety of different field locations. Eventually, the results will be incorporated into models for planning and risk assessment.

## Study Sites and Treatment Descriptions

The study sites are located on Forest Service lands in the mountains of southern California (Figure 1). Although the study areas have differing site characteristics (Table 1),

*Figure 1. Study locations in southern California.*


*Table 1. Selected study site characteristics*

| Attribute | Mixing Fire | Williams Fire | CedarFire |
|---|---|---|---|
| Elevation | 1500 m | 900 m | 700 m |
| Bedrock | Granitic | Metamorphic | Granitic |
| Soil Texture | Loamy sand | Loamy sand | Sand |
| Watershed Area | 1 ha | 1-2 ha | 2-3 ha |
| Aspect | N to NW | SW to SE | W to S |
| Hillslope Angle | 37% | 68% | 21% |
| Channel Gradient | 27% | 34% | 14% |

they were all burned in wildfires during the late summer or early fall. Fires in southern California are especially intense at this time of year, occurring at the end of the summer drought and often fanned by strong Santa Ana winds. For this study, we chose small burned watersheds, 1 to 3 hectares in size, which were treated operationally with various rehabilitation measures. Sediment yield from these treated watersheds was then compared with similar nearby burned but untreated control watersheds.

### The Mixing Fire

In September 1999, the Mixing Fire burned over 1200 ha on the San Jacinto Ranger District of the San Bernardino National Forest. The fire occurred in an area of granitic terrain at an elevation of 1500 m in the San Jacinto Mountains. The general area receives annual average precipitation of 550 mm, including snow in the winter and occasional thunderstorms in the summer. The specific study site supported a mixed forest of pine (*Pinus coulteri*), black oak (*Quercus kelloggii*), and canyon live oak (*Quercus chrysolepis*) with an understory of buckbrush (*Ceanothus leucodermis*) and manzanita (*Arctostaphylos* spp.) (Wohlgemuth et al. 2001).

Much of the area burned by the Mixing Fire was treated with log erosion barriers (LEBs). LEBs are built by felling and placing fire-killed trees along the hillside contours (Figure 2). They are designed to retard the overland flow of water and sediment on hillside slopes, reducing post-fire hillslope erosion and sediment delivery to stream channels (Robichaud et al. 2000). LEBs are placed in an overlapping arrangement that maximizes ponding (fostering infiltration and sediment deposition) and minimizes potential barrier failure.

### The Williams Fire

In September 2002, the Williams Fire burned over 15,000 ha on the San Gabriel River Ranger District of the Angeles National Forest. The fire occurred in an

*Figure 2. Overlapping network of log erosion barriers (LEBs) on the Mixing Fire site.*

area of metamorphic terrain at an elevation of 900 m in the San Gabriel Mountains. The general area receives annual average precipitation of 700 mm generated almost exclusively by winter cyclonic storms. The specific study site supported brushfields of mixed chaparral dominated by buckbrush, chamise (*Adenostoma fasciculatum*), and scrub oak (*Quercus berberidifolia*) (Wohlgemuth 2003).

A portion of the Williams Fire area was treated with polyacrylamide (PAM), a proprietary soil-flocculating agent. The intent of this helicopter-applied treatment is to aggregate the fine soil particles, thus promoting infiltration and thereby reducing overland flow (Flanagan and Chandhari 1999), especially in areas of suspected water repellent soils. Other sections of the Williams Fire were treated with prefabricated small-diameter log structures placed perpendicular to the flow, roughly 5-10 m apart along the stream courses. These barriers were intended to serve as sediment storage sites and grade control structures to prevent the scouring of the channel bed and banks by accelerated post-fire runoff (Wohlgemuth 2003).

### The Cedar Fire

In October 2003, the Cedar Fire burned over 117,000 ha on the Descanso Ranger District of the Cleveland National Forest. The fire occurred in an area of granitic terrain at an elevation of 700 m in the foothills of the Laguna Mountains. The area receives annual average precipitation of 415 mm, primarily generated by winter cyclonic storms with rare summer thunderstorms. The specific study site supported chaparral brushfields composed almost exclusively of chamise (Kirsten Winter, Cleveland National Forest, personal communication).

Approximately 350 ha of the Cedar Fire were treated with aerial hydromulch. A wood and paper fiber matrix with a non water-soluble binder, the mulch was mixed as a slurry and applied by helicopter. It was delivered at two application rates: 100 percent cover, and 50 percent cover in 30 m contour strips. The intent of the mulch treatment was to bind the loose surface soil together, reducing detachment and transport by rainsplash and overland flow, while still allowing infiltration across the landscape.

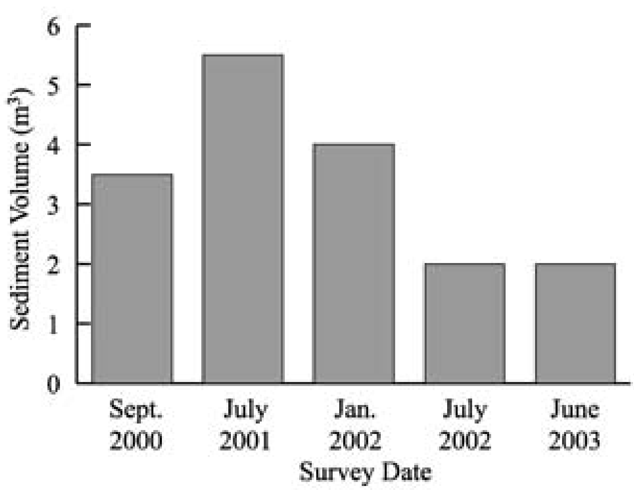
## Methods

Monitoring facilities and equipment were installed at the Mixing Fire site within two months after the wildfire. One watershed was instrumented in an area treated with LEBs and a nearby catchment was instrumented as an untreated control. The monitoring installations consisted of wood and sheet metal debris dams constructed across the stream channels to impound sediment; raingages; and a weather station (temperature, relative humidity, solar radiation, wind speed, and wind direction). Initial LEB sediment storage capacities were estimated by measuring two or three ground surface profiles across the storage area perpendicular to the log, obtaining an average, and multiplying by the length of the log. LEB accumulations were determined by periodically re-surveying the profiles and calculating the difference in storage volumes. Sediment yield from the watershed was measured by collecting the trapped debris from behind the dam in buckets and weighing it on a portable scale. Subsamples of the sediment were taken back to the laboratory to correct the field weights for moisture content. Results were normalized by watershed area as megagrams per hectare, Mg/ha (metric tons), to facilitate comparison.

The Williams Fire burned over existing small watershed monitoring facilities on the San Dimas Experimental Forest. Two watersheds were selected for a PAM application and two nearby catchments were chosen as untreated controls; PAM application occurred two months after the fire. Two other watersheds had 25 to 35 log structures placed in the channels and were compared against a single nearby control catchment. The monitoring facilities consisted of earth-fill dams with concrete outflow structures (Rice et al. 1965), raingages, and a weather station (temperature, relative humidity, solar radiation, wind speed, and wind direction). Sediment yields were calculated as volumes using an engineering end-area formula (Eakin 1939) based on repeated sag tape surveys of permanent cross sections (Ray and Megahan 1978). The volumes were converted to weights using measured debris densities, and the results were normalized by watershed area as Mg/ha to facilitate comparison.

Monitoring facilities and equipment were installed at the Cedar Fire site within three months after the wildfire. One watershed was instrumented in an area treated with 100 percent aerial hydromulch cover, a second nearby catchment was instrumented in an area with 50 percent contour strips, and a third catchment was instrumented as an untreated control. The monitoring installations were configured as for the Mixing Fire, above. Small sediment accumulations were also handled in the same way as those from the Mixing Fire. However, large sediment accumulations were handled differently. As with the Williams Fire sites, volumes were calculated from sag-tape surveys and converted to weights using measured debris densities. The sediment was then removed with a mechanical excavator and the surveys were repeated to obtain the new baseline geometry. Regardless of the measurement technique, results were normalized by watershed area as Mg/ha to facilitate comparison.

*Figure 3. Sediment accumulation behind the log erosion barriers (LEBs) on the Mixing Fire site by survey date. Initial survey – January 2000.*




## Results and Discussion

### Mixing Fire

The 1.2-ha treated watershed at the Mixing Fire site contained 157 LEBs with an initial total sediment storage capacity of 72 $m^3$. Overall, the LEBs performed as designed. Only about 6 percent of the LEBs failed due to undermining and another 6 percent had a significant flow of water around the ends of the logs (Wohlgemuth et al. 2001). At present, less than 4 percent of the LEBs have had their storage area filled with sediment, while about 5 percent have been rendered useless after being struck by wind-toppled fire-killed trees. The LEB accumulations for the first four years of the study are shown in Figure 3. Cumulatively, a total of 17 $m^3$ of sediment has been trapped by the LEBs, less than 25 percent of their capacity. Note that the vast majority (over 75 percent) of the material accumulated during the first two years of the study (Figure 3).

Sediment yield for the Mixing Fire, separated by winter cyclonic storm and summer thunderstorm seasons, is shown in Table 2. These values are small compared to the Williams Fire and Cedar Fire sites, as well as to other published rates of southern California post-fire sediment yield (Rowe et al. 1954; Loomis et al. 2003). However, there are spectacular differences in sediment yield between the treated and untreated watersheds.

Initially, the treated catchment on the Mixing Fire site produced an order of magnitude more sediment than the untreated. This can be explained in part by the fact that the soil depths on the treated watershed are only half those of the untreated (Wohlgemuth et al. 2001). With the fire in late summer, the soils must have been nearly de-watered. With the low precipitation in the first post-fire winter (see

*Table 2. Precipitation amounts and sediment yield results for the Mixing Fire by rain season.*

| | 2000 | | 2001 | | 2002 | | 2003 | |
|---|---|---|---|---|---|---|---|---|
| | Winter | Summer | Winter | Summer | Winter | Summer | Winter | Summer |
| **Precipitation (mm)**[a] | 254 | 47 | 301 | 68 | 167 | 8 | 550 | 49 |
| *Watershed Treatment* | | | | Sediment yield (Mg/ha) | | | | |
| **Log erosion barriers** | 0.20 | 0.20 | 0.04 | 0.06 | 0.10 | Trace | 0.05 | Trace |
| **Untreated** | 0.01 | 0.02 | 0.01 | 1.70 | 1.10 | Trace | 0.05 | Trace |

[a] *Average annual precipitation is 550 mm.*

*Table 3. Precipitation amounts and sediment yield results for the Williams Fire by year.*

| | Watershed | 2003 | 2004 |
|---|---|---|---|
| **Precipitation (mm)**[a] | | 525 | 435 |
| *Watershed Treatment* | Sediment Yield (Mg/ha) | | |
| **Polyacrylamide (PAM)** | Treated 1 | 33.7 | 0 |
| | Control 1 | 24.6 | 1.5 |
| | Treated 2 | 53.9 | 0 |
| | Control 2 | 59.8 | 0 |
| **Log structures** | Treated 1 | 10.0 | 1.3 |
| | Treated 2 | 8.4 | 0 |
| | Control | 34.7 | 0 |

[a] *Average annual precipitation is 700 mm.*

*Table 4. Precipitation amount and sediment yield results for the Cedar Fire.*

| | | 2004 |
|---|---|---|
| **Precipitation (mm)**[a] | | 170 |
| | | Sediment Yield (Mg/ha) |
| *Watershed Treatment* | 100 percent cover | 6.7 |
| **Aerial hydromulch** | 50 percent cover | 20.5 |
| | Untreated | 14.9 |

[a] *Average annual precipitation is 415 mm.*

Table 2), water storage in the shallow soils was presumably exceeded on the treated watershed but not on the untreated catchment. The saturated soils in the treated catchment generated sediment delivery from the hillslopes to the streams by overland flow, and the routing of this sediment to the debris basin by channel runoff.

The pattern of watershed response on the Mixing Fire then reversed itself, starting with the second summer after the fire (see Table 2). A high-intensity thunderstorm produced a large sediment pulse in the untreated watershed, but had little effect on the treated catchment. Site inspection revealed that the source of the sediment in the untreated watershed was a large area of bare ground directly adjacent to the stream channel. The massive overland flow off this bare patch extensively rilled the hillside, and channelized flow scoured the channel bed and banks. Erosion from this section of bare ground continued to generate high levels of sediment yield into the winter of 2002 (Table 2).

It is unfortunate that sediment yield on the Mixing Fire site was governed more by the inherent site characteristics than by the presence or absence of the LEBs. This demonstrates the need to carefully choose comparable study watersheds. It also points out the problem with lack of replication in the study design. Because of the differences in soil depths and vegetation cover, any watershed response that would relate to the efficacy of the LEBs as a post-fire rehabilitation treatment has been effectively masked.

### Williams Fire

The sediment yield results of the post-fire treatment comparisons for the Williams Fire (Table 3) indicate that, for this study site, PAM does little to reduce small watershed sediment yields. Although site differences may once again be a factor, with multiple treated and untreated catchments [with Treated 1 paired with Control 1 (untreated), and Treated 2 paired with Control 2 (untreated)], minimum replication was achieved. Observations over the course of the first post-fire winter revealed pervasive rilling on all watersheds, suggesting substantial overland flow. Although infiltration tests were not performed on the different watersheds, presumably the PAM did not work as intended. Alternatively, it is possible that these coarse-textured upland soils had too few fines to allow the PAM to be effective.

In contrast, the results indicate that, on the Williams Fire, the log structures in the two treated watersheds reduced the sediment yield by two-thirds compared to the single untreated control (Table 3). Although the untreated catchment is unreplicated, previous work (Rice et al. 1965) suggests that the sediment yield in the untreated watershed was actually lower than the two treated catchments prior to the Williams Fire. Virtually all of the storage space created by the log structures filled with sediment, and only a few of the structures failed by undercutting or side cutting. Debris retention and the protection against downstream channel incision could easily account for the observed difference in watershed sediment yield (Wohlgemuth 2003). There was also a rapid sediment yield decline in all watersheds during the second post-fire year (Table 3). This presumably attests to rapid watershed recovery in the fire area, although low precipitation values were undoubtedly partially responsible.

### Cedar Fire

The first-year post-fire sediment yield results for the aerial hydromulch treatment comparisons on the Cedar Fire indicate that the 100 percent coverage produced less than half the sediment of the untreated control (Table 4). Paradoxically, the 50 percent coverage watershed generated half again as much material as the untreated watershed. This suggests that perhaps the hydromulch treatment is effective only at full coverage. Alternatively, with no replication, there is a distinct possibility that inherent site characteristics may again be obscuring treatment effects.

However, tests of water repellency, infiltration, soil depths, and landscape morphometry have thus far revealed no differences between the watersheds.

Curiously, there is little evidence across the Cedar Fire study area of hillslope overland flow, as observed on the Williams Fire. In contrast, there is a dramatic hydrologic response in the ephemeral stream channels to even comparably small rainstorms of moderate intensity (less than 10 mm of rain in an hour). In the absence of overland flow, it is unclear how the water reaches the channels so quickly after a burst of rain. Observations in the stream courses also reveal substantial erosion of the channel bed and banks. This suggests that the majority of the material captured in the debris basins consists of remobilized channel sediments. Thus, the whole premise of treating hillslopes to reduce watershed sediment yields may be unfounded in this environment. However, the catchment with the 100 percent aerial hydromulch treatment produced fewer runoff events with smaller stormflow peaks than the other two watersheds under very similar rainfall patterns. This indicates that perhaps the value of this rehabilitation treatment is not to reduce hillslope erosion but rather to control water on the hillsides before it can reach the stream channels.

## Conclusions

Accelerated erosion following fire is inevitable, magnifying the risk of sedimentation-related damage to biological and human communities at the wildland/urban interface. Land managers will continue to seek out post-fire erosion control measures that are both effective and environmentally benign. The methods of erosion control employed in this study show some promise, but were not an unqualified success. The studies presented here suggest that LEBs were successful in retaining some sediment on the Mixing Fire, but that a test of treatment effectiveness was inconclusive because differences in site characteristics may have masked LEB performance. Results from the Williams Fire were likewise inconclusive, but suggest that for coarse-textured upland soils, PAM may be ineffective. However, log structures placed in the stream channels soon after burning showed great promise as a means of reducing sediment yield downstream. Aerial hydromulch at high percent coverage rates may have been an effective treatment on the Cedar Fire, but exactly how it worked remains unclear. The foregoing uncertainties illustrate the need for continued testing on these and other BAER treatments before they become standard practices. Furthermore, robust economic analyses are necessary to determine whether the various treatments are a cost-effective means of reducing erosion from hillslopes and sediment yields from burned watersheds.

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# Detecting Smoke Plumes and Analyzing Smoke Impacts Using Remote Sensing and GIS for the McNally Fire Incident

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Remote sensing and GIS techniques were developed and evaluated to retrospectively analyze the impacts of the McNally Fire on air quality. The McNally Fire was a large wildfire over 54,700 ha (150,000 acres) in size that occurred in the Sequoia National Forest, California, 21 July through 26 August 2002. MODIS satellite images and NOAA pictures were used to digitize smoke plumes. Smoke plumes were analyzed using ESRI ArcGIS Spatial Analyst. Air monitoring data was acquired from 23 locations for $PM_{10}$. Ozone data was acquired from 40 locations. ArcGIS Geostatistical Analyst was used to analyze and produce prediction maps using Kriging as an interpolation method. A strong positive correlation between $PM_{10}$ maximums and number of smoke plumes was observed. The correlation between $PM_{10}$ averages and number of smoke plumes observed was not as strong. Very high ozone concentrations generated by the the McNally fire were observed northeast of the fire, and affected mainly mountain sites. Ozone impacts due to the fire were not observed at valley sites. Remote sensing and GIS techniques were useful in assisting with the evaluation of fire smoke impacts on air quality.

Keywords: *wildfire, air quality, smoke, remote sensing, GIS, $PM_{10}$, ozone*

## Introduction

Wildland fires are a complex combustion source that involve several categories of fuels, and are characterized by fire behavior that changes over time with fuel and weather conditions. Smoke from wildfires is composed of hundreds of chemicals in gaseous, liquid, and solid forms (Ottmar and Reinhardt 2000). Some of the main concerns for land managers are the production of particulate matter and ozone from prescribed burns and wildfires. Managing fire to comply with national ambient air quality standards (NAAQS) requires an increasingly detailed base of scientific knowledge and information systems. Wildfire smoke is transported across state and land management agencies. Smoke impacts during these episodic events can threaten public health and may be the dominant cause of visibility reduction. Particulate matter (PM), the direct product of smoke is one of the greatest concerns due to its impacts on public health and visibility (Billington et al. 2000). Burning of forests can generate the precursors for substantial ozone concentrations downwind of the fire (Cheng et al. 1998). But, there is little research that links fire emissions with ground-level ozone concentrations. Also, there is uncertainty about the effects of ozone formation caused by mixing of fire emissions with urban sources (Sandberg et al. 2002).

The McNally fire was a large-scale wildfire, over 54,700 ha (150,000 acres). It occurred in the Sequoia National Forest, in the Sierra Nevada of California, during the period of 21 July through 26 August 2002. Smoke from this fire was transported over hundreds of kilometers across the California state boundary, degrading air quality and reducing scenic values. Characterization of effects of wildland fires on ambient air quality is incomplete due to the deficiency of air quality monitoring sites in rural areas. Knowledge about fire's effects on air is needed to meet regulatory and management requirements. New methods

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and information are needed to assess, monitor and predict smoke plumes.

This report evaluates the use of remote sensing and GIS techniques as a decision support tool to retrospectively analyze the McNally fire impacts on air quality. Also, the report evaluates the extent and duration of wildfire smoke on communities and provides insight to the magnitude of smoke impact from the fire on $PM_{10}$ (particulate matter, 10 microns or less) and ozone.

## Methods

### Aerial Data Acquisition

The MODIS images came from the TERRA satellite. MODIS or Moderate Resolution Imaging Spectro-radiometer is an instrument aboard NASA's TERRA and AQUA satellites. The daytime pass of TERRA goes over California at approximately 12:00 pm (1900 UTC). MODIS images were compiled and processed over the duration of the McNally Fire by the Remote Sensing Application Center (RSAC). The bounding coordinates of the image subset were: (west) 119.95° W, (east) 116.96°W, (north) 37.41°N, and (south) 34.41°N. The images were set to a spatial resolution of 250 meters, and georeferenced using the Lambert Azimuthal projection parameters. MODIS data were input into NASA processing software application for reflectance correction. The images were then imported into ERDAS Imagine[1] and saved in IMG (.img) format. Twenty-five images were collected.

Pictures were also collected from National Oceanic & Atmospheric Administration (NOAA) in JPG format. NOAA pictures helped us digitize plumes that went across state boundaries, as NOAA pictures covered a larger area than MODIS images. There were a total of 15 NOAA pictures collected for the whole incident.

### Plume Analysis Procedures

To view smoke plumes, the best band combination to use is the natural color composite. The bands are 1 (red), 4 (green), and 3 (blue). Imagine files have seven bands (Table 1).

MODIS images were screen digitized in ArcGIS, as shown in Figure 1, and further processed in ArcInfo Workstation. ArcInfo Workstation was used to clean and build the topology of the polygons created in ArcGIS.

NOAA pictures were used to help digitize smoke plumes that went across state boundaries, because they covered a larger area than MODIS images. It was complicated to differentiate between clouds and smoke using NOAA pictures, but these pictures were good for depicting the overall direction and distance of the plume.

*Table 1. The seven bands and wavelengths of MODIS imagery.*

| MODIS Band | Wavelength (nm) | Name |
|---|---|---|
| 1 | 620-670 | red |
| 2 | 841-876 | near IR |
| 3 | 459-479 | blue |
| 4 | 545-565 | green |
| 5 | 1230-1250 | mid IR |
| 6 | 1628-1652 | mid IR |
| 7 | 2105-2155 | mid IR |

*Figure 1. MODIS images were screen digitized.*

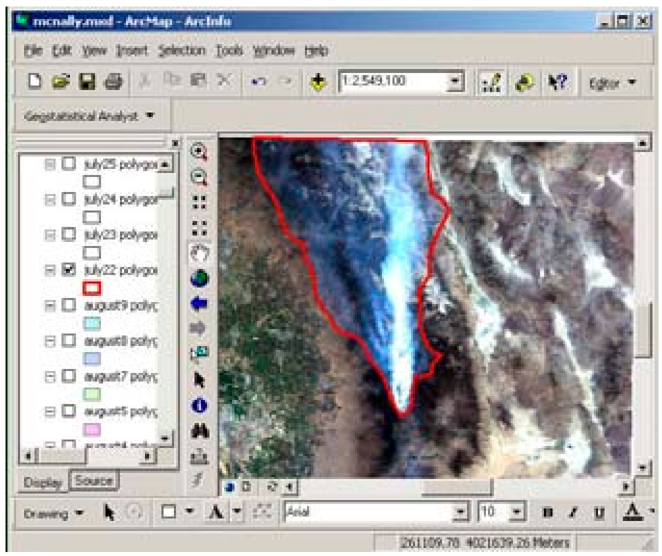
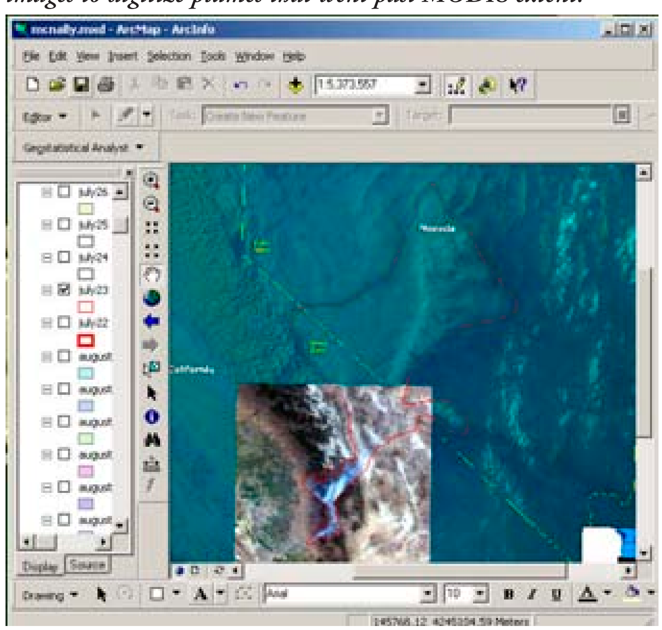
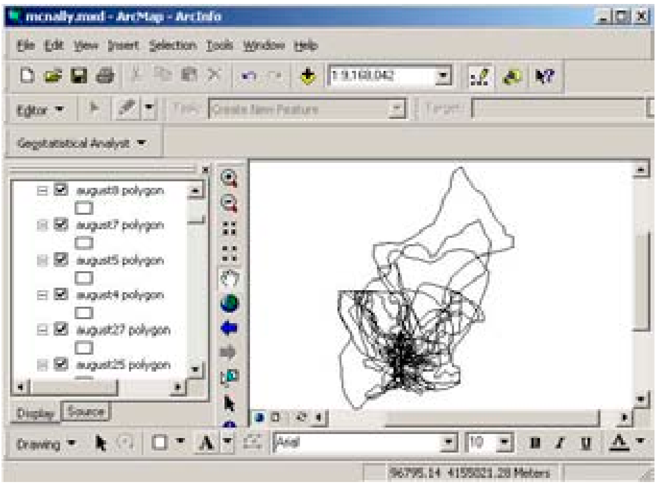



*Figure 2. NOAA pictures were used in conjunction with MODIS images to digitize plumes that went past MODIS extent.*




[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

*Figure 3. Twenty-five smoke plume polygons were digitized over the entire duration of the fire.*




A total of 25 smoke plume polygons were created (Figure 3), each representing a smoke plume observed one time per day. The MODIS satellite takes a snapshot once per day around noon. The fire lasted for 35 days. Plumes were digitized for 25 days out of a total of 35 days possible days of the fire, because on some days the images weren't available, or the image wasn't clear. All polygon coverages created were projected in NAD 1927, UTM Zone 11N. The Geographical Coordinate System used was GCS North American 1927.

All polygons were converted to raster format (Figure 4, Figure 5). The area inside the polygon was given a band value of 1, and a band value of 0 was assigned for the area outside of the polygon.

Raster datasets were created from each polygon and became thematic data. The Spatial Analyst extension in ArcGIS was used to describe the raster created from polygons. The cells created had a size of 3108 m with a total of 250 rows and 266 columns, and one band. This output resolution was determined by the Spatial Analyst. The optimum cell size to capture the appropriate detail varies from study to study. The smaller the cells, the greater the resolution and accuracy, but coding, database storage, and processing speed are more costly.

A zonal function was chosen to continue with the processing of all 25 raster datasets. Zonal functions compute an output raster dataset. The output value for each location depends on the value of the cell at that location and the association that the location has within a cartographic zone. All raster datasets must share the same coordinate system and the same projection.

The Raster Calculator provides the tools to perform mathematical calculations such as arithmetic operations. All 25 raster datasets were added together to produce the final raster. Each single input raster had a band value of 0 and 1, which represents the times that a plume was

*Figure 4. A single smoke plume polygon.*

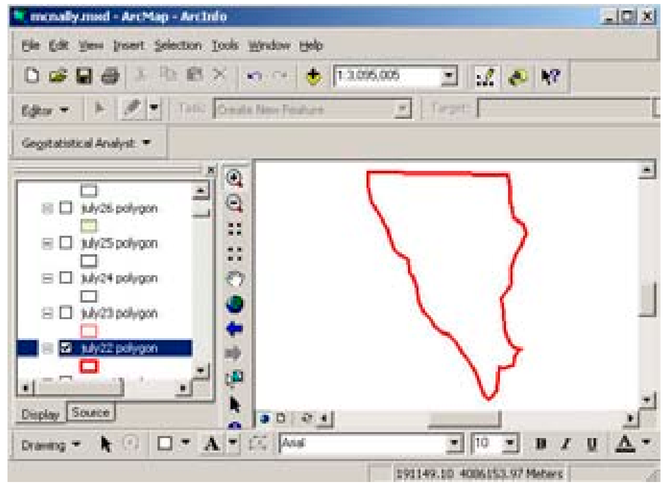



*Figure 5. The polygon in figure 4 is converted to raster format.*

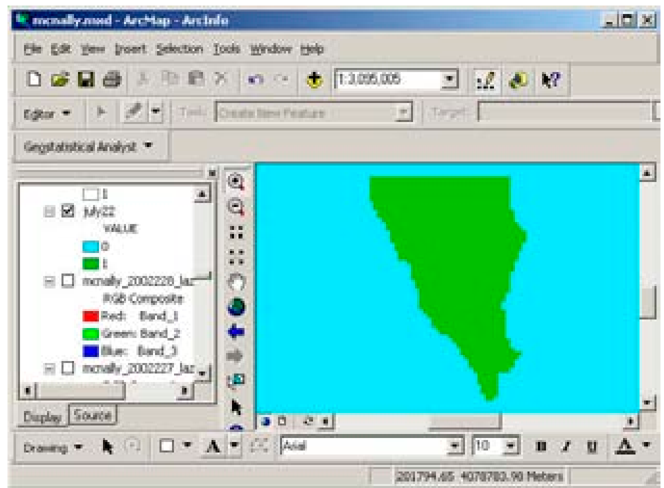
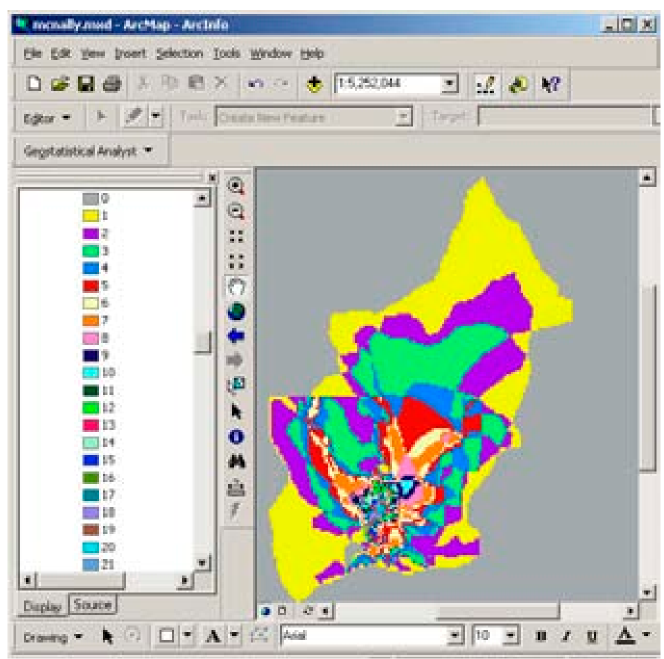


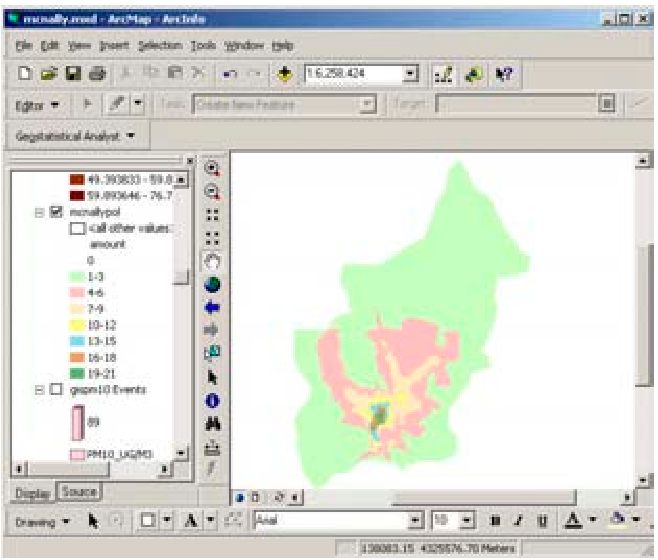

*Figure 6. Map produced by the Raster Calculator.*



observed. The final raster has a band value of 0-21; the value describes the number of times or days a plume was observed over a given location. The highest value was 21, which indicates that when overlaying all of the 25 plumes (raster) together only 21 overlapped. In other words, 21 out of the 25 plumes was the highest frequency observed over the same location (Figure 6).

The final raster was converted into a polygon coverage and classified by the number of plumes observed in a given location, grouped in threes. There were a total of seven groups (1-3, 4-6, 7-9, 10-12, 13-15, 16-18, and 19-21). The coverage was classified into seven groups because it is easier to interpret output images with seven colors than with twenty-one colors (Figure 7).

*Figure 7. Frequency of plume occurrence classified into seven groups. The numbers refer to the frequency of plumes observed.*




## Air Quality Data Acquisition for Particulate Matter

Air monitoring data for particulate matter was acquired from 23 locations. The air monitoring data collected hourly concentrations of $PM_{10}$, which were converted into 24-hour averages. The data included air quality data from the Air Resources Board network, IMPROVE (Interagency Monitoring of Protected Visual Environments), the Great Basin Air Pollution Control District in Bishop, CA (north and east of the fire), and the Forest Service's Kernville Work Center (just south of the fire). IMPROVE data is part of the long term monitoring program establish to monitor visibility trends. The monitoring data from Bishop is part of the Great Basin Air Pollution Control District monitoring network. The data from the Kernville Work Center came from a monitoring station set up by the Forest Service at the beginning of the fire.

## Air Quality Data Acquisition for Ozone

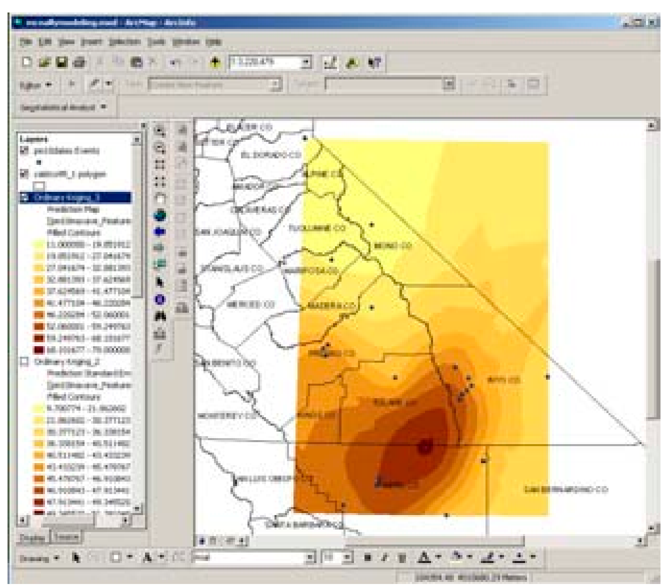
Air monitoring data for ozone was acquired from 40 locations. Twenty-four locations used ozone passive samplers and 16 used active monitors. The ozone passive concentrations were provided in two-week averages, thus hourly data from the active monitors was converted to two-week averages as well. The ozone passive data were provided by the USDA Forest Service Riverside Fire Lab. The active monitor data were provided by the Sequoia National Park, San Joaquin Air Pollution District and Air Resources Board network.

## Air Quality Data Analysis Procedures

Interpolation methodologies were used to create a prediction map (Figure 8 and 9) in Geostatistical Analyst to showcase what could be done using GIS. Ordinary Kriging is a quick interpolator that is very flexible, allowing investigation of spatial autocorrelation. Inverse Distance Weighting (IDW), the simplest of all interpolators, could also be used, but it does not provide a standard error map. IDW is a quick, exact deterministic interpolator. It allows a few choices regarding model parameters, and there are no assumptions required for the data. For the purpose of this project Ordinary Kriging was used because it allows the creation of a prediction standard error map, although no manipulations were done. Geostatistical Analyst was used to create a prediction map and a standard error map.

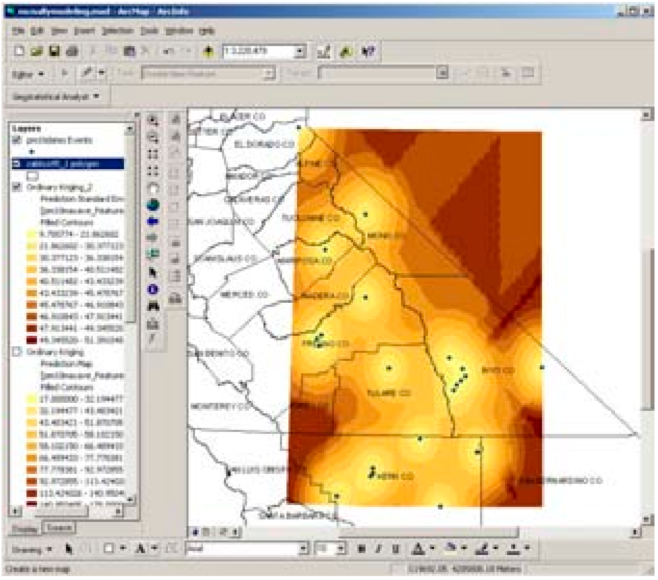
Air quality data from monitoring stations were transferred into ArcGIS, and a point coverage was created.

*Figure 8. Prediction map created using ordinary Kriging. Blue dots symbolize monitoring station locations. The map displays the $PM_{10}$ 24-hour average concentrations in µg/m$^3$ averaged over the duration of the fire.*



The $PM_{10}$ 24-hour averaged data covered the duration of the fire from 21 July through 27 August. Ozone data was collected in two week averages and covered the following dates: 2 - 16 July, 16 - 30 July, 30 July - 13 August, and 13 - 28 August 2002.

*Figure 9. Standard error map. The blue dots represent the monitoring sites. Predictions are more reliable closer to the monitoring sites.*



## Results and Discussion

The following discussion used the satellite plume data, $PM_{10}$, and ozone air quality data processes outlined in the methodology to analyze the impacts of the McNally fire.

### Data Analysis Using Remote Sensing and GIS for $PM_{10}$

Looking at Figure 10, it is evident that the locations with the highest frequency of smoke plume occurrences also had the highest $PM_{10}$ 24-hour Maximum concentrations. This finding indicates a positive correlation between frequencies of plume observed over the general fire area and production of particulate pollution measured as $PM_{10}$.

The correlation between plumes and the average of the $PM_{10}$ 24-hour concentrations was not as strong (Figure 11).

When looking at the correlation coefficient $r^2$ for $PM_{10}$ 24-hour averages and $PM_{10}$ 24-hour maximum, the interpretation is the same as the observations made before using GIS and remote sensing. A strong positive correlation between the frequency of smoke plumes and the concentrations of $PM_{10}$ 24-hour maximums for the duration of the fire was observed (with $r^2$ = 0.820 and alpha = 0.05). For the duration of the fire, the correlation between frequency of smoke plumes and $PM_{10}$ 24-hour

*Figure 10. The $PM_{10}$ 24-hour maximum concentrations (µg/m³) bar graph overlay over the plume layer.*

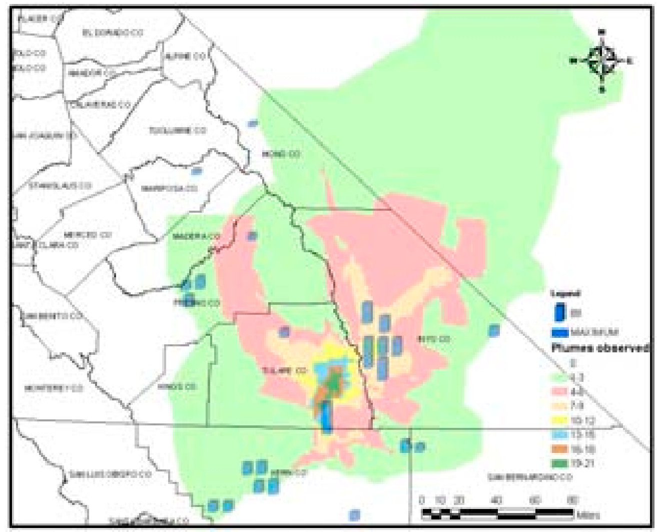


*Figure 11. The average of the $PM_{10}$ 24-hour concentrations (µg/m³) bar graph overlay over the plume layer.*

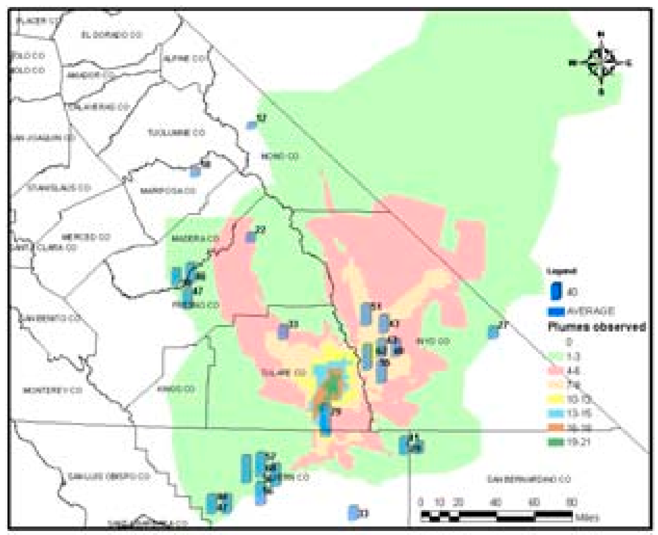


*Figure 12. Two-week averages of ozone concentration (ppb) overlaid over the plume layer.*

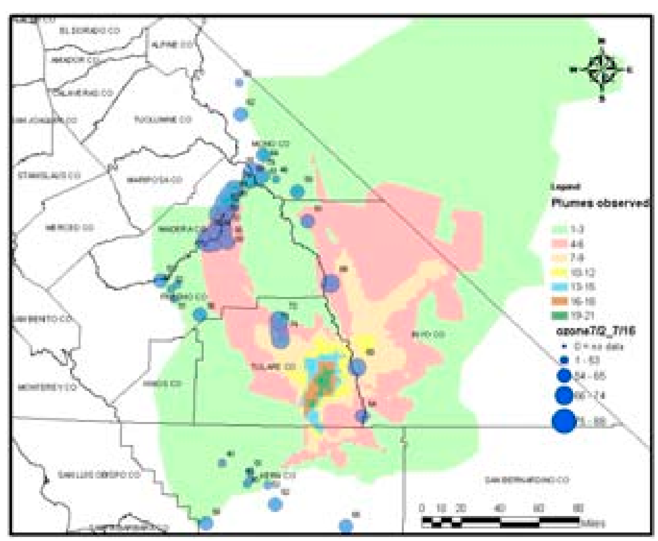


*Figure 13. Ozone concentrations (ppb) and ozone monitoring locations, before the McNally fire.*

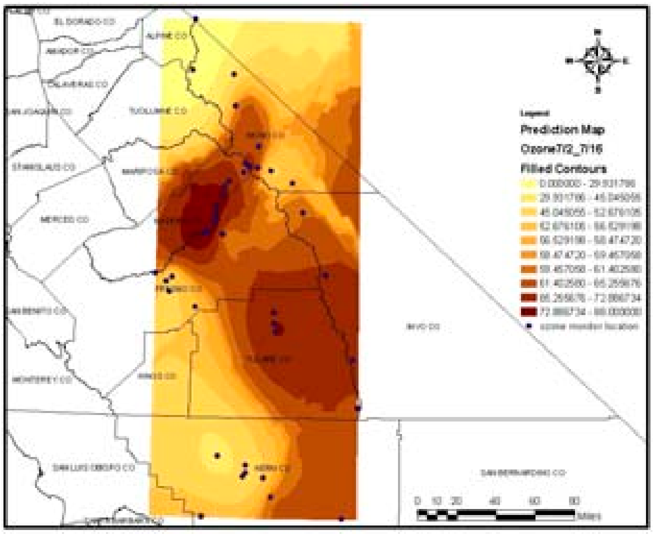
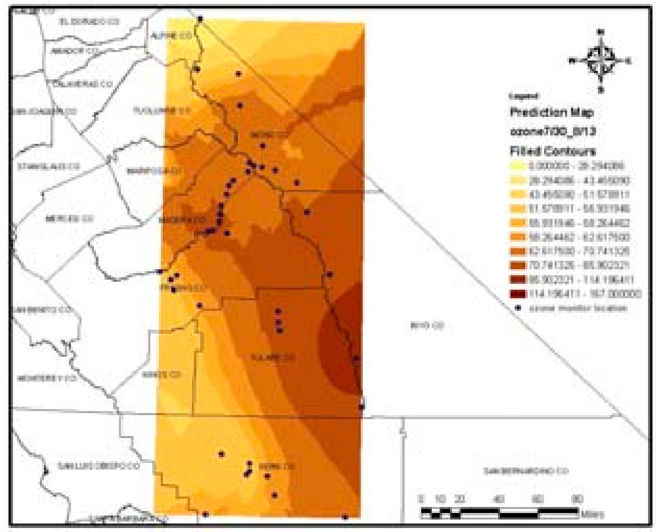



*Figure 14. Ozone concentrations (ppb) and ozone monitor locations, on 30 July 2002, during the McNally fire.*




averages was also positive, but not as strong (with $r^2$ = 0.492 and alpha = 0.05). It is clear that a large area of the Sierra Nevada experienced very high levels of $PM_{10}$ concentrations during the fire.

## Data Analysis Using Remote Sensing and GIS for Ozone

There is no observational evidence of correlation between frequency of smoke plumes and ozone concentrations (Figure 12).

Before the McNally fire started, the highest ozone two week concentration averages occurred in the mountain sites. Figure 13 illustrates a typical ozone distribution in the area before the fire started. During that period (2 - 16 July 2002), the maximum two week average did not exceeded 90 ppb.

During the fire (30 July - 13 August), the distribution of ozone concentrations is completely different. The highest concentrations occurred in the eastern part of the Sierra Nevada, downwind of the fire, with the maximum two week averages over 160 ppb. Figure 14 provides evidence of correlation between ozone generation and catastrophic forest fires. In the Sierra Nevada, due to the proximity of the urban-related California Central Valley plume, which is rich in nitrogen oxides ($NO_x$), there is a strong potential for generation of very high ozone concentrations when elevated concentrations of volatile organic compounds (VOCs) are present as a result of forest fires.

Ozone monitoring locations located in the San Joaquin Valley or in urban locations apparently were not affected by the McNally fire. Descriptive statistics are about the same before and during the fire for monitoring sites located in cities. Monitoring sites located in the mountains did show differences in ozone concentrations before and during the fire (Table 2).

## Conclusions

In this paper, we outline a method for relating fire emissions to particulate matter and ozone concentrations using remote sensing and GIS. Locations that had the highest frequency of plume impacts also had the highest $PM_{10}$ 24-hour maximums concentrations. There is clear observational evidence of positive correlation between frequencies of plumes observed over a site with particulate

*Table 2. Descriptive statistics of two-week ozone averages (ppb) for 40 ozone monitoring stations before and during the fire. The monitoring sites were classified as city (urban location), or mountain location.*

| | 2 - 16 July | | 16 - 30 July | | 30 July - 13 Aug. | | 13 - 28 Aug. | |
|---|---|---|---|---|---|---|---|---|
| **Ozone Concentration (ppb)** | **city** | **mtn.** | **city** | **mtn.** | **city** | **mtn.** | **city** | **mtn.** |
| Mean | 52.95 | 67.79 | 52.5 | 71.47 | 53.89 | 76.19 | 55.32 | 87.8 |
| Maximum | 65 | 88 | 65 | 90 | 68 | 167 | 73 | 186 |
| Minimum | 40 | 46 | 44 | 51 | 42 | 41 | 44 | 59 |
| Average | 24 | 42 | 21 | 39 | 25 | 126 | 29 | 127 |
| Standard Deviation | 7.4 | 10.8 | 6.4 | 11.2 | 9.2 | 24.1 | 9.7 | 24 |

matter air pollution. The highest $PM_{10}$ maxima occurred in the eastern part of the Sierra Nevada closer to the fire and downwind of the fire. The McNally fire produced very high two-week average ozone concentrations in mountain sites, but there is no evidence that the fire affected sites in urban locations. During the fire, the highest ozone episodes occurred in the eastern part of the Sierra Nevada downwind of the fire.

Remote sensing and GIS approaches used in this paper could be beneficial for other air quality concerns such as for $PM_{2.5}$, and could be applied to analyze other wildfires. We conclude that GIS techniques and remote sensing could be extremely useful in evaluating wildfire impacts on air quality.

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# Sierra Nevada Framework Smoke Monitoring: Testing Implementation Through a Pilot Program

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An increasing need to treat hazardous fuel conditions in the Sierra Nevada combined with a geographic relationship to surrounding air basins with very serious air quality issues has resulted in challenges for land management and air regulatory agencies. A series of policies, plans and regulations at federal, state, and local levels addresses issues that require attention in order to increase treatment with prescribed fire while protecting public health. Monitoring fine particles ($PM_{10}$) produced by smoke provides land management and regulatory agencies with information necessary to avoid significant community impacts. Recently, new filter-based monitoring systems have been developed. Met One's BAM-1020 beta attenuation mass monitor is a federal reference method that meets the EPA requirements for monitoring $PM_{10}$ compliance, but can be limited in use by land management agencies due to a lack of portability and reliance on line power. Met One's E-BAM is a portable real-time beta gauge. While not a federal reference method, the EBAM has shown strong correlation with BAM data and is highly portable. A pilot program has been developed to test the utility, accuracy, reliability, and data management requirements of these instruments in a comprehensive network. The test network will include three fixed-site BAMs in sensitive communities and approximately 10 portable EBAMs that will be deployed in communities as needed to characterize the impacts of smoke from prescribed fire and wildland fire.

Keywords: *air quality, air pollution, smoke, monitoring, regulations, hazardous fuels*

## Introduction

California has a significant number of sources that emit fine particles (defined as particles with an aerometric diameter of 10 μm ($PM_{10}$) and 2.5 μm ($PM_{2.5}$) and smaller, respectively). The climatic, meteorological, and geographic features in many parts of the state provide suitable conditions for these pollutants to accumulate and reach serious levels. Fine particle concentrations in much of the state are at levels that cause respiratory illness and premature human mortality. About half of the state, primarily central and southern California, does not attain the federal $PM_{10}$ and $PM_{2.5}$ standards. Virtually all of the state, with the exception of Siskiyou and Lake counties, is non-attainment or unclassified for the more stringent California $PM_{10}$ standard.

California is divided into 35 regulatory air pollution control districts with oversight provided by the California Air Resources Board (CARB) and the US Environmental Protection Agency (EPA). This regulatory framework is considered effective at developing local accountability and control strategies tailored to local issues. However, it also presents a very challenging and complex environment to land management agencies attempting to manage an increasing fuels issue. California leads the nation in aggressive strategies to reduce air emissions, and with major emitting industrial sources largely controlled, the focus is now on smaller sources.

Generally there is good public support both for air quality and for the need to reduce hazardous fuels. However, when the two issues are seen to conflict, the urban population is often more air quality sensitive, and is pitted against more fire-sensitive rural communities. In this setting of air quality and fuels issues the public increasingly expects agencies charged with the stewardship of these resources to resolve conflicts and negotiate a path that protects public health, maintains public safety, and protects forest resources. High quality information, including monitoring of fine particles, is necessary to help define the operational area that can accomplish fuels reduction while minimizing the impacts of smoke on air quality.

## Issues Leading to the Investment

A successful smoke monitoring program can lead to a wealth of information adding more certainty to issues related to public health, and a better understanding

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

of spatial and temporal trends that effect community exposure.

Irrespective of regulatory requirements, Forest Service managers require smoke monitoring information to assist in better fire management, air quality stewardship, and maintaining good community relationships. Some of the management questions that a monitoring program can help answer include:

***What are the tradeoffs between prescribed fire and wildfire impacts?*** A better understanding of emission production and exposure of wildfire and prescribed fire is necessary to fully understand the role of prescribed fire in eventually reducing emissions generated from wildfire.

***How does urban air pollution and smoke contribute to visibility impairment?*** Visibility in national forests, especially in Class I wilderness areas, is an important resource and wilderness value. Understanding the entire mixture of pollutants and sources will be critical in working with states to improve visibility.

***What is the natural and current background of smoke?*** Comparing current background of smoke and PM concentrations with pre-European estimates will be important in defining natural background. Natural background may be used to determine regulatory allocations.

***What is the impact on communities and public health?*** This is the essence of regulatory pressure on public land agencies, and monitoring is necessary for informed decisions to protect public health.

***What is the public tolerance?*** In addition to regulations for prescribed fire California regulates actions that create public nuisances. More monitoring data will help understand thresholds of public tolerance that differ from health thresholds.

***How can monitoring contribute to the testing and validation of models?*** Models being developed to predict smoke dispersion, such as the Blue Sky smoke model, can be validated if the modeling domain is characterized with monitoring.

***What mitigation and contingencies are the most successful in minimizing smoke and public exposure?*** The Forest Service has developed guidelines and training to institute measures that can be effective in reducing emissions. Monitoring in conjunction with these mitigations can validate their effectiveness.

In addition to management needs, regulatory requirements and policy in California dictate or strongly recommend monitoring in some situations. California's Title 17 (Smoke Management Guidelines for Agricultural and Prescribed Burning) has provided the template for local regulations and requires smoke management plans to include appropriate monitoring, which may include visual monitoring, ambient particulate matter monitoring or other monitoring approved by the district for:

(1) projects greater than 250 acres (101 ha);

(2) projects that will continue burning or producing smoke overnight;

(3) projects conducted near smoke sensitive areas; or

(4) as otherwise required by the district (CARB 2001).

Monitoring data also contributes to more informed regulatory decisions. Serious air quality issues in California require action with or without data and often daily regulatory decisions, such as burn-day allocations, are supported by meteorology data, but not air quality data. Air quality monitoring data can also be used to test, validate, and adjust $PM_{10}$ reduction strategies.

## Pilot Study Design

The Forest Service has experimented with a number of particulate samplers over the last 20 years with varying success. Nephelometer based optical monitors have been used with some success, but California has expressed more support for filter-based monitoring systems such as MetOne Instruments BAM 1020 and E-BAM samplers. These systems measure a radioactive isotope passing through filter paper before and after particles are deposited on the filter (Trent 2003).

The southern Sierra Nevada National Forests have steadily emerged as a candidate to test monitoring equipment due to serious fuels issues and the proximity to the San Joaquin Valley Air Basin, which is one of the most severely polluted air basins in the United States. An approach to characterizing smoke in the Sierra Nevada was developed during the Sierra Nevada Framework project and suggested different approaches for regional scale characterization and project level / community characterization. The Sierra Nevada Framework smoke monitoring study plan recommends using the Interagency Monitoring for Protected Visual Environments (IMPROVE) monitoring network in coordination with the state network to examine regional scale trends. The study plan recommends using BAM 1020 and E-BAM technology to evaluate community impacts. The Sierra Nevada Smoke Monitoring Pilot (SNSMP)) was designed to test the study plan recommendations.

BAM 1020 instruments were installed where the objective was to monitor year-round background, and where a secure site with line power was available. These instruments are located on the Sequoia National Forest in the communities of Pinehurst, Springville, and Kernville. The BAM 1020 is an EPA approved equivalent method for $PM_{10}$. Seven additional tripod mounted E-BAMs were deployed on the Sequoia, Sierra, Stanislaus, and Inyo National Forests. E-BAMs, although not an EPA approved "equivalent monitoring method", provide quality data and portability, allowing good flexibility in deployment for short-term smoke events. These tripod mounted instruments also require line power. In addition three portable solar powered E-BAMs mounted on trailers are available for events where line power is not available. Some of the E-BAMs are equipped with basic meteorological instrumentation, including wind speed and direction, air temperature, relative humidity, barometric pressure, solar radiation, and precipitation.

## Data Delivery

Particle data related to monitoring smoke is most useful in near real-time. Data that can be returned to land management and air regulatory agencies in near real-time allows for fire management strategies that can reduce smoke production or alter the transport. It also provides information to air regulatory agencies that can be used to better manage allocations and more information for burn day designations.

The SNSMP is testing the use of satellite modems via ORBCOMM combined with data delivery to a Web page that satisfies the real-time needs. The Website can be accessed at *http://www.satguard.com/usfs4*. Graphics of one, eight, and twenty-four hour averages are displayed along with tabular data details. Air Resource Specialists, Inc., in Fort Collins, Colorado provides data quality assurance reviews, monthly and annual data reports, and equipment support for the project.

## Pilot Review

The SNSMP is planned to continue through March 2006. At that time the Region 5 Forest Service Air Program will review the durability, portability, maintenance, and data delivery of the network. In addition, we will review how well the instrumentation was used by air regulatory agencies and the Forest Service to improve coordination and make more informed decisions.

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# Air Quality and Prescribed Fire Management–Moving Toward a Solution Space

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Smoke issues have come to the forefront as National Forests increase prescribed fire management treatments to implement the Healthy Forests Initiative and the Healthy Forests Restoration Act. Increases in the population living within the wildland-urban interface have resulted in a larger population exposed to prescribed fire smoke. The combination of increased burning and public smoke exposure has created a need for detailed public involvement plans; planning and prioritization of areas for treatment; interagency coordination between regulatory agencies, smoke managers, and public health officials; better predictive tools for weather forecasting, smoke production and dispersion; real-time air quality monitoring; creative methods of responding to legitimate health conditions; and derivation of realistic, quantifiable air quality objectives. The Okanogan-Wenatchee National Forests (OWNFs) in north-central Washington are a focal point for implementing a prescribed fire program of landscape-scale burns. Local objective levels of air quality particulate have been defined, and are monitored using an air quality instrumentation network. An extensive program of public information has been developed. Collaborative forest health treatments have been initiated with private property landowners and homeowner associations. The forests and the Washington State Department of Ecology (DOE) have entered an agreement whereby the Forest Service operates a network of nephelometers that are incorporated into a DOE air quality website. The desired outcome is the successful completion of an accelerated prescribed fire program with minimal exposure of the public to unhealthy levels of smoke concentration. This paper focuses on OWNFs' efforts since the wildfires of 1994 to develop quantifiable air quality objectives and incorporate them into an interagency prescribed fire management regulatory framework for an expanding burn program.

Keywords: *air pollution, air quality, smoke, prescribed fire, fire management*

## Introduction

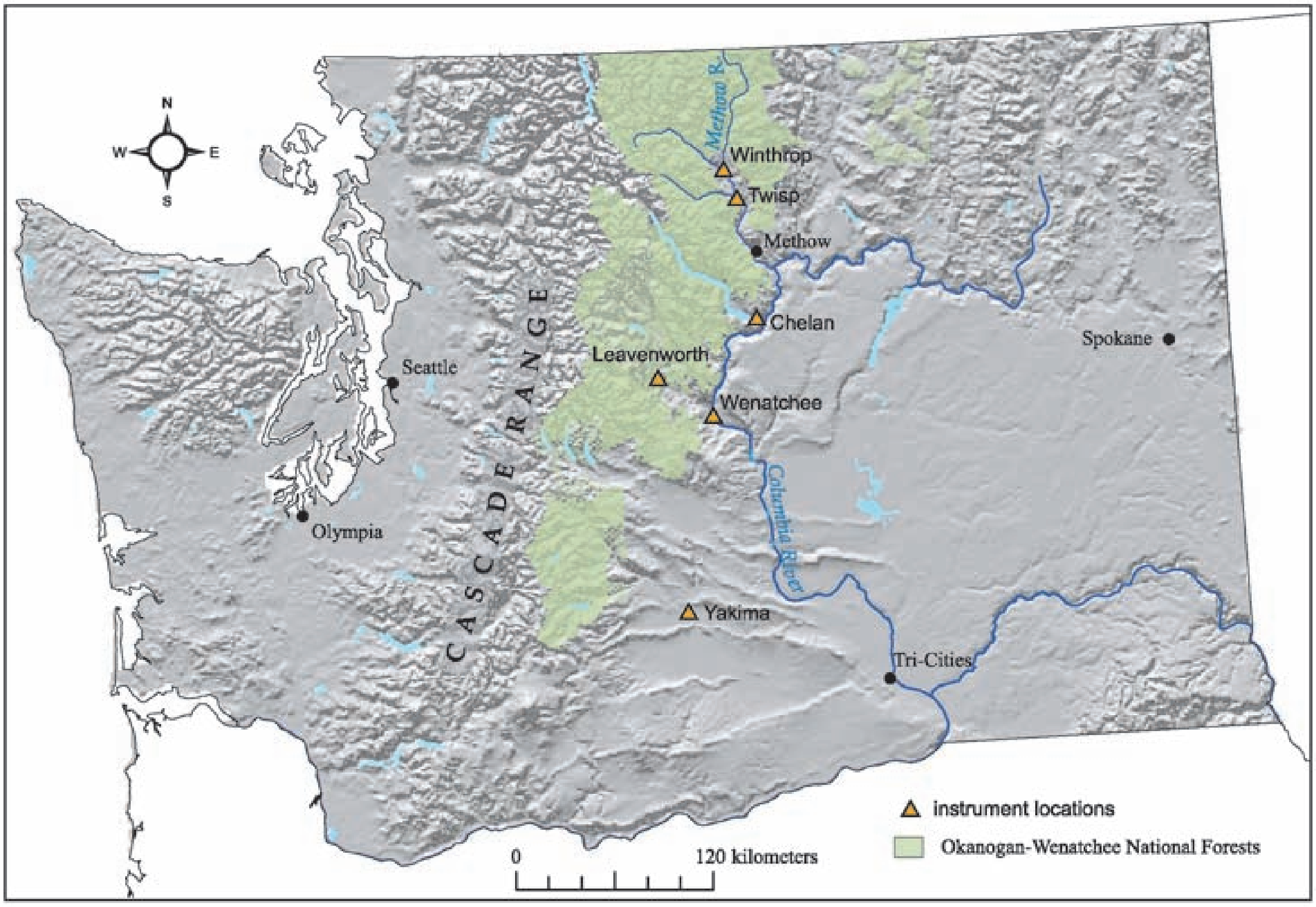
On 28 July 1994, dry-lightning storms started multiple wildfires across the Eastern Cascades of central Washington State. Conditions were extremely dry in the national forests. The 1994 water year was the third in a row in which annual streamflow had been well below average at various long-term gaging stations (USGS 2004; Robison 2004). Water years 1993 and 1994 were more than one standard deviation below period of record average values for the Wenatchee, Stehekin and Methow Rivers. The largest of the fires burned 185,000 acres (74,867 ha) on the Wenatchee National Forest. At that time, it was the largest wildfire complex within a single national forest in the history of the Forest Service (FS). The fires caused many weeks of impaired air quality in all five cities of Chelan County. This paper discusses the evolution of two resource management programs, the Healthy Forests Initiative, relying heavily on prescribed fire, and the Air Quality Management Program, both of which have evolved since the fires of 1994. The subject area is the Okanogan-Wenatchee National Forests (Forests) of central Washington State (Figure 1).

Following the 1994 wildfires, emergency fire restoration efforts began immediately with a detailed assessment of the burn area. Burn intensity mapping showed that sixth-field subwatersheds had as much as 50-75% of total drainage area in a condition of moderate to high burn severity. This fact as well as the large area burned increased the emphasis on quickly accomplishing emergency fire restoration. Various efforts to seed, fertilize, contour-fell burned snags across steep slopes, remove road culverts and improve road drainage were completed in what became the largest and most expensive emergency fire restoration effort in agency history.

In addition to the emergency restoration efforts, the forest supervisor chartered a science team to review the fires and make specific recommendations as to actions that could be taken to reduce the risk of recurrence of such large and intense wildfires. The team was charged with finding answers to three specific questions: Why were the

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

*Figure 1. Location of air quality instruments within the Okanogan-Wenatchee National Forests of central Washington state.*




fires so large? Why did they burn with such intensity? Were they within an expected range of natural variability?

## Scientific Review Findings

The science team effort produced a number of key findings regarding changes in fire ecology, and the composition and structure of vegetative stands across the Eastern Cascades, especially on sites in the lower elevational range of coniferous vegetation. This broad area was labeled "dry site forest". It parallels but is east of the crest of the Cascades. These observations were packaged into a "Dry Site Initiative" which became one of a number of resource discussions that have led to the "Healthy Forests Initiative" (HFI) on a national scale (Office of the President 2002; Townsley 2004). The initiative focuses on identifying areas of "dry site forest", reducing fuel loadings, removing understory vegetation, reducing potential for insect and disease infestation across large landscapes, and creating a vegetative mosaic less prone to catastrophic fires on the scale of the 1994 fires. The amount of silvicultural burning, and especially the use of large-scale prescribed fire, has increased as a result of the initiative.

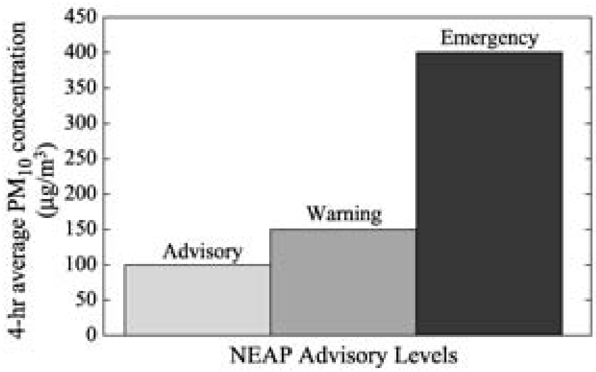
## Chelan County Natural Events Action Plan

A second outcome of the fires of 1994 was the preparation of a Natural Events Action Plan (NEAP) for Chelan County. The Washington State Department of Ecology (DOE) led an interagency effort to prepare this contingency plan for wildfire. The NEAP was published in June 1997 and contained three goals: educate the public about wildfire, mitigate health impacts, and institute best available control measures (Greef 1997).

The NEAP defined three threshold levels of air particulate concentration: advisory, warning and emergency, and prepared a public health news release for each. The levels were based on a 4-hour average concentration of fine particulate less than 10 microns in diameter ($PM_{10}$) as measured in micrograms per cubic meter ($\mu g/m^3$) (Figure 2). This was the first NEAP in the country prepared as a contingency plan for wildfire and a subsequent adverse air quality situation.

Agency roles and responsibilities were defined. The Forests' role is to provide information about weather and wildfire conditions, and alert state and local agencies whenever a wildfire could potentially grow to such size

*Figure 2. Natural Event Action Plan (NEAP) advisory levels of particulate.*




as to generate a smoke incident. The DOE will review nephelometer data both from permanent DOE operated instrument sites and from any temporary sites established for the fire emergency, release public health information, and provide advice and counsel to the local public health agencies. Local public health officials issue public service news releases as needed. The NEAP has been implemented in Chelan County for wildfire situations almost every year since publication in 1997.

## Air Quality Management During Prescribed Fire Operations

The emphasis on prescribed burning as a result of the local "Dry Site Initiative" and the national-scale HFI has increased attention on refining working relationships, roles and responsibilities of all agencies involved in fire management. The Washington State Department of Natural Resources (DNR) administers the Smoke Management Plan for the State of Washington via statute. DNR reviews each silvicultural burn request and makes daily approval decisions based on meteorological forecasts and projections of smoke production and dispersion (Washington Department of Natural Resources 1993). DOE operates air quality monitoring instrumentation, posts air quality information, and issues approvals for agricultural burning for the State. The FS is the prescribed fire manager for fires occurring on the national forests.

Prior to 1994, DOE's air quality focus was monitoring air quality in major population centers; it operated only two air samplers in the Eastern Cascades. In 2002 the Forest Service and DOE signed an agreement for the operation of five additional instruments, to provide better definition of background air quality, define impacts from all particulate sources including prescribed burning, and identify acceptable windows for burning. The Forest Service purchased and operates Radiance Research Nephelometers, but pays DOE for quality control oversight and posting of data on a state-wide DOE website. Figure 1 shows the location of instruments in the Eastern Cascades.

The collective knowledge and experience of the agencies involved in wildland fire management and public health since the 1994 fires has led to some consensus as to how to successfully operate these programs. It has become clear that wildfires occur on an almost annual basis, causing negative air quality impacts across a broad geographic area of the Eastern Cascades. Smoke becomes an air quality issue when trapped in local valley bottoms. Upper Columbia River valley communities, and often other states and Canada, are affected by adverse air quality conditions when major wildfire events occur. The causative events of air quality incidents can be a considerable distance away, but still may result in impacts on valley communities. Fires as far away as western Washington, Canada, and Alaska, and at least on one occasion, a dust storm in China, have resulted in noticeable air quality impacts. Agencies have concluded that the public should be given as much advance notice as possible when adverse air quality conditions are anticipated.

Forest fire management specialists have concluded, based on local experience and observation, that fuel reduction treatments have made a difference in control of wildfires (Harrod 2004). Wildfires have different burn behavior in stands where site treatments have reduced stocking of standing trees, minimized fuel ladder structure, and reduced volume of fuels. Agencies further concluded that strategic placement of these treatments has been effective in protecting areas of urban interface from fast-moving wildfires. Although these treatments have shown to be effective, they are limited in number. It will take many more treatments across a broader landscape to accomplish HFI objectives.

### 2003 Issuance of a Notice of Violation

The 2003 burning program in the Methow Valley began on 15 May and continued until 10 June. The Methow Valley Ranger District (MVRD) burned over 2,000 acres (809 ha) of prescribed fires. On 18 June, as a result of air quality conditions in the Methow Valley, DOE issued a Notice of Violation (NOV) to the Regional Forester, Pacific Northwest Region, "for causing and/or allowing air pollution from prescribed silvicultural burning in violation of the Washington Clean Air Act…that caused a nuisance, obscured visibility on roads, and presented a risk to the health of people who were residing in the area of the fires". The peak hourly $PM_{2.5}$ particulate value was 129 $\mu g/cm^3$ at the Twisp nephelometer on 5 June. Figure 3 shows daily maximum hourly nephelometer readings converted to $PM_{2.5}$ particulate in units of micrograms per cubic

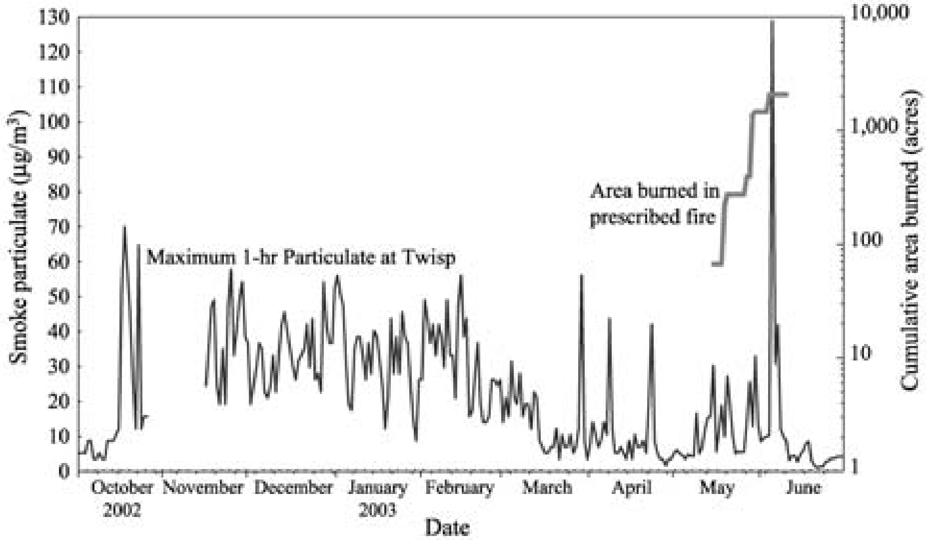



*Figure 3. Twisp nephelometer daily 1-hour maximum $PM_{2.5}$ values for October 2002 to June 2003, with burn acreage.*

meter (µg/m³). The monitor at Twisp was the only air quality instrument in the Methow Valley at the time. Observations of local conditions at Winthrop, eight miles further up valley and closer to the burns, were reported to be considerably worse.

The legal basis for this NOV is still debatable given that the burns had been ignited following daily dialogue between the Forests and DNR, and approval had been given by DNR. However the incident did highlight the fact that further dialogue was needed between the three agencies involved, especially given the increase in the prescribed fire program and the use of landscape scale burns. Because of the magnitude of air quality impacts, the forest conducted an internal review and initiated a number of corrective actions. These actions were incorporated into a settlement agreement between the three agencies and became the basis for further refinement of working relationships.

***Settlement Agreement Action Items.*** A number of action items were implemented immediately as part of the settlement agreement.

- A Forest Service nephelometer was moved to Winthrop in the Methow Valley and added to the DOE state network, supplementing the existing DOE instrument at located at Twisp.
- A camera was installed at the Forest Service IMPROVE monitoring site overlooking the lower Methow Valley to provide live images of air quality conditions in the lower valley on the FS website. The live camera image can be viewed at *http://www.fsvisimages.com/pasa1/pasa1.html.*
- The MVRD started routinely requesting an on-site meteorologist for landscape-scale fires when conditions warranted.
- The forests began identifying landscape burns when requesting burn approval from DNR.
- This allowed DNR to issue three-day, instead of one-day, approval windows when warranted for these multiple day burns.
- DOE was given a daily listing of approved burns.

Longer-term improvements were also implemented. The MVRD improved and expanded the district public involvement plan (USDA FS 2004). A Forest Service complaint tracking system was developed and implemented so the District could document every inquiry from the public about burn activity and record agency responses. Coordination meetings and field reviews were scheduled for the three agencies. Attention was focused on coordinating public information messages issued through the news media regarding burning. Collaborative work continued with the Pacific Northwest Research Station and University of Washington research scientists to refine smoke dispersion computer models (Ferguson 2004). A resolution to settle the NOV was signed by DOE, DNR, and the Forest Service Pacific Northwest Region in September 2003.

### 2004 Refinements to the Air Quality Management Program

Action items were implemented in 2004 with good results. Between 29 March and 1 June over 7,600 acres (3,075 ha) were burned on the Forests. The MVRD burned 3,200 acres (1,295 ha), including several multiple-day landscape burns. Ranger district personnel implemented an expanded public involvement plan, while recording and responding to all public contacts (USDA FS 2004). DOE monitored complaints, coordinated responses with the MVRD, and monitored air quality data. The Forests continued to submit landscape burn requests as a special category, and DNR reviewed these for multiple day burn approval. DNR agreed that in the event a three-day approval was given for a landscape burn, approval would not be rescinded, even if conditions deteriorated on day 2 or 3. In that case the prescribed fire manager and forest staff would make the decision whether to proceed on each subsequent day.

The forests began tracking data from the network of nephelometers to show daily conditions, seasonal variability and trends, downloading data each morning from the DOE website. Data were converted to $PM_{2.5}$ particulate concentration in units of micrograms per cubic meter using relationships established by Trent et al. (2001). Daily concentrations were graphed as daily 24-hour average, daily maximum hourly average, and daily maximum 4-hour average values. The daily trend lines for these three indices were compared graphically to the U.S. Environmental Protection Agency (EPA) 24 hour Air Quality Index (AQI), the EPA 1-hour AQI, and the Chelan County NEAP advisory levels, respectively. These graphical presentations were reviewed daily to view background conditions prior to ignition of a new prescribed burn, and to monitor conditions during and following a burn, in an attempt to better define the contribution of each prescribed burn to local particulate air quality levels. The forests selected the daily maximum hourly average value of particulate as the key indicator of background air particulate because experience showed considerable variation in daily conditions during a burning event that was not registered with either the 24-hour average or 4-hour-average values. The Forest defined an air quality objective of maintaining particulate levels resulting from prescribed burning between 41 and 80 $\mu g/m^3$, within the "Moderate" level EPA 1-hour AQI category (Hardy 2001). EPA defines six condition categories: Good, Moderate, Unhealthy for Sensitive Groups, Unhealthy, Very Unhealthy and Hazardous. The Forests' procedure was to monitor air quality particulate levels and avoid new prescribed fire ignitions when particulate measurements approached the lower end of the Moderate range.

On 28 March, early in the 2004 prescribed burning season, an approved multiple-day landscape-scale fire was burning in the Methow Valley. The maximum hourly reading for the Twisp nephelometer the previous day was 39 $\mu g/m^3$. The forest elected not to ignite a second portion of the prescribed burn area scheduled for 28 March because of potential adverse smoke impacts in Methow Valley. The same situation occurred on 26 April when the prior day maximum particulate reading was 37 $\mu g/m^3$. In both cases, though approval had been given for ignition of an adjacent unit within the project perimeter, ignition was postponed, and within one day, air quality conditions improved enough so that burning could be resumed.

By defining an air quality objective, the Forests attempted to incorporate ambient air quality conditions into the daily prescribed burning decision-making process, in order to avoid new ignitions when background air quality conditions are poor, to postpone additional ignitions for ongoing multiple-day burns when conditions are marginal, and to better monitor the contribution of particulate from a burn to local air quality conditions. A number of factors were considered in selecting the 41 to 80 $\mu g/m^3$ particulate level as the numeric objective. This particulate level is comparable to local air quality conditions during winter months, based on a two-year period of air quality data collection. The "Moderate" level EPA 1-hour AQI category is an established index. Particulate concentration is monitored by local real-time instruments. Data can be accessed essentially real-time via web sites and are available for daily prescribed fire decision-making. And finally, experience has taught us that when local conditions

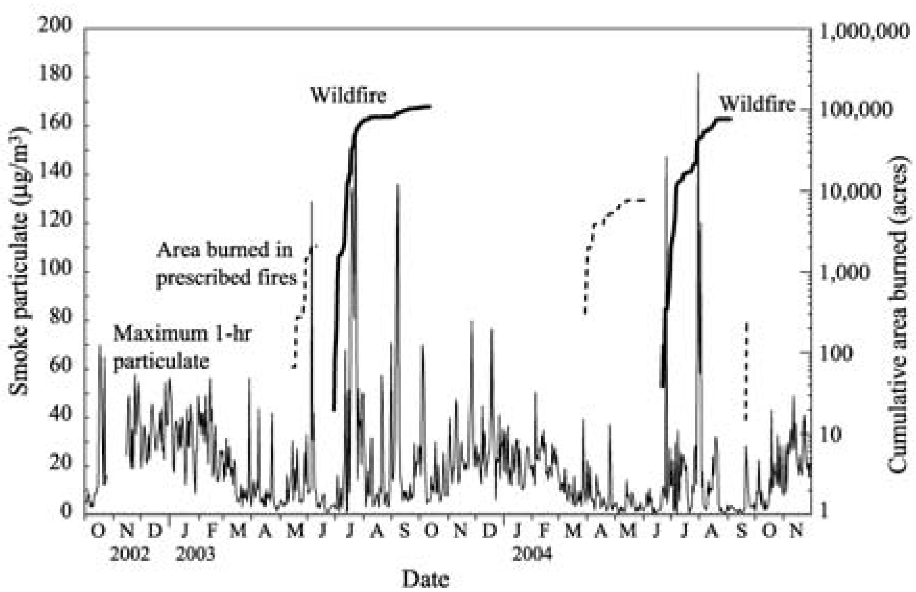
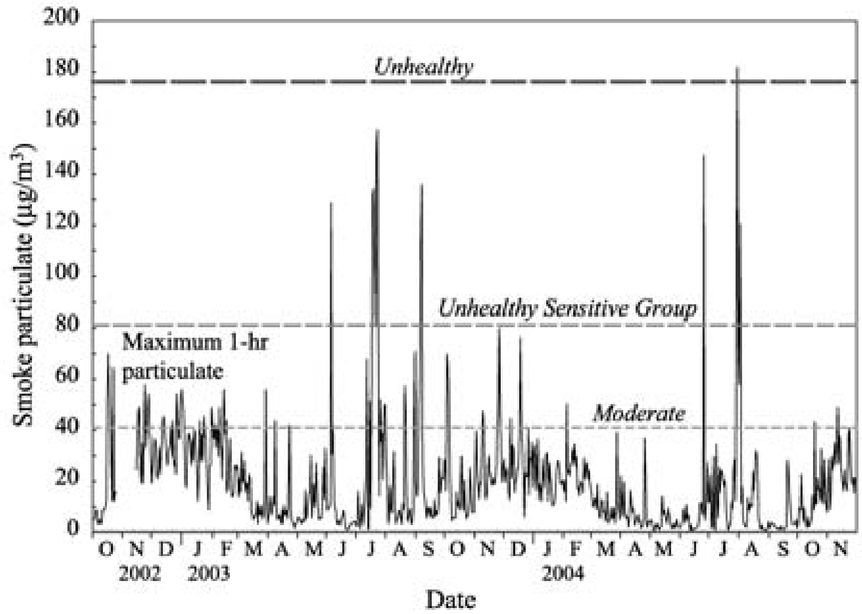



*Figure 4. Twisp nephelometer daily 1-hour maximum $PM_{2.5}$ values for October 2002 to November 2004 with burn acreage.*

*Figure 5. Twisp nephelometer daily 1-Hour maximum $PM_{2.5}$ values, EPA 1-Hour AQI for October 2002 to November 2004.*




reach the objective level the general public starts to express concern. With the guidelines in place, particulate values did not exceed 41 µg/m³ for the 2004 prescribed burn season at any nephelometer site. However hourly values reached 182 µg/m³ later in the year, during the 2004 wildfire season (Figure 4).

## Summary

Experience gained from increased use of prescribed fire in an area where wildfire is an annual occurrence, urban interface issues are escalating, and air quality can suffer significant impacts, has led to a better understanding of how to protect air quality while implementing the HFI.

A local public involvement plan is an essential component of a HFI strategy. Reliable sources of information and opportunities for public involvement and comment are needed at both the program and project planning stages. There should be multiple opportunities for agency contact with local residents. The general public has a wide range of opinions about HFI prescribed fire treatments. Most of the public is supportive where treatments have been applied, reviewed on the ground, and obviously been effective in wildfire control and protection of urban interface developments. But there are those who feel that prescribed fire should not be used as a treatment because smoke intrusions are invasive, harmful, and unnecessary. We have found that public misinformation abounds regarding the relevant pollutants in smoke, possible health effects, and how to interpret monitoring values. The public feels that the FS has an obligation to study health impacts of smoke and inform them of both negative impacts and benefits of burning; to provide air quality and public health information; and to find, explore, analyze and fund alternative treatments. Individuals who wish to burn agricultural residues on private land off-forest continue to express confusion and frustration because of the two state regulatory agencies involved and duplicate processes for approval of agricultural versus silvicultural burn requests.

Smoke can be life threatening to those predisposed to respiratory ailments. Smoke impacts are real, and include a range of health conditions ranging from eye and respiratory tract irritation to asthma, bronchitis, and reduced lung function, to significant respiratory and cardiovascular-related effects (USEPA 2003; Hardy 2001; Therriault et al. 2001). Even with limited period-of-record data, annual patterns are becoming apparent. Average daily particulate concentrations are higher during winter months, and lower in spring and fall (Figure 5). One-hour and 4-hour maximum spikes can occur from prescribed fire but are of short duration. The maximum hourly values over the period of record are the result of wildfire events. These latter air quality incidents last for a considerably longer period of time.

Air quality objectives need to be developed for prescribed burns. It is apparent that 24-hour $PM_{2.5}$ air particulate standards are not an appropriate measure for determining accomplishment of air quality objectives, given that significant peak values can occur for much shorter periods of time. A 1-hour daily maximum value provides a better identifier of significant particulate events on a local scale. It is important to have local real-time monitoring data to assess ambient conditions and to monitor attainment of air quality objectives. This allows management decisions regarding a day's burn activities to be based on the prior day's values, and even the current day's early morning conditions.

## Opportunities

There are a number of opportunities for refinement of air quality objectives for use in prescribed fire management. There should be further discussion of the use of a specific air quality numeric value of 41 $\mu g/m^3$ as a project scale objective. It should be understood that this air quality objective is not proposed as a regulatory standard, requirement, or threshold, but as an objective that incorporates a quantitative air quality measurement into a decision making process that includes many factors including legal requirements, regulatory procedures, public and fire fighter safety, costs, resource management objectives and local public health.

The ability to project the impact of a particular landscape burn relative to an air quality objective needs improvement. Spatial models that project particulate production and dispersion, given site-specific fuel loading, topographic features, and meteorological forecasts, do not currently have the resolution to accurately project particulate dispersion at a local scale. Research scientists are refining the BlueSkyRAINS computer model to incorporate a finer resolution of detail for project-scale landscape burns in Eastern Cascade valleys (Ferguson 2004). This predictive tool would allow fire managers to design prescribed burn projects, and select areas to be burned that optimize natural smoke dispersion and minimize local public exposure to adverse smoke conditions.

## Conclusion

The Healthy Forests Initiative is a forest management priority on a national scale because of the extensive wildfires that occurred in the Eastern Cascades in 1994, and those that occurred on an even larger scale elsewhere. The forests are implementing this initiative with a variety of treatments including more frequent use of landscape-scale prescribed fire. Landscape burns will be conducted by the forests within a State Smoke Management Plan regulatory framework administered by DNR. The forests will respond to air quality issues by implementing a comprehensive local public involvement plan and by establishing local site-specific air quality objectives that will be used as one criterion in reviewing daily burn approvals and in making a final decision to burn. Following two years of air quality monitoring, we conclude that these air quality objectives have value on the OWNFs because they allow immediate assessment of local conditions and input to a daily go, no-go decision-making process. Data now available allow an immediate read on whether objectives have been attained for the previous day. The forests will collaborate with DOE in monitoring air quality conditions, reviewing air quality data and in responding to public comments.

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# Advances in Fire Convection Dynamics

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The convective column created by a fire has a strong impact on the behavior of the fire. This paper examines three aspects of fire-atmosphere interaction that influence the development of the convective column. The stratification of temperature, humidity and wind near the ground influences the early formation of the fire and its convective column, and can lead to unexpected variability in the fire's behavior. Moisture produced by combustion of woody fuels has the potential to enhance the convective column's vigor, but research is needed to determine whether this happens in actual fires. The structure of the atmosphere over large regions (the synoptic structure) can bring dry, high-momentum air down from heights of 10 or more km, affecting the convective column and fire behavior. Each of these topics represents an aspect of convective behavior around fires that is the subject of current research and has implications for fire behavior and firefighter safety.

Keywords: *fire, weather*

## Introduction

For almost 100 years, the paradigm of fire behavior taught and employed in the United States has held that three main factors dictate fire behavior (Graves 1910). These factors are fuels, weather, and terrain. Historically, research and management have ranked the importance of the three factors for funding, time, and manpower in the aforementioned order. The fastest changing component of the behavior triad is the weather, and while it is not directly manageable or predictable over the long term, it is also one of the major causes of fire-fighter fatalities and fire escapes. (Whether human error or weather is the greater cause is not clear, especially in cases where human actions compromise the quality of the weather information available during fire management.)

A further common division of fire behavior is separation into "plume dominated" and "wind-driven" (sometimes called "wind dominated") fires. These categories seem reasonable and somewhat intuitive, but in reality it is quite difficult to decide whether a fire belongs in one or the other class. A particular fire may alternate between plume and wind dominated repeatedly during its existence. All fires are dangerous, but because a wind dominated fire spreads primarily in the direction of the prevailing winds, the danger is more predictable than for a plume dominated fire. Conditions above the ground play a major role in determining the behavior of plume dominated fires, and can lead to abrupt changes in direction or rate of spread. A strong updraft, whether tilted over due to strong winds or vertical in their absence, generates a stronger inflow of air at the ground and more vigorous fire development in general, so that updraft strength is directly related to many aspects of fire behavior that are important for firefighter safety.

Researchers and analysts have used two parameters, Byram's convection number (Nelson 1993) and the convective Froude number (Clark et al. 1996) to classify fires in the past. In practice, it is rare to have the data necessary to make such a classification. Even when data are available, these numbers change values over time and space, so that one part of a column may qualify as "plume dominated" for a time, while the remainder of the column at times is "wind driven." Because of this, the most common criterion used to determine a plume or wind dominated fire is purely subjective observation.

It is possible there is some discrete, definite boundary between plume and wind dominated fire behavior. It is more likely that while some fires are quite visibly in one class or the other at a particular time, most fires at most times fall in a grey area where it is unclear which process dominates. Because of this it is important to understand

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

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the physics of how fires interact with the atmosphere. Decades, if not centuries, of observations and anecdotes provide some understanding. In the last fifty years, that understanding has gone from statistical or qualitative in nature to more analytical and quantitative. The complexity of the situation has limited the utility of all of these types of understanding, however. To develop an analytical understanding of a complex system starting with a simplified model often allows progress that would otherwise be impossible. In the case of fire, starting with the "no wind" case, unrealistic though it is, does just that.

In this paper, we describe three aspects of fire convection and the interaction of fire with the atmosphere: layering of air near the ground, potential impacts of moisture, and synoptic influences on convection. We ignore wind in our discussions in order first to better understand the nature of the convection. Eventually, a complete theory of fire convection must include the influence of wind profiles. For now, however, the "simple" case of no wind presents enough unanswered questions.

## Describing the Environment

The basic properties of the atmosphere that influence convective development during fires are the temperature and wind profiles. Generally speaking, fires of significant size develop under conditions of high atmospheric pressure. High pressure usually means clear skies and dry conditions, while low pressure indicates clouds and often rain. For this reason, the following discussion emphasizes high pressure situations.

The daytime temperature profile for an idealized atmosphere has four basic parts, depicted in Figure 1. At the bottom is the surface layer. Strong solar heating, especially when there is little available moisture, creates a region where the ground is very hot and the air temperature drops rapidly with height. This is generally an unstable layer, where vertical movement of air releases stored energy and adds to the turbulent energy. Above this, where air flow is unobstructed by the ground and surface structures, is the mixed layer. In this region, turbulence and heating from below churn the air so that moisture, momentum, and thermal energy are fairly uniform. This layer has neutral stability, meaning that when a bubble of air rises or falls it neither releases nor requires any energy. Above the mixed layer is, by definition, a relatively unmixed region. This layer is generally stable, often a thermal inversion, where vertical motion requires some energy input. Finally, in the situation typical for many large fires, a region of neutrally stable subsiding air tops the stable layer.

Generally, the mixed layer deepens from sunrise through midafternoon. As the sun heats the ground, which in turn heats the air near it, the increasingly buoyant air can rise and mix upward to greater heights. At night, the surface and mixed layers are often absent. Under high pressure, the clear skies lead to enhanced cooling at the ground so that a surface inversion forms. Above this, there may be a remnant mixed layer from the daytime, and another inversion above this. The lowest inversion has the greatest influence on fire behavior.

Moisture plays an important role in the short-term processes of fire convection and fire behavior, but less so than stability. Moisture in the surface layer can be low or high, compared to the mixed layer. For example, air from the Gulf of Mexico blowing northward into Missouri would be relatively moist. Air moving into the same area from the northwest, perhaps behind a cold front, would be relatively dry. For this reason, one cannot generally describe surface layer moisture in the same way as stability, even when focusing on conditions typical of large fires.

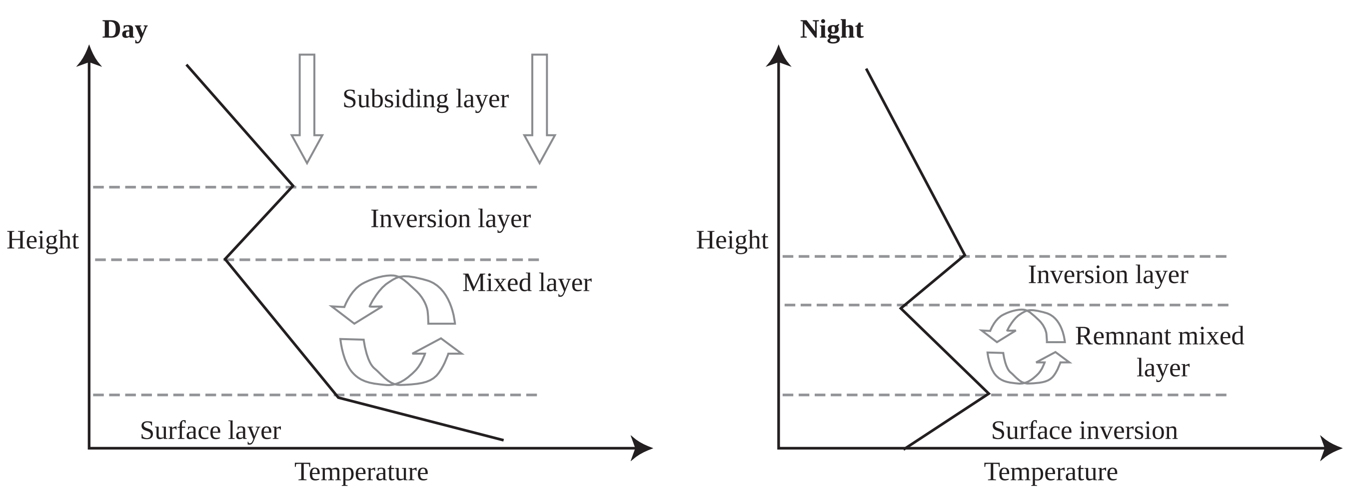


*Figure 1. Idealized model of the vertical structure of the troposphere.*

*Table 1. Stages of fire-atmosphere interaction, based on the three-layer model. Air Layer is the layer of the atmosphere interacting with the fire during the given stage, while Stability, Plume Growth, Winds, and Moisture describe the qualities of the air properties typical of the layer involved in that stage.*

| Stage | Air Layer | Stability | Plume Growth | Winds | Moisture |
|---|---|---|---|---|---|
| Surface | Surface | Unstable | Rapid, energy added | Light and variable | Moist |
| Deepening | Mixed layer | Neutral | Moderate, no change | Stronger, variable | Dry |
| Penetration | Inversion and Subsiding | Stable | Slow, requires energy | Strongest, more steady | Drier |

Above the mixed layer, the atmosphere is typically dryer than it is in the mixed layer. Subsidence above the inversion generally represents the driest part of the atmospheric profile.

## Three Layer Model for Fire-Atmosphere Interaction

There are several ways to describe the stages, phases, or regions of fire. These include simple frameworks such as ground/surface/canopy or smoldering/creeping/running, and more complex concepts like Countryman's (1969) six zone framework describing stationary mass fires. These all have legitimate, valuable uses. The ground/surface/canopy distinction is useful for understanding behavior and fuel consumption patterns. The smoldering/creeping/running distinction tells a fire manager how quickly the fire is moving and what sorts of management actions are most appropriate. Countryman's (1969) zones divide a mass fire into six zones, based on a combination of visual properties and the apportionment of energy. None of these models, however, provides insight into the relationship between the fire and the atmosphere in a way that clarifies the influence of the atmosphere.

Potter (2002) proposed a three stage model for describing fire that emphasizes the relationship between the fire and the layers of the atmosphere described above. The stages of the model are the surface stage, the deepening stage, and the penetration stage. These stages are tied to fire's interactions with, and influence on, air in the surface layer, the mixed layer, and the inversion and subsidence layers, respectively. (In the penetration stage, the fire may interact with the inversion and then the subsidence layers, depending on the strength of the fire and the inversion.) Table 1 summarizes atmospheric properties during these three stages. In addition to the wind and stability aspects shown in the table, the moisture of the layers influences both fuel moisture (and therefore fire rate of spread and energy release) and plume development.

In this model, a fire does not necessarily go through all stages, and it can exist in a given stage more than once. All natural and prescribed fires begin in the surface stage. If there is a surface inversion, this is also a penetration stage – the surface air is stable, and any plume development requires the fire to do work. If a fire burns through a day and into a night, it may go from the deepening stage during the day back to a surface or penetration stage at night. In general, fires in the eastern U.S. tend to burn for one day, and would go through the stages in the listed order, before they return to the surface stage and die out. In the western U.S., fires are more likely to shift back and forth among the stages over multiple days. Because smoke can block sunlight and outgoing longwave radiation, it can affect stability so that yesterday's smoke influences the stages of today's fire.

The atmospheric three stage model has proven useful for some applications beyond research. In case studies of prescribed burns in Missouri and Michigan, we found that looking at the temperature, humidity, and wind of the layers involved in the stages and their contribution to BEHAVEPlus (Andrews et al. 2003) estimates of rate of spread and flame length, could explain some otherwise unexpected variations in these fire properties during prescribed burns. As a result, the Eastern Area Modeling Consortium (Heilman et al. 2003; USDA Forest Service 2004) now provides estimated values for temperature, humidity, and wind for the surface, mixed, and above-mixed layer air up to 48 hours in the future for use in BEHAVEPlus calculations. If the three sets of weather values yield widely varying fire property estimates, this suggests the potential for real-world variations in fire behavior.

## Released Moisture

The main difference between small, scattered fair weather cumulus clouds and a towering, destructive cumulonimbus cloud is the amount of water available in the atmosphere. Water and the energy released when it changes from vapor to liquid and from liquid to solid drive large storms, including tornadoes, downbursts, and strong straight-line winds.

Byram (1959) and Johnson and Miyanishi (2001) present a chemical equation for the combustion of woody material. The latter authors state that complete combustion of 1 kg of woody material yields 0.56 kg of water substance and 20 MJ[1] of energy. Potter (2003) proposes that during the combustion process, and after turbulent mixing of air near the ground, this moisture adds from 1 g to 5 g of water to each 1 kg of air rising in the fire's convective plume. (Moisture in air is often stated in terms of grams per kilogram (g/kg), with the understanding that this means "grams of water per kilogram of air". We follow this convention here.) The following discussion assumes that the air in the updraft from a large fire has been moistened by 2 g/kg. Potter (2003) presents a detailed discussion of the implications of this moisture, so we present a much abbreviated discussion here.

When air remains at a constant pressure and temperature, and water is added, one of the effects is a decrease in the average density. This is simply a result of the fact that the molecular weight of water is 16, while the average molecular weight of air is slightly less than 29 (Wallace and Hobbs 1977). The change is very small, but it can be important in calculations involving similarly small differences in density as air rises or descends. For example, at Mack Lake, MI on 5 May 1980 – the date of the Mack Lake fire (Simard et al. 1983) – calculations of the density of air without and with background moisture differ by only 0.004 kg/m$^3$. Using density without accounting for moisture, calculations indicate this air will freely rise to a height of 3000 m, and will not reach a height where the moisture in it condenses. When moisture is considered, the slight decrease in density is sufficient to allow the air to rise to the condensation level. The subsequent release of latent heat as the water condenses keeps the air warm enough that it can freely rise to 8800 m. If the fire had added 2 g/kg to the air, this height would increase to 9600 m.

The basic force behind thunderstorms is buoyancy, driven by the density differences between a parcel of air and the air around it. Consider, as an analogy, an ice cube in a glass of water. If the cube were pushed to the bottom of the glass, it would bob to the surface when released. If the ice cube were in peanut oil instead of water, the density of the cube would be greater than that of the oil, and the ice cube would sink. In the atmosphere, density differences are primarily due to temperature and moisture differences. Relatively hot or moist air is less dense than its environment, and will rise more energetically. If the moisture in the air condenses as the air rises, the condensation process releases energy that heats the air, further increasing its buoyancy and allowing higher, more vigorous ascent. One can calculate the energy released during this ascent and estimate the effect of increased temperature or moisture on that energy. For the Mack Lake Fire, warming the surface air by 2 K would have doubled the buoyant energy. Adding 2 g/kg of moisture to the surface air, instead, would have increased the buoyant energy by a factor of 2.9, almost tripling it. Raising temperature by 2 K and moisture by 2

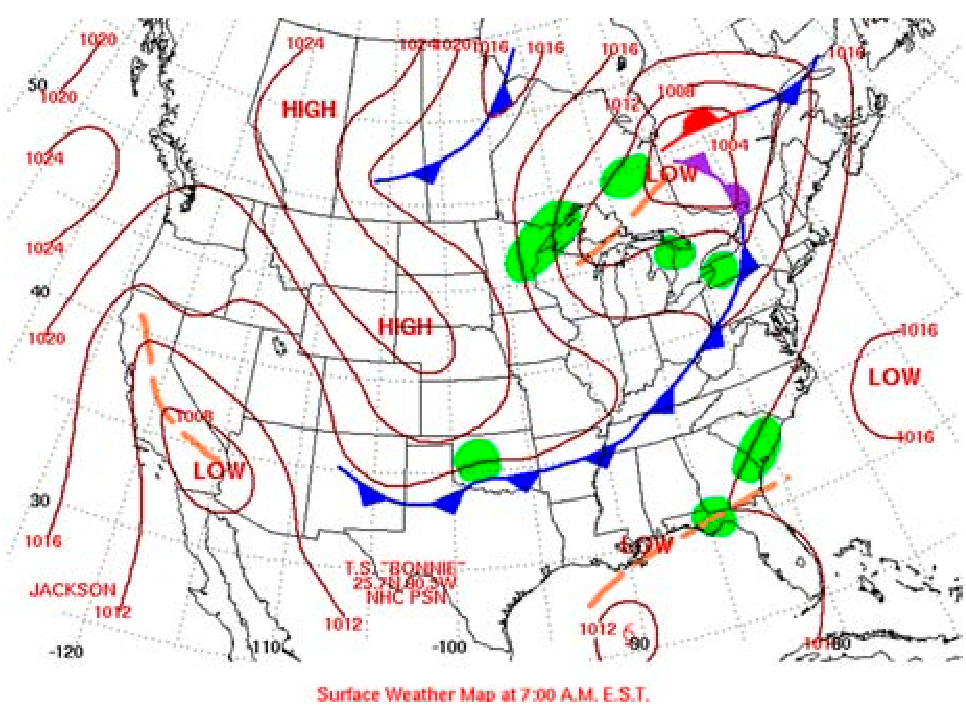


*Figure 2. An example of a synoptic-scale low pressure system, with associated cold (blue) and warm (red) fronts. This map shows the pressure pattern for 1200 UTC (0800 EDT) on 11 August 2004.*

[1]MJ = Megajoules

g/kg at the same time would have increased the buoyant energy of the surface air four-fold. Any of these increases in buoyant energy would have been sufficient to produce a vigorous updraft with strong inflow near the ground and strong near-fire horizontal winds.

Moisture in a fire plume has potential implications for downdrafts, as well. Downbursts, macrobursts, and microbursts are all types of downdrafts, varying in their spatial extent, duration and intensity - we will refer to them all simply as “downdrafts” here. Downdrafts develop through a combination of evaporative cooling and frictional drag from falling raindrops, snow, and hail. Without moisture to form rain, snow and/or hail, strong downdrafts would not form. More moisture means a greater potential for downdraft formation, though the manifestation of that potential depends on a variety of other factors. The connection between moisture and downdraft development is generally accepted and understood by meteorologists, and at least one fire study cited a downdraft as a cause of firefighter fatalities (Goens and Andrews 1998). Presently, however, the role released moisture could play in the formation of downdrafts is not known.

## Synoptic Influence

In meteorology, “synoptic structure” refers to patterns that cover an area roughly one-half to two-thirds the size of the United States. The most common example of a synoptic structure is a low pressure system with cold and warm fronts (Figure 2). Synoptic weather systems can be thought of as the broad-scale organizing mechanism behind local weather. For instance, when a front passes over a given location, an observer on the ground might note a shift in wind speed and direction, a temperature drop or rise, rapid variations in humidity, or some combination of these changes. But observations at a single point seldom reveal the overlying synoptic system ultimately responsible for the formation of the front, the timing of its passage, the environmental changes that occur as it passes, and its lifespan.

Synoptic weather systems change throughout their lifetime. The fronts associated with low pressure systems can have varying intensities, which lead to different horizontal and vertical temperature and wind structures, so that one should not expect all fronts or other types of weather systems to affect fires equally. Furthermore, synoptic structures have varying effects on fires developing in different locations within them (Schroeder et al. 1964). As discussed above, information about atmospheric conditions in near-ground atmospheric layers can offer insight into the potential for unusual fire behavior. Synoptic weather patterns can, in turn, offer weather forecasters insight into how the near-ground atmospheric layers might vary. For this discussion we focus on how synoptic-scale weather systems can enhance or inhibit dry, windy conditions at the surface.

Earlier, we described how the mixed layer deepens throughout the day. If the top of the mixed layer rises

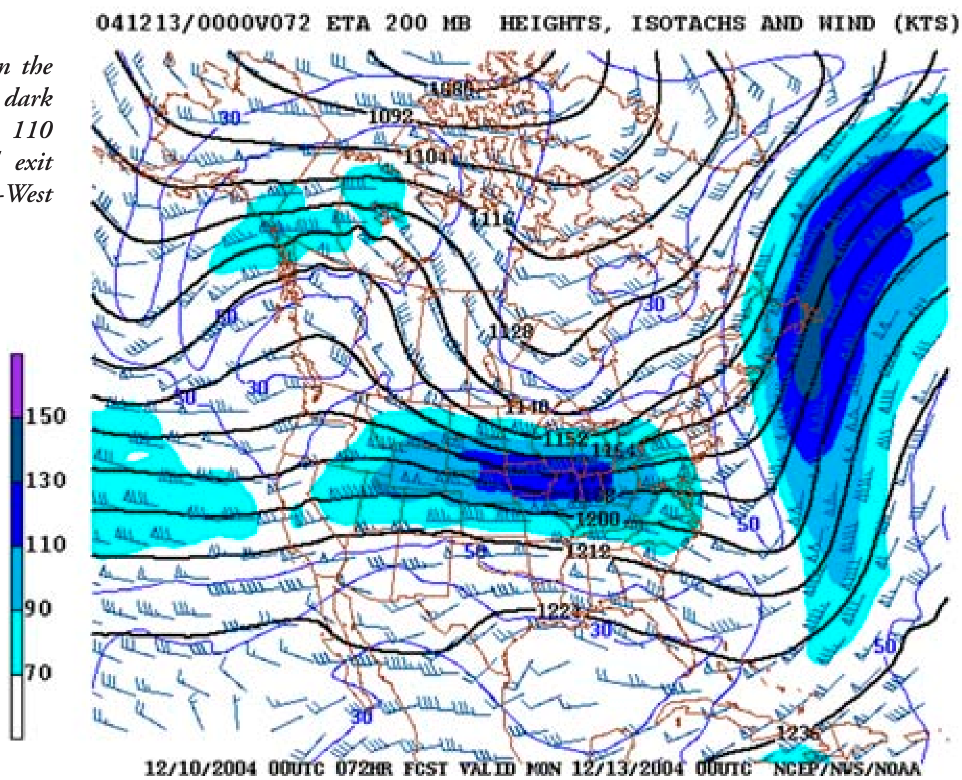


*Figure 3. Example of a jet streak in the upper troposphere (250 mb). The dark blue area indicates winds between 110 and 130 knots. The equatorward exit region would be over the Kentucky-West Virginia area.*

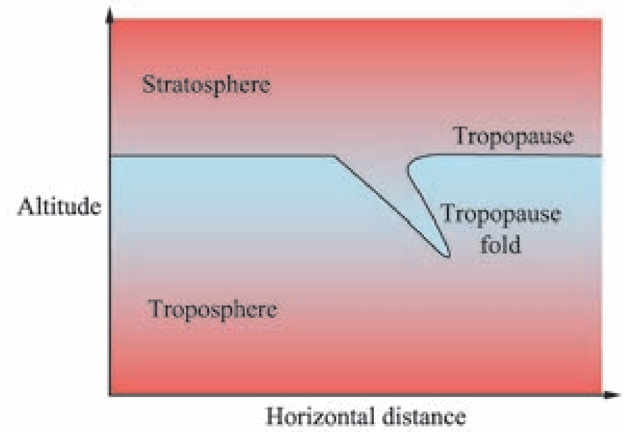


*Figure 4. Illustration of a tropopause fold (not to scale).*

upward at a time and place where dry, windy air sits above but close to the top of the mixed layer, that dry and windy air may be drawn into the mixed layer. It may then descend to the surface, where it may influence fire behavior. Since the mixed layer can reach depths of 3 to 4 km, this type of interaction can draw down air that is substantially different from surface air.

Presently, two mechanisms have been identified as potential sources of descending, dry, windy air. One involves descent associated with regions 3 to 5 km above the ground where bands of high speed winds, known as "jet streaks", decelerate (Figure 3) These regions, known as jet exit regions, can span thousands of square kilometers. They typically have dry, fast moving air descending on the equator-ward side. Kaplan et al. (personal communication, manuscripts in preparation[2]) have found jet exit regions over several historically notable wildland fires.

The second potential source of descending, dry and windy air is known as a tropopause fold (Charney et al. 2003). The tropopause is the boundary, roughly 7 to 12 km above the ground, between the part of the atmosphere known as the troposphere (where temperature generally decreases with height) and the stratosphere above it (where temperature is constant or increases with height). Air in the stratosphere is much drier than air in the troposphere, so the tropopause marks a transition not only in temperature gradient, but also in moisture. Tropopause folds (Figure 4) are long, narrow intrusions of dry air that form in association with cold fronts, bringing air from the stratosphere down towards the ground. They do not typically reach the ground, except at high elevation locations, but it is possible for the mixing layer to rise upward to meet them, or for the energy from a fire to allow local mixing to reach a tropopause fold.

## Conclusions

While thinking of fires in terms of the character of their convective columns is not new, recent work is connecting on-the-ground fire behavior more directly with the atmospheric processes within the convective column. These connections tie together the vertical temperature, moisture, and wind structures of the atmosphere, from the ground up to ten or more kilometers in altitude, with fuels, combustion, and subsequent fire behavior. This recent work brings many years of research in meteorology that was not originally associated with fire into the conversations and mental models now being used to understand fire behavior, especially extreme or erratic fire behavior.

The three topics (the three-layer model of fire-atmosphere interactions, the question of moisture's importance, and synoptic influences on fire behavior) discussed here provide examples of these new developments in the study of fire-atmosphere interaction and fire-driven convection. The three-layer paradigm is a simplistic framework that illustrates the potential for even small fires to behave in unexpected ways, and has potential as a planning tool. Questions about fire-released moisture indicate that there are potential ties between fuel load and fuel moisture, and the intensity and development of the fire's convective column, that go beyond simple heating of the air. The synoptic studies in progress now can provide insight into regional weather conditions that could influence fire behavior in previously unexpected ways. Each of these – and many topics that are sure to come to light as research proceeds over the next decade – has implications for fire fighter safety and resource management.

[2]Kaplan, ML, C Huang, YL Lin, and JJ Charney. [N.d.] A Multi-Scale Paradigm for Rapid Vertical Airmass Coupling Resulting in High Fire Weather Potential. Part I: Observations of the Double-Trouble Case Study. and Part II: Numerical simulations of the Double-Trouble Case Study. Manuscripts in preparation. On file with J. Charney, USDA Forest Service, 1407 S. Harrison Road, Suite 220, East Lansing, MI 48823.

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# Section 1. Applied Science and Technology

## Part 2. Watershed Management

Overleaf:
Twin Falls, Richland Creek, Ozark Plateaus. Photo by A.C. Haralson, Arkansas Department of Parks & Tourism, Little Rock, Arkansas.

# Using Stream Channel Reference Data to Guide Land Management Decisions

Pete Bengeyfield
*Beaverhead-Deerlodge National Forest, Montana*

In order to make informed land management decisions, managers concerned with aquatic resources need information at a variety of scales. "Project level" decisions require fine-scale information relating to specific small watersheds or stream reaches, while planning level decisions require a characterization of broad scale patterns that will influence allocation and scheduling of activities. Quantified reference data can provide a basis for decisions at both scales by defining conditions that would exist in stream channels under the present climate and tectonic regimes in the absence of land management. At smaller scales, data from undisturbed reaches can be directly compared with similar managed reaches to determine departures from reference conditions, while at larger scales reference data from a number of reaches can be use to define desired conditions across a region.

Keywords: *reference reach, TMDL, forest planning, sediment, channel morphology*

## Physical Setting

Most of the data for this study were collected on the Beaverhead-Deerlodge National Forest (B-D), covering approximately 3.4 million acres (1.4 million hectares) in southwest Montana. The region is bordered by the continental divide on the west, and contains the headwaters of four major river systems (Big Hole, Beaverhead, Madison and Ruby). Wide valley bottoms are separated by isolated mountain ranges. The valley bottoms of the major rivers are mostly in private ownership, with public land located at higher elevations.

The dominant physical realities of this region are high elevation and low precipitation. Valley bottoms are semi-arid, averaging about 5800 feet (1769 m) in elevation and receiving an average of 13.6 inches (34.5 cm) of precipitation a year. The mountains receive more precipitation (27.2 inches [69.1 cm] per year), with most of that in the form of snow. Overall, annual precipitation has averaged 20.4 inches (51.8 cm) since 1980.

Livestock grazing is the land use that most affects aquatic values on the Beaverhead-Deerlodge National Forest. Seventy-eight percent of the forest is located in grazing allotments. Roadless and wilderness areas account for 62% of the forest, so some of the more common effects to aquatics from roads, timber harvest, and mining are either isolated or minimal. There is a wide range of suitable rangeland contained within the allotments. Some allotments, mainly on the eastern portion of the forest, are predominately suitable, while others are heavily timbered with little suitable range.

Additional data were collected throughout the Greater Yellowstone Ecosystem, which stretches south and west of the Beaverhead-Deerlodge into Wyoming and Idaho. Some of the Ecosystem mimics conditions on the B-D, although precipitation levels are often somewhat higher.

## Methods

A comprehensive stream channel survey was initiated on the Beaverhead-Deerlodge National Forest in 1991. The survey was designed to collect stream channel data that would characterize physical channel attributes at the reach scale. Survey sites were chosen to: 1) identify reference conditions; 2) identify problem areas for restoration; and 3) portray the range of stream conditions throughout the forest. The following parameters were measured as part of the standard survey:

1. A monumented cross-section depicting floodplain, bankfull elevation, water surface, and thalweg. The cross section is used to compute entrenchment and width-to-depth ratio. (Rod and level)
2. Sinuosity (Pacing)
3. Gradient (Rod and level)
4. Stream substrate (Wolman pebble count, Wolman 1954)
5. Fifty bankfull widths and depths (measuring rod)
6. Channel Stability Evaluation (Pfankuch 1975)
7. Bank Erosion Hazard Index (Rosgen 1996)
8. Valley Bottom Width (pacing)
9. Reach photographs
10. Notes describing overall conditions with respect to previous and current management effects.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

The sites are permanently established with painted rebar and surveyed to local benchmarks, usually a nail in a tree. Where applicable, measurement protocols given in Harrelson et al. (1994) were used.

By 2002, a total of 682 stream reaches had been measured throughout the forest. Forty-four percent of the total streams on the forest have at least one survey, with many streams having multiple sites. On average, 3.3 survey sites were measured per 6th-code HUC (Hydrologic Unit, or watershed). Measured sites were considered to be a "representative reach" (Gordon et al. 1992), and depict conditions along a greater length of stream channel. The survey sites depict conditions on 3.7% of the stream length on the forest. Of the 682 sites, 137 were determined to be in reference condition. These have been combined with an additional 78 reference sites measured throughout the Greater Yellowstone Area (GYA) in the summer of 2002 to create a reference dataset of 215 reaches. The dataset includes stream reaches that represent watersheds of a variety of sizes, geologies, and precipitation ranges.

## The Use of Reference Reach Data in Project Planning (NEPA Analysis)

Under the National Environmental Policy Act (NEPA), federal agencies initiating land management activities must complete an analysis to determine the effect of the project on the natural environment. The Affected Environment section of the NEPA analysis requires a determination of the existing condition before the effect of the proposed project is evaluated. One way to evaluate existing condition is to compare current conditions with reference data for similar sites (Frissell et al. 1986). The stream surveys enabled us to do this for the Beaverhead-Deerlodge National Forest.

The concept of using minimally disturbed sites as references has appeared in the literature in recent years (Dissmeyer 1994; Minshall 1994; Maxwell et al. 1995). Recent methodologies for analyzing watershed conditions (USDA et al. 1994, 1995; McCammon et al. 1998) recommend the use of reference watersheds as a means of determining the effects of land management

Reference reaches are matched with project reaches on the basis of the similarity of their valley bottom widths, valley bottom gradient, and the drainage area above the reach. Rosgen (1996) demonstrated that valley types provide an indication of stream channel morphology. Bengeyfield (1999) showed the relationship between valley features and drainage area to stream types for southwest Montana. Using a Classification and Regression Tree procedure (Brieman et al. 1984) and an earlier version of this data set, he used valley bottom width, valley bottom gradient, and drainage area to predict Level One stream types. A cross-validation procedure showed that E stream types, for example, were correctly predicted 89% of the time. Analyzing the data from the reference data set and project reach stream surveys produces a comparison table (Table 1).

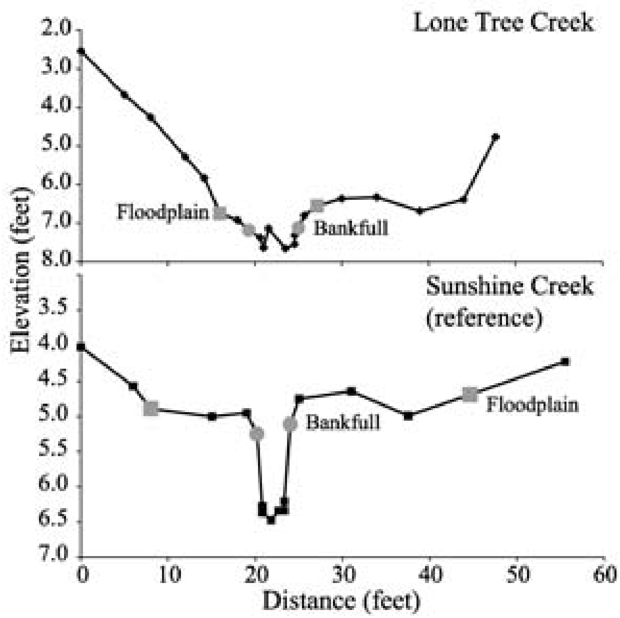
*Table 1. Comparison of stream survey parameters between project reach (Lone Tree Creek) and reference reach (Sunshine Creek). * indicates data not collected.*

| Parameter | Lone Tree Creek | Sunshine Creek |
|---|---|---|
| Valley Bottom Width (VBW) (ft) | 25 | 75 |
| Valley Bottom Gradient (VBG) (%) | 2.53 | 2.75 |
| Area (acres) | 1500 | 704 |
| Stream Type | B4 | E4 |
| Entrenchment | 1.96 | 9.63 |
| Width/Depth Ratio | 28.5 | 3.3 |
| Sinuosity | 1.05 | 1.8 |
| Gradient (%) | 2.41 | 1.53 |
| $D_{50}$ (mm) | 30 | 13 |
| $W_{50}$ (ft) | 3.7 | 5.9 |
| Channel Stability | 64 - Fair | 48 - Good |
| BEHI | * | 24.8 |

A comparison of the data for Lone Tree Creek (project) and Sunshine Creek (reference) shows that both valley bottoms are narrow and moderately steep, and their watersheds are small (Table 1). However, they contain different stream types (B4 vs. E4). Lone Tree Creek is more entrenched (1.96 vs. 9.63), wider and shallower (width-to-depth ratio = 28.5 vs. 3.3), straighter (sinuosity = 1.1 vs. 1.8), and steeper (gradient = 2.4 vs. 1.5) than the reference. It is not only wider at the cross section, but along the entire reach ($W_{50}$ = 5.9 vs. 3.7). Lone Tree Creek is not as stable as Sunshine Creek. (Channel Stability = 64 vs. 48), and is more susceptible to streambank erosion (Bank Erosion Hazard Index [BEHI] = 30.5 vs. 24.8). The relationships between the project and reference reaches can be displayed graphically as shown in Figures 1 and 2.

An analysis of the data and graphs shows Lone Tree Creek differing from the reference for most of the stream parameters measured. The largest differences are in channel dimension, with somewhat smaller differences in pattern and profile. Lone Tree Creek is wider, straighter, and steeper than Sunshine Creek. Channel Stability and Bank Erosion Hazard reflect similar patterns. Notes taken onsite at the time of the survey indicate heavy trampling by livestock, willows that are in poor condition, and a species of sedge that increases with grazing pressure.

*Figure 1. Cross-sections of Sunshine Creek (reference) and Lone Tree Creek (project).*




By comparing onsite data from Lone Tree Creek to reference conditions, the departure from expected channel dimensions can be quantified and displayed graphically. In this case, the notes describe a disturbance (livestock grazing) that would logically produce the channel conditions measured, suggesting a cause/effect relationship for the existing condition. Similar effects due to grazing have been documented by Clifton (1989), Clary and Webster (1990), and Kovalchik and Elmore (1992). The data and analysis suggest there is considerable difference between the existing and desired conditions in Lone Tree Creek, necessitating a change in grazing management in order to restore reference conditions.

Lone Tree Creek is one of five reaches surveyed for the Antelope Creek Grazing Allotment. Employing reference data, site specific conditions were described for individual reaches and then compared to the reference data. This allowed departure from desired conditions to be displayed. By including these data in Chapter 3 of the NEPA document, the need for change was established, and an alternative was generated that prescribed more stringent standards for livestock management.

## The Use of Reference Reach Data in a Regulatory Framework (TMDL Analysis)

In recent years, states have identified Water Quality Limited Segments (WQLS) as impaired water bodies that are in need of restoration in order to meet the requirements of the Clean Water Act. This process is designed to be quantitative, and specific levels of a pollutant are required to be met before the stream can be removed from the impaired list. The use of reference conditions is considered to be an acceptable concept for determining target levels of pollutants (EPA 1999). Furthermore, it is recommended that reference conditions be measured across a region to define variability (Frissel et al. 1986; Minshall 1994).

Data from the measurement of 215 reference reaches throughout southwest Montana and the Greater Yellowstone Ecosystem provides information that can be used to establish acceptable target levels for specific Rosgen stream types (Rosgen 1996). Figures 3 through 5 display cumulative distribution curves for substrate size and width/depth ratio derived from the reference data set for stream types B, C, and E.

For example, if a stream were placed on a state's 303(d) list as being impaired for sediment, and the impaired reach were a B4 stream type, then Figure 3 could be used to establish target levels for substrate distribution. If fine sediment were a concern, the target might be that only 16% of the substrate could be below 6 mm in size. If bedload transport were a concern, the $D_{84}$ of the impaired reach might be targeted at 160 mm. Confidence intervals define acceptable range of variability for monitoring purposes.

If an E stream were placed on the 303(d) list for habitat alteration as a result of streambank alteration due

*Figure 2. Cumulative distribution curve for bankfull stream widths for Sunshine Creek (reference) and Lone Tree Creek (project).*

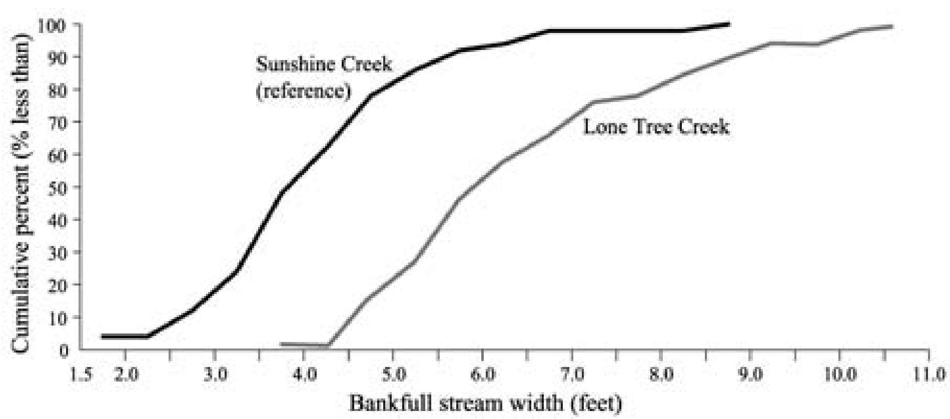
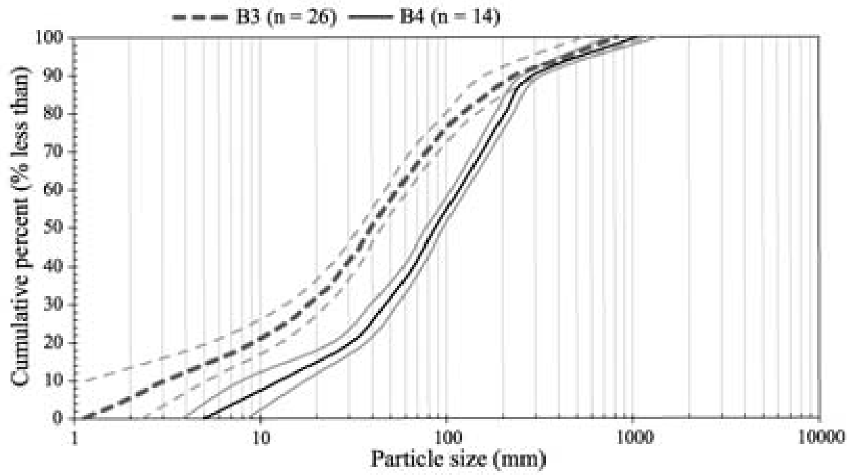


*Figure 3. Particle size distribution, B stream types, with 95% confidence limits.*



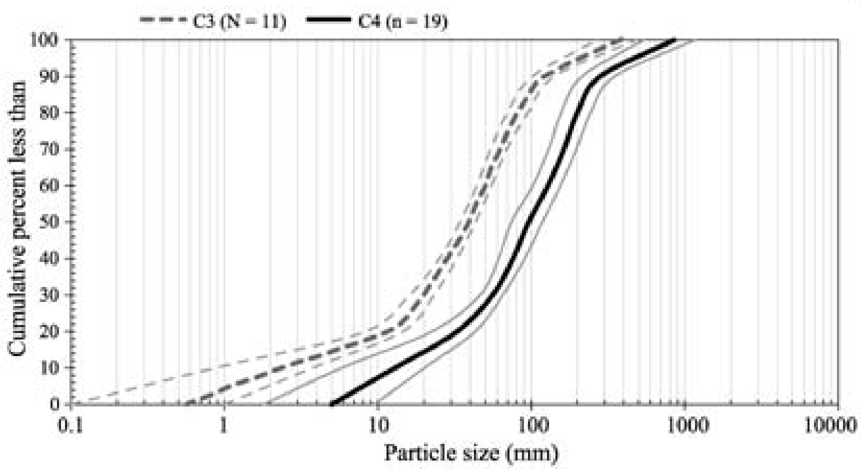




*Figure 4. Particle size distribution, C stream types, with 95% confidence limits.*

*Figure 5. Particle size distribution, E stream types, with 95% confidence limits.*

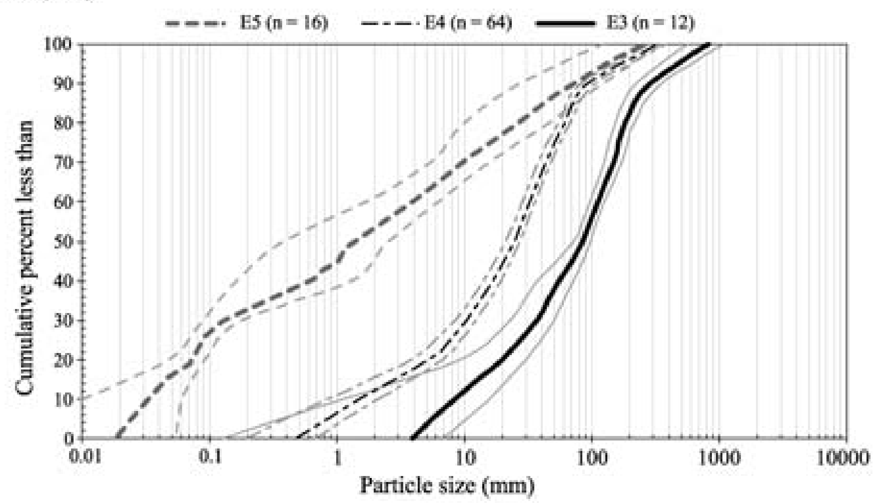



*Table 2. Distribution of stream types in Beaverhead/Greater Yellowstone Area dataset.*

| Level 2 Stream Type | B Streams | C Streams | E Streams |
|---|---|---|---|
| 2 | 1 | | |
| 3 | 26 | 12 | 10 |
| 4 | 16 | 22 | 65 |
| 5 | | 2 | 18 |
| Ea | | | 25 |

to livestock grazing, then a target might be established for width/depth ratio in order to restore overhanging banks. The distribution throughout the reach should be such that the average width/depth ratio should be about 3 to 3.5.

## The Use of Reference Reach Data at the Landscape Scale (Forest Planning)

National Forests throughout the country are presently going through a revision of Forest Plans that were first completed in the 1980s. As part of that process, the Desired Future Condition (DFC) for individual resources must be described (CFR 219). For stream channels, a logical DFC would be to maintain the dimension, pattern, and profile that have been developed by natural flow regimes under the present climate and tectonic regimes. Reference reach data can help in describing these conditions and establishing goals for management.

The reference reach dataset for the Beaverhead-Deerlodge and Greater Yellowstone Ecosystem contains 215 reaches. These were stratified by stream type, with results summarized in Table 2. The B2 and C5 strata were dropped from further analysis because their sample size was too small. This left a reference dataset of 213 reaches. The remaining strata were subject to statistical analysis for mean, standard deviation, and 90% confidence interval (Table 3).

These data localize the Rosgen classification and can form the basis for describing DFC for each of the stream types. For example, for E stream types to maintain stable channels given the natural flow regime, they should have a width/depth ratio close to the mean for E stream types, in this case, 6. If the width/depth ratio of a given reach fell between 5.5 and 6.5, a manager could be 90%

*Table 3. Statistics for reference reach strata representing various stream types. Confidence Intervals are all $\alpha = 0.1$. W/D ratio is width to depth ratio; % < 6mm is the percent of the substrate smaller than 6 mm in diameter; $D_{50}$ is median particle size; $D_{84}$ is the particle size 84% of the substrate is smaller than; $W_{50}$ is average channel width; CS is the channel stability rating (Pfankuch 1975) ; BEHI is the Bank Erosion Hazard Index (Rosgen 1996).*

| Stream Type | Statistic | Entrenchment | W/D ratio | Sinuosity | Gradient | % < 6mm | $D_{50}$ | $D_{84}$ | $W_{50}$ | CS | BEHI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B3 | Mean | | | | | 6 | 107 | 306 | | | |
| N=26 | SD | | | | | | 41 | 195 | | | |
| | 90% CI | | | | | 3 - 8 | 120-94 | 369-243 | | | |
| B4 | Mean | | | | | 17 | 41 | 148 | | | |
| N=16 | SD | | | | | | 18 | 70 | | | |
| | 90% CI | | | | | 12 - 22 | 48-34 | 177-119 | | | |
| Total B | Mean | 1.7 | 13.3 | 1.22 | 0.039 | | | | 13.4 | 64.7 | 25.5 |
| N=42 | SD | 0.3 | 5.9 | 0.14 | 0.026 | | | | 6.5 | 16.1 | 7.4 |
| | 90% CI | 1.78 - 1.62 | 14.8 - 11.8 | 1.26 - 1.18 | 0.049-0.029 | | | | 15.5-11.3 | 69.6-59.8 | 27.9-24.1 |
| C3 | Mean | | | | | 5 | 91 | 206 | | | |
| N=12 | SD | | | | | | 29 | 84 | | | |
| | 90% CI | | | | | 0 - 10 | 104-78 | 244-168 | | | |
| C4 | Mean | | | | | 16 | 39 | 104 | | | |
| N=22 | SD | | | | | | 14 | 53 | | | |
| | 90% CI | | | | | 13 - 18 | 44 - 34 | 133 - 85 | | | |
| Total C | Mean | 18.2 | 23 | 1.48 | 0.013 | | | | 29.4 | 71.1 | 24.3 |
| N=34 | SD | 16.6 | 11.9 | 0.35 | 0.014 | | | | 19.5 | 18.8 | 6.8 |
| | 90% CI | 22.8 - 13.6 | 26.2 - 19.8 | 1.57 - 1.39 | 0.017-0.009 | | | | 41.4-17.4 | 82.5-59.7 | 28.5-20.1 |
| E3 | Mean | | | | | 8 | 82 | 201 | | | |
| N=10 | SD | | | | | | 22 | 79 | | | |
| | 90% CI | | | | | 0 - 18 | 93 - 71 | 160 | | | |
| E4 | Mean | | | | | 22 | 25 | 70 | | | |
| N=65 | SD | | | | | | 16 | 45 | | | |
| | 90% CI | | | | | 19 - 25 | 28 - 22 | 79 - 61 | | | |
| E5 | Mean | | | | | 64 | | 38.5 | | | |
| N=18 | SD | | | | | | 0.48 | 73.8 | | | |
| | 90% CI | | | | | 60 - 71 | 0.54 | 67.1- 9.9 | | | |
| Ea | Mean | | | 1.25 | 0.062 | | 0.69-0.27 | | | | |
| N=25 | SD | | | 0.21 | 0.022 | | | | | | |
| | 90% CI | | | 1.32 - 1.18 | 0.069-0.055 | | | | | | |
| Total E | Mean | 11.1 | 6 | 1.6 | 0.017 | | | | 6.6 | 62.5 | 20.9 |
| N=118 | SD | 14.4 | 3.4 | 0.4 | 0.01 | | | | 6.1 | 15.3 | 4.9 |
| | 90% CI | 13.3 - 8.9 | 6.5 - 5.5 | 1.66 - 1.54 | 0.019-0.015 | | | | 8.6-4.6 | 67.6-57.4 | 22.7-19.1 |

certain it was representing that mean. By describing each of the parameters in these terms, the DFC for that particular stream type can be described. How these data are eventually displayed in the Forest Plan will be determined in an interdisciplinary mode. For example, in the Rosgen classification, reaches that are slightly entrenched really have no upper limit on entrenchment ratio. Therefore, establishing a range of 13.6 to 22.8 for C reach entrenchment would be unrealistic and unnecessarily constraining. In this case, the DFC for C reach entrenchment might be better expressed as > 13.6.

## Discussion

The measurement of a variety of physical parameters in watersheds that are undisturbed or minimally disturbed can be used to define physical stream conditions that reflect the present climate and tectonic regime of a region. If these measurements are used as references, land managers can estimate the dimension, pattern, and profile that would be the result of natural processes for stream channels within their area. By measuring the parameters that are used as delineative criteria in the Rosgen classification, stream types can be locally defined. For example, E stream types are defined in the classification system as having a width/depth ratio of less than 12. In the Greater Yellowstone Ecosystem/southwest Montana area, measurements of 118 E stream reaches show an average width/depth ratio of 6. Consequently, if a given E reach had a width/depth ratio of 10, and the stream banks were trampled by livestock, that reach might be determined to be trending away from stability as a result of getting wider and shallower.

These data can be used at various scales depending on the situation. For NEPA documents, where very site specific data is required to characterize stream conditions, reference and project reaches may be matched based on valley bottom characteristics. Demonstrating the difference between reference and project conditions will give the manager an idea of the status and trend of streams in the project area and how they may respond to a proposed action. On the Beaverhead-Deerlodge National Forest, NEPA documents have incorporated this approach since 1997.

In the TMDL arena, targets for parameters that define the condition of a stream with respect to beneficial uses must be established. Reference data, sampled throughout the area, can help define the conditions whereby beneficial uses can be expected to be self-maintaining. In Montana, the Ruby River and Yaak River TMDLs are presently using reference data to help establish targets for sediment and channel dimensions. At the Forest Planning scale, Desired Future Conditions define the hoped for end result of a suite of management operations over the entire forest. In past planning efforts, the DFCs for streams were often simple narratives that were neither quantitative nor measurable. The ability to gather reference data over a wide geographic area and a variety of stream types allows the DFC for each stream type to be described in a manner that provides the land manager a picture of the conditions that should exist regardless of the suite of management activities applied to the land. In the Forest Plan Revision process, the Beaverhead-Deerlodge National Forest is basing its DFCs for aquatics on local reference data. Across all scales, the ability to quantify standards, targets, and DFCs, makes any subsequent monitoring program more effective.

Reference data can provide land managers timely and excellent information with which to make decisions. However, they are not a panacea, and should not be applied in a vacuum. The need for professional interpretation at all levels of analysis is paramount. Choosing individual reference reaches, setting confidence limits, establishing acceptable risk, and determining the relative importance of different types of reference data, all require field-based knowledge of the watersheds in question. Rather than dogmatically establishing limits to management, reference data should be looked on as a tool that enables specialists to make better recommendations, and allows managers to gain a better understanding of how aquatic systems work.

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# Sediment From a Small Ephemeral Gully in South Carolina

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Since acquired in the 1930s, the Sumter National Forest, South Carolina, U.S.A., has emphasized land stabilization and restoration of eroded landscapes. Public concern over ground disturbance associated with some gully treatments suggested the need to verify sediment contributions, since many ephemeral gullies remain barren. We answered the questions, "Can a gully be barren, actively eroding, and not contribute sediment?" This paper summarizes the sediment measured from a discontinuous valley-side gully approximately 0.10 hectares (0.25 acres) in size. Measurement began in July 1994 with the installation of a filter fabric fence. In August 1994, runoff from Tropical Storm Beryl delivered 4.5 tonnes (5 tons) of sediment. By February 1999, a total to 40 tonnes (44 tons) of sediment accumulated. Remeasurement in March 2004 indicated a total of 48 tonnes (53 tons) with an average annual sediment delivery rate of 51 tonnes/hectare. Soil erosion occurred during intense rainfall events and freeze-thaw cycles; however, only severe storms produced enough stormflow to deliver sediment. During inactive periods, leaf-fall effectively hid the sediment transport path, giving an appearance of stability. Results suggest that small ephemeral gullies can be sources of sediment and should not necessarily be neglected. Carefully selected indicators may help determine if sediment delivery is a concern from ephemeral gullies.

Keywords: *ephemeral gully, filter fence, survey laser, erosion, sediment yield, storms, stream order, stormflow*

## Introduction

The Sumter National Forest (SNF) was acquired in the 1930s within the authority granted in the Weeks Law of 1911 to obtain and improve denuded and eroding lands within navigable watersheds to help produce sustained water and timber resources. Historic agriculture, logging and road practices contributed to the severe erosion and declining watershed conditions within the piedmont of South Carolina. National Forest emphasis on controlling erosion began with the Civilian Conservation Corps reforesting denuded lands and stabilizing gully networks. Ongoing efforts continue to address control and improvement of severely eroded lands through reforestation and treatment of actively eroding sites (Hansen 1991; Hansen and Law 1996). Many others have studied or discussed various aspects of gullies (Hoover 1949; Heede 1976, 1982; Singer et al. 1978; Yoho 1980; Schumm et al. 1984; Hansen 1995), reporting a wide range in conditions and sediment delivery. In most cases, sediment delivery was estimated from large ephemeral gully systems as a result of significant runoff or by calculating the volume lost from the gully dimensions.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

This study began in an effort to help address a public concern relative to proposals to treat gullies that are barren, eroding, but with limited apparent effects downstream. A barren, ephemeral gully in Chester County, South Carolina, with unknown downstream sediment delivery was selected in 1994 for measurement of sediment. At that time, leaves covered the downstream channel, and the gully did not appear to be actively delivering sediment. Treatment was not being proposed or contemplated at that time.

## Area Description

The study site is in Chester County, east of Union, South Carolina, on formerly farmed land acquired by the SNF in 1992. The ephemeral gully forms a Strahler order 1 channel within the Little Turkey Creek drainage (Figure 1) (Strahler 1957). The gully to be scrutinized is a discontinuous valley-side gully, with a drainage area of about 0.1 ha (0.25 acres). Adjacent to the site are several other barren, ephemeral gullies somewhat smaller in size. Based on examination of aerial photos, the gullies were formed prior to the 1940 aerial photo, but some noticeable headcut migration was visually detected in the measured gully until the 1969 photo. Aerial photos in 1974 (Figure 2) and 1990 (Figure 3) suggested that gully expansion had reached its limit with no major changes in the gully shape or extent during that period. So logically, there was uncertainty in whether the ongoing surface erosion

*Figure 1. Gully vicinity LEEDS, S.C. Quadrangle - USGS Topographic Contour Map, Lat. 34°44′N, Long. 81°25′W. Distance from the gully southeast to the sharp bend in the road is about 0.57 km (0.36 miles). Contour interval is 3 meters (10 feet).*

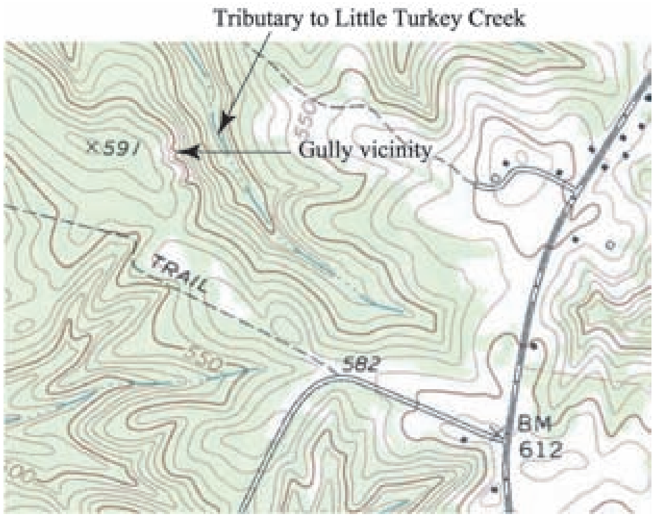
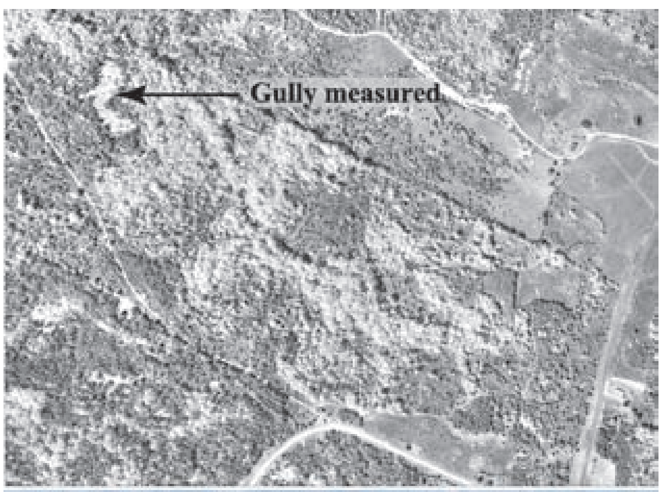



*Figure 2. Aerial photo taken in April 1974, with gully marked. Note the 6-meter width of the gravel road at photo bottom.*



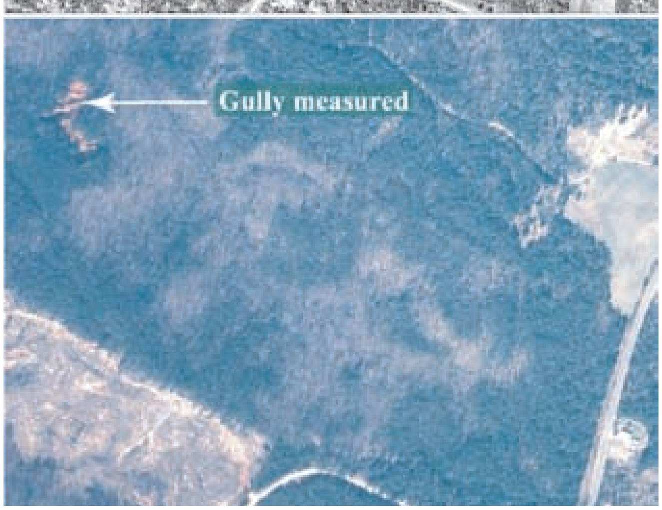




*Figure 3. Aerial photo taken in February 1990. No major changes in gully size were noted in comparison to 1974 photo.*

associated with the barren soils could be delivered as sediment sufficient to justify treatments. The downstream channel appeared stable and well covered in leaves suggesting limited or no sediment delivery.

Portions of the study area were probably farmed about a century ago. Eventually much of the farmed area on sloping terrain became depleted of nutrients, resulting in poor crop yields, abandonment, severe sheet erosion, and continued exposure to the elements, with gullies forming in areas where flow concentrated (Figure 4). Portions of the landscape were either planted to loblolly pine (*Pinus taeda*), or naturally recovered to mixed pine and hardwood forest after farming ceased. However, the severely eroded soils within the measured gully and adjacent gully barrens have been unable to support significant vegetative cover for many decades (verified at least 65 years). Many of the bottomland trees adjacent to the area are mature timber probably over 80 years old. The skid or temporary roads in the 1940 aerial photo suggested that logging likely occurred in the 1930s. Concentrated flow from skid roads or skidding practices onto heavily eroded soils may have contributed to the localized gully expansion or enlargement noted between 1940 and 1969. However, this is speculation and has not been substantiated beyond observing that a logging road contouring the hillslope, ends abruptly near the gully barrens. The sparse trees within the gully exhibit characteristics of low site conditions such as fusiform disease, chloritic needles, rank branching, rough bark, exposed roots and poor form.

*Figure 4. General view of gullied area within tract. Sharp pinnacle-like boundaries separated the individual gully channels.*

Rainfall averages about 114 cm (45 inches) per year in this area of the South Carolina piedmont, and is variable, but typically well dispersed through the year with average monthly rainfall between 7 and 13 cm (3 and 5 inches) (NOAA 2004). Water yield averages about 43 cm (17 inches) per year based on the gaged larger streams (Cooney et al. 2003). The less eroded hillslopes were typically Pacolet soil series that have thin A and B-horizons. Inclusions of Catuala soil series exist locally and have a fragipan-like B-horizon that is noticeable on the exposed upper margins of the gully. Soils within the gully are severely eroded and entrenched about 10 meters at the deepest into the saprolite materials of the C-horizon. Most of the gully has no remaining A-horizon or B-horizon, except for moderately eroded remnants along the gully upper margins near the ridge.

## Methods and Materials

In July 1994, filter fabric dams were constructed to capture sediment within an ephemeral channel. Materials included steel T posts, wire fencing, filter fabric, and wire C clamps and post ties. Methods were derived from Dissmeyer (1982) but differed from the construction materials and hillslope location described (Figure 5). Steel fence posts (1.8 m or 6 feet long) were initially installed at 0.9 - 1.5 m (3 - 5 ft) spacing, but more posts were added later to handle the weight of the sediment and water. The 1.2 m-high (4 ft) wire fence and filter fabric were buried about 0.15 m (6 inches) beneath the soil surface and oriented across the ephemeral channel to assure that the sediment would be retained and the water filtered through the fabric. The filter fabric was attached to the wire fence with C clamps using hognose pliers. During installation, care was taken to align the designed overflow dip in the fabric with the center of the channel so overflow could occur if needed without going around the edges and damaging the integrity of the structure. Since the initial fabric dam was nearly full within the first year, two other sediment dams were added in 1995 downstream of the initial site to maintain filtering and sediment capacity. The weight of sediment bent some steel posts and pulled the fence from the slope, leaving a gap for water and sediment to escape. The structures were reinforced with more posts and any gaps were filled with cloth bags containing soil, sand, concrete, or a combination of these.

Measurements were made in 1994, 1999 and 2004. Sediment deposits behind the dams were taken by measuring the elevation changes as sediment accumulated at 0.3 - 0.6 m (1 to 2 ft) spacing intervals for cross sections every 0.9 m (3 ft) up the channel. Elevation differences were measured with a Nikon Laser Level[1] with rod sensor, and cross sections were marked with rebar pins. Measurements were located with an expandable 7.6-m (25-ft) survey rod adjusted to fit between the rebar pins at either end. Soil samples were taken to determine bulk densities at each measurement time to be sure that any settling was taken into account. In March 2004, a total station survey instrument (Topcon Model GTS-605) was used to survey the area and establish more benchmarks for future needs.

*Figure 5. The fabric dam was installed in July 1994 below the 0.1-hectare ephemeral gully. The filter fabric was supported with steel posts, wire fencing and C clamps.*

The fine detail of the drainage boundary was surveyed using a Criterion 400 Survey Laser (Griswold 1993) (Figure 6). Traverse (PC) software was used to map station locations by distance, angle and slope from base locations. The survey laser was used to determine the gully boundary including a narrow, pinnacle-like section.

## Results and Analysis

In August 1994, about 13 cm (5 in) of rain from Tropical Storm Beryl delivered over 4.5 tonnes (5 tons)

*Figure 6. A Criterion 400 survey laser provided quality measurements to determine gully drainage extent. Laser has selective filter that can detect prism through vegetative cover, or can shoot directly to any solid surface, measuring distance, azimuth, slope and elevation change.*

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

*Figure 7. About 4.5 tonnes (5 tons) of sediment were deposited from Tropical Storm Beryl in August 1994. Sediment surface elevations and bulk density measurements were taken to estimate sediment amount.*

of sediment (Figure 7) (NOAA 2004). The amount of sediment captured from one storm event in such a small drainage area was a surprise. The filter fence was nearly half full of sediment and the steel fence posts were bent from the weight of the sediment and water. Some of the sediment was lost due to overflow. By February 1999, a total of 40 tonnes (44 tons) of sediment accumulated behind the sediment fences indicating an average sediment delivery rate of 89 tonnes $ha^{-1}$ $yr^{-1}$ (39 tons $ac^{-1}$ $yr^{-1}$) (Figure 8). Tropical Storms Jerry (1995) and Danny (1997) each contributed about 15 cm (6 inches) of rainfall, which produced enough flow to deliver sediment (NOAA 2004). The delivery of sediment was relatively dormant during the period 1997 to 2002 due to extended drought conditions. During the spring and summer of 2003, much higher than normal rainfall reactivated the delivery of sediment within the gully. The March 2004 measurement indicated an additional 8 tonnes (9 tons) of sediment had accumulated since 1999. After 9.5 years, total sediment accumulation was 48 tonnes (53 tons), resulting in an average annual sediment delivery rate of 51 tonnes/ha (22 tons/ac). This amount is probably conservative due to the amount lost in the initial overflow, and the extended drought between 1997 and 2002. During the study, ten storms produced flows in the nearby Enoree River at or above the flows associated with Tropical Storm Beryl, with Tropical Storm Jerry (1995) producing the 30-year flow of record (Cooney et al. 2003). It is likely that most if not all of these storm events, and perhaps a few others, contributed to the sediment captured.

Measurements and site visits after some of the major storms led to our curiosity to find other indicators of gully activity. Erosion of the bare gully surfaces occurred regularly in response to intense rainstorms, freezing rain and freeze-thaw events that dislodged soil particles. During most events of any significance, particles were moved by gravity or water, relocated on-site with moderate events with most accumulating at the toe of the slope or in the ephemeral channel for storage. Much of the gully remained sparsely vegetated or barren during the decade due to continuing erosion of the saprolite materials of the C-horizon. The highly weathered saprolite also has low available nutrients. Without treatment, most gullies and galled barrens in saprolite materials remain exposed for decades. Although erosion events are fairly common, sediment delivery downstream is episodic. Two distinct, buried organic layers were found in the sediment deposits delivered between August 1994 and February 1999 (probably Tropical Storms Jerry in 1995 and Danny in 1997). These layers as well as site visits after major events testify to the episodic nature of sediment delivery. Downstream reconnaissance following severe storm events led to identifying the historic sediment path of the gully onto a nearby stream terrace. Areas were found with recent sediment deposits, buried organic layers, clay stained trees and buried tree trunks in the flow path. It was apparent that the sediment path on the low gradient terrace had changed with time due to the accumulation of materials and occasional woody debris falling, accumulating sediment and diverting the path. The red clay stains on lower tree trunks and the lack of the buttressed root collars in older hardwoods due to their burial were persistent indicators of accumulated sediment in the delivery path.

*Figure 8. Additional dams were added to capture sediment. After 4.5 years (February 1999), a total of 40 tonnes of sediment were captured for an average sediment yield of 89 tonne $ha^{-1}$ $y^{-1}$ (36 tons $ac^{-1}$ $y^{-1}$). Most of the sediment was delivered during three major tropical storm events.*

A summary of the sediment measurements for the study is provided in Table 1. During the March 2004 sampling of the sediments, the bulk densities varied from 1.38 to 2.3 $g/cm^3$. When comparing the densities with

*Table 1. Summary of sediment volume, density and weight measurements with total volume and accumulated weight adjusted for sediment density changes. Data from Wade Tract gully sediment measurements taken from July 1994 to March 2004.*

| Fence | July - Sept. 1994 Added Volume ($m^3$) | July - Sept. 1994 Added Weight (metric tons) | Sept. 1994 -Feb. 1999 Added Volume ($m^3$) | July 1994 - Feb. 1999 Added Weight (metric tons) | Feb. 1999 - Mar. 2004 Added Volume ($m^3$) | July 1994 - March 2004 Added Volume ($m^3$) | July 1994 - March 2004 Added Weight (metric tons) |
|---|---|---|---|---|---|---|---|
| 1 | 4.16 | 4.50 | 11.40 | 21.09 | 1.95 | 17.51 | 4.29 |
| 2 | | | 6.92 | 12.80 | 0.53 | 7.45 | 1.17 |
| 3 | | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total Volume ($m^3$) | 4.16 | | 18.32 | | 2.48 | 24.96 | |
| Accumulated Weight (metric tons)* | | 4.50 | | 39.92 | | | 48.34 |

** Accumulated metric tons are based on weighted soil densities of sediments resampled for each measurement.*
*Sept. 1994 – Density of material averaged 1.08 g/cm³ for the August 1994 storm.*
*Feb. 1999 – Density averaged 1.45 g/cm³ for August 1994 storm, and 1.85 g/cm³ for Sept. 1994 - Feb. 1999 sediment.*
*Mar. 2004 – Density averaged 1.5 g/cm³ for August 1994 sediment, 2.0 g/cm³ for 1994 - 1999 sediment, and 2.2 g/cm³ for 1999 - 2004 sediment.*

the location and depths of the accumulated sediment, it became apparent that the sediment from the August 1994 event (derived from Tropical Storm Beryl) continued to be substantially lower in bulk density than the rest of the sediments. High winds from unstable air masses documented elsewhere during Tropical Storm Beryl may have caused an unusual amount of tree sway, twist, lean or blowdown, exposing finer soil materials to erosion. The August 1994 sediments initially had bulk densities averaging about 1.08 $g/cm^3$, and these materials settled to 1.45 $g/cm^3$ in 1999 and to 1.5 $g/cm^3$ in 2004. Sediments deposited between August 1994 and February 1999 filled the upstream fabric dam (fence number 1 in Table 1) and part of the second, with bulk densities averaging 1.85 $g/cm^3$ in 1999 and 2.0 $g/cm^3$ in 2004. Sediments added since 1999 and measured in 2004 accumulated primarily at the upper end of the upper fabric dam (fence 1) with a lesser amount added to the second dam, with bulk densities averaging 2.2 $g/cm^3$. With time, the materials captured have increased in their density and the more recent sediments are also denser. Over the study, 70 percent of the captured materials were retained in the upper structure, 30 percent in the middle structure and no measurable quantity in the lower structure.

Sediment accumulated from 1999 to 2004 primarily in the upper reaches of the first dam, suggesting that the coarse or the heavier particles may be settling out before they reach the first fabric dam. It is not known if this is due to storm differences in effective runoff or due channel changes from the fabric dam. The fabric dam and resulting sediment accumulation have changed the channel gradient, width and depth upstream. Perhaps larger storms would be needed to move materials into the second and third fabric dams. But the subtle changes associated with the filling of the first fabric dam may be enough to alter the delivery and lead to the current trend in upstream channel sediment storage.

Besides the sediment measured in the fabric dams, many observations were made over the extended study that provide useful information for assessing small ephemeral gully erosion and sediment delivery. On-site erosion was evident within the exposed gully area basically anytime, but especially following intense rainfall events and freeze-thaw cycles. Rainfall events left areas where soil pedestals were protected by small rocks and roots from raindrop impact and erosion. Freeze events expanded ice crystals that heaved soil and small plants above the surface. During thaw events, particles lifted from the surface were heard and seen tumbling down the slope as their ice support weakened upon melting. Many of the processes eventually undermined the fine surface roots and left them exposed after surface erosion (Figure 9). These processes help to perpetuate the soil exposure that has been maintained for decades without recovery. Only the large magnitude, severe rainfall events generated enough flow energy to transport sediments downstream in the small ephemeral channel to accumulate in the sediment dams. During inactive periods, the seasonal leaf-fall and wind-blown leaves hide much of the sediment accumulation within the channels, giving an appearance of low activity, with no apparent sediment being delivered (Figure 10).

*Figure 9. Soil erosion was evident on low to moderate sloping areas with exposure of fine roots and pedestaling of soils are indicators of the raindrop energy and poor infiltration on these barren soils.*

*Figure 10. Following autumn leaf fall, indicators of gully activity with respect to sediment delivery disregarding the filter fabric fence are masked to the casual observer.*

Other indicators of erosion within the gully and adjacent gully areas included headcuts (primary or uppermost nickpoint), cavitation, slope failure, root exposure, tree decline or mortality along gully margins, areas of sediment aggradation and in some instances secondary nickpoints (Figure 11). These indicators obviously helped verify erosion processes, but did little to actually confirm that sediment was being delivered downstream. Indicators of sediment delivery became more obvious after major events, when fresh sediments covered the channel and the sediment path was dominated by the red clay color.

We noted that the red clay stains at the base of trees in the channel persist and appear to be a reliable indicator of sediment delivery (Figure 12). The stains are a result of red piedmont clay materials in sediment laden runoff or rainfall splash from fresh sediment deposits onto trees. Stain depth was sometimes higher and brighter on the portion of the tree facing the flow delivered from the gully channel. Within the sediment path on an alluvial terrace, the trunks of mature bottomland hardwood trees showed no enlargement at their base, another indicator that the sediment had buried their trunks some time ago. The sediment track and stained trees continued to a small perennial stream, several hundred feet away. Red clay deposits along the channel margins continued downstream. Soil cores in the sediment track revealed brighter soil colors of fine alluvial materials, while areas outside of the sediment path had darkened red alluvial soils from historic

*Figure 11. Surface erosion along the upper edges of the gully was enough to remove almost all the soil supporting this pine tree during its lifetime.*

*Figure 12. Sediment marks within the flow path are especially evident from the reddish clay soils onto the base of trees.*

gully erosion that has had more time to incorporate organic materials and change colors during weathering processes. Buried organic layers are more likely to be present where flow velocity is low, and less likely where flow has a defined path, velocity and depth sufficient to move organic materials.

## Discussion and Conclusions

Our study was a result of public concerns associated with having clear reasons for stabilizing and restoring ephemeral gullies. Upon visiting the site and reviewing the findings, individuals concerned about past gully control measures have a much better appreciation of how ephemeral gullies function. Even small gullies can remain barren and continue to erode and deliver sediment for decades, affecting soil, water and aquatic resources. During the study, we identified many storms and events that produced erosion from a small ephemeral gully and associated gullies and other barren areas nearby. More importantly, we identified that severe tropical storms were necessary to deliver sediments from extremely small ephemeral gullies. Until we evaluated the storm and flow frequency of these type events over the study period, it was not apparent that they recur so frequently. Water quality and aquatic habitat are much more likely to be affected by sediment delivery downstream from small ephemeral gullies than we had thought. Since funding to treat gullies is limited, we can use this information to help prioritize treatments. Gullies that are not only eroding, but also actively and frequently delivering sediments to streams would get a higher priority for treatment.

Gullies have many characteristics that make them difficult to understand. Sometimes a relatively simple study as this can help answer public concerns and be beneficial in forming responsible recommendations and decisions. Although this study was intended to only characterize sedimentation associated with a specific gully, it has provided information on how ephemeral gullies function in the piedmont of South Carolina. Following the gully activity for nearly 10 years demonstrated that ephemeral gullies may have their own timing and activity level, and effects are not always obvious. Ephemeral gullies can erode and not produce measurable sediment. However, as evidenced in this study, severe storms can generate the flow needed to deliver sediment from very small gullies.

Other information of the study is interesting, but in some instances would need more verification. The information collected on differences in sediment density seemed to support the idea that the low-density sediments delivered in the August 1994 storm were unusual, even after almost a decade. Perhaps this could be linked to the severe winds and many localized tornadoes experienced outside of the study area during Tropical Storm Beryl. However, the increase in material density with time should be expected and considered when measuring sediment accumulations over time. The increase in coarse materials settling in the upper reaches of the upper fabric dam may be due to channel changes associated with the accumulating sediments. Changes in channel gradient, width and depth occur with aggradation. In addition, sediments captured by the fabric dam may absorb stormflow and filter particles or organics before they can be delivered as sediment. Although interesting with potential implications to the results, the study was not set up to determine the specific processes that may be associated with sediment deposits, as they may vary with channel changes, storm intensities and time.

This study provides an example of simple but effective sediment observations and measurements that helped address a public issue of concern. The approach has been effective in describing and communicating some of the erosion and sediment delivery processes that may occur in small ephemeral gullies. Even without detailed measurements, the fabric dams with accumulated sediment effectively illustrate these results to varied audiences that visited the site or were shown pictures of the results.

The reader should be aware of some precautions and limitations before applying these methods. Under normal circumstances and construction methods, silt fences and concentrated surface waters in channel systems are incompatible. Careful design and installation are needed to contain concentrated flow and accumulating sediment.

We believe that filter fabric dams may have many potential uses in addressing erosion, sediment and water quality issues. As suggested by Dissmeyer (1982), they are very useful in storing sediments derived from hillslope surface erosion. Under most circumstances, hillslope erosion in forests is very low because ground disturbance and concentrated flow is generally limited. The fabric dams have been used to help determine effects from more severe ground disturbances such as wildfire, bladed fireline and temporary road construction. Ground disturbances may contribute concentrated flow from compacted or exposed surfaces. The fabric dams have been used to determine effectiveness of mitigation measures such as drainage dips and erosion control methods. Sediment effects become more likely to be measurable in affected ephemeral channels than on hillslopes because the drainage area increases. Until this gully study, a turbid watermark to light sediment accumulation would commonly be left across the fabric with little or no accumulation at the base of the fence. In those instances, these observations indicate that a flow event occurred, but little sediment was produced. This is still valuable information in monitoring the effectiveness of methods.

We have some advice or considerations for those attempting to use fabric dams to measure sediment. Consider low gradient channel sections that offer some reduced stream velocity, more channel storage and stable banks. Tall sediment retention structures are unstable. The effective height of the structures used for this study was about a meter. Reducing the height of the structure will limit the amount of sediment captured, but improve its stability under the force and pressure of the flow and sediment. As sediment fills the structure, detention of flow and filtering capability of the exposed filter cloth is reduced. Adding another filter dam downstream can help maintain the filtering capacity and prevent loss of data during overflow. Do not forget that the accumulated sediments within the structure may alter the channel gradient and dimensions and improve the channel's ability to detain or accumulate sediments upstream. Measure the channel dimensions substantially beyond the elevation of the effective dam height. Under the circumstances of this study, the longevity of the filter fabric dams is at least a decade.

We feel that the fabric dams would be well suited to many other conditions. This study area has some of the most severe land use and erosion history in the piedmont of South Carolina. The severity of conditions is also evident when a 0.1 ha ephemeral gully repeatedly delivers sediment downstream over a decade. The severity is also suggested by the Universal Soil Loss Equation average annual rainfall/runoff index (R-factor) for the area: a relatively high rating at 4,600 (megajoules/ha) (mm/hour) [i.e., 275 in units of 100 (foot tons/ac) (inches/hour)] (Wischmeier and Smith 1978). The R-factors in the southeastern U.S. are substantially higher than most of the rest of the country. We have used the fabric dams in ephemeral drainages in the Blue Ridge Mountains with areas of about 1 ha (2-3 ac), and they withstood severe to record events associated with Tropical Storms Jeanne and Ivan in 2004.

Advantages of the filter fabric dams include low to moderate cost, flexibility of scheduling measurements to fit study details desired, and their ability to provide a visual indicator of the accumulated sediment captured. The study costs over the decade were not closely tracked, but expenditures are estimated at $10 000, which included $1000 to install the three fabric fences, $500 for the boundary survey, $500 for deposition and stream sediment measures, $3000 for the three measurements and data compilation of sediment accumulations and probably about $5000 in analysis, documentation and reporting. The flexibility of scheduling measurements to fit individual schedules and having a visible field demonstration are important considerations. Whether seen in a picture or on a site visit, the filter fences are effective communication tools. Disadvantages may be the time needed to measure the elevation changes in the sediments, sample the sediment density during each measurement, and compile the data. The fabric dams are not permanent structures, and failure may eventually occur. The deposits may need to be stabilized or removed when the study is complete.

Assessment of ephemeral gullies and downstream areas after major disturbance events may be a realistic approach in the southeastern U.S. due to the frequency of events. However, for many other areas, the frequency of disturbance events would make the fences difficult to rely on. Even without field assessment, analyzing gully history using aerial photos can be a viable tool in identifying changes in land use, gully shape, size and extent through time. This approach is more difficult where gullies expand into forested terrain. We recommend the fabric dams as a useful tool if the other erosion and sediment indicators are inconclusive. They provide a low technology approach to monitoring sediment under certain conditions that could be adjusted to produce higher levels of accuracy or detail if required.

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# Quantifying the Effects of Livestock Grazing on Suspended Sediment and Stream Morphology

Pete Bengeyfield

*Beaverhead-Deerlodge National Forest, Montana*[1]

Suspended sediment measurements, physical channel measurements, and allotment inspection notes are combined to describe the effects of livestock grazing on a 12-square-mile (31 $km^2$) watershed in southwest Montana. In years when streamflow reached bankfull stage, suspended sediment produced during the grazing period (post-1 July) was 4.3 times greater when livestock were present. In absolute terms, livestock are responsible for about 5.6 tons (5.1 metric tons) of suspended sediment per day during the grazing period. Stream channels within the watershed became wider and shallower, and had increased fines as a result of streambank trampling by livestock. Although a rest-rotation grazing system was implemented in 1974, stream surveys indicate continued shifts in channel morphology away from the most probable stable form of channel. Allotment inspection notes provide support for cause/effect suspended sediment relationships.

Keywords: *stream morphology, livestock grazing, sediment*

## Introduction

Livestock trampling on streambanks leads to two major adverse effects on the functioning of the channel. First, streams become wider and shallower as trampling leads to channel widening (Braun 1986). The same disturbance mechanism often leads to increased suspended sediment concentrations either through direct introduction of particles, or by creating raw areas on streambanks that are susceptible to erosion by subsequent high flows (Skovlin 1984; Clifton 1989; Clary and Webster 1990). Overton et al. (1994) compared reference and grazed conditions to show effects on physical channel attributes. Because of its effects on spawning gravels, the amount of fine sediment in a stream channel has been used as an indicator of the quality of salmonid habitat (Duncan and Ward 1985). However, because of the difficulty in spatially and temporally measuring suspended sediment, combined with the difficulty of isolating the effects of livestock, there has been little quantification of sediment loading solely as a result of livestock use. On the South Fork of Blacktail Creek, measured suspended sediment data, quantified channel surveys, and allotment records combined to provide an opportunity to determine suspended sediment concentrations and loading for a watershed in which the only land uses were livestock grazing and occasional dispersed recreation.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

## Background and Physical Setting

The South Fork of Blacktail Creek is located in the Southwest Corner Allotment on the Madison Ranger District of the Beaverhead-Deerlodge National Forest, Montana. The mainstem and tributaries generally have the potential to be E stream types (narrow, deep channels that are sinuous and relatively flat with ready floodplain access) (Rosgen 1996) throughout their lengths, as shown by reference reaches in similar nearby valley bottoms. Table 1 displays important physical and land use characteristics of the S.F. Blacktail Creek watershed. The allotment was converted from sheep to cattle in 1974. Livestock were managed on a three-pasture rest-rotation grazing system, and thus were present in the watershed only during certain times in any given year. July 1 was the "on date" for the allotment, so livestock were not present during the peak flow period for Blacktail Creek. Pasture moves were scheduled in the permit for 11 August, but in practice that date could vary a few days either way depending on annual conditions. The pasture was rested during 1986, 1989, and 1992.

## Methods

In the fall of 1985 a series of monitoring stations were established on the Beaverhead National Forest for the purpose of quantifying suspended sediment from various land uses. The South Fork of Blacktail Creek was chosen because it represented a watershed where livestock grazing was virtually the only land use taking place.

[1] Retired

*Table 1. Summary of physical characteristics and land use for South Fork Blacktail Creek.*

| | |
|---|---|
| Area | 12 mi² |
| Annual precipitation | 35 inches |
| Slope | 30-65% |
| Mean elevation | 8500 ft |
| Geology | Tertiary sediment/shale |
| Road density | 0.4 mi/mi² |
| Stream crossing density | 0.1 crossings per stream mile |
| % watershed grazed | 100% |
| AUM density | 109/mi² |
| Timber harvest | 0 |
| Number of mines | 0 |

Monitoring operations began in April 1986. A stilling well and water level recorder, in conjunction with a rating curve constructed from approximately 15 streamflow measurements per year, were used to determine hourly discharge. An ISCO sediment sampler[1] collected four samples per day at six-hour intervals for an integrated daily sample. The station generally operated from early May through mid September from 1986 -1992. The area immediately around the stilling well and ISCO intake was fenced to exclude livestock.

Stream surveys were initiated on the Beaverhead National Forest in 1991 to determine the effects of land uses on channel morphology (Bengeyfield, this volume). Standard channel measuring techniques were employed (Harrelson et al. 1994). Additionally, at each survey site, fifty bankfull widths were measured to display in a cumulative distribution curve, to show the change in width along a reach of stream. In 1995 and 1999, a total of eight stream surveys were undertaken in the South Fork Blacktail watershed. Three were on the mainstem of South Fork Blacktail Creek, three were on the Bonita Fork tributary, and one each on the Greys Fork and Dukes Fork tributaries. Physical stream attributes from these surveys were compared to reference data from similar channel segments to determine the condition of the reach (Bengeyfield, this volume).

Streamflows were stratified by whether they were above or below bankfull stage. The bankfull flow is important because it is instrumental in maintaining channel dimensions and sediment transport (Dunne and Leopold 1978).

Livestock entered the allotment on 1 July each year, and their direct effect on sediment production is limited to the time they are present in the pasture in which the stream gage is located. Consequently, this analysis is focused on comparing post-grazing sediment production between years when livestock are present versus when they are absent, and between those years when bankfull flow was attained versus sub-bankfull years.

The combination of water column data (suspended sediment), physical channel data (channel morphology, cumulative width distribution), and allotment inspection notes allow a cause and effect picture to be drawn for the effects of livestock grazing on suspended sediment production.

## Results

### Suspended Sediment Production During Grazing Period

Stream discharge varied considerably throughout the study period (Figure 1). There were three years when bankfull flow was attained (1986, 1991, 1993), two years of extremely low flow conditions (1987, 1989), and three years of moderate flow (1988, 1990, 1992).

Table 2 displays the results of sediment monitoring stratified by time of year and streamflow regime.

Post-grazing sediment loading data (measured as cubic feet per second [cfs] x mg/L x 0.0028) indicate that livestock increase post-grazing sediment loading during bankfull years by 430% (15.5 tons per day with livestock vs. 3.6 tons per day without livestock), and by 157% during low/moderate flow years (4.1 tons per day with livestock vs. 2.6 tons per day without livestock) (Table 3). It is likely that bankfull years produce greater post-grazing sediment totals because higher discharges from the peak flow period extend into the summer, providing more energy for streambank erosion and sediment transport, while at the same time, the presence of livestock on streambanks provides a source of sediment.

Figures 2, 3 and 4 are examples of bankfull years showing the dependency of suspended sediment concentrations corresponding to both streamflow and livestock presence.

The three graphs demonstrate the relationship between stream flow and suspended sediment concentration (mg/L). During the peak flow period, flow and sediment are highly correlated, especially in 1986 and 1991. In 1986, the rest year (Figure 4), and 1991, when livestock were not present until 11 August (Figure 2), sediment remains streamflow dependent. As streamflow drops, sediment remains low. In 1993, when livestock enter the pasture on 1 July (Figure 3), sediment begins to rise as stream flow declines and remains independent of stream flow throughout the time livestock are present. In 1991, suspended sediment appears to increase about the time livestock enter the pasture, but data after 11 August are lacking. During 1991 and

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

*Figure 1. Annual streamflow, South Fork Blacktail Creek, 1986 - 1993.*

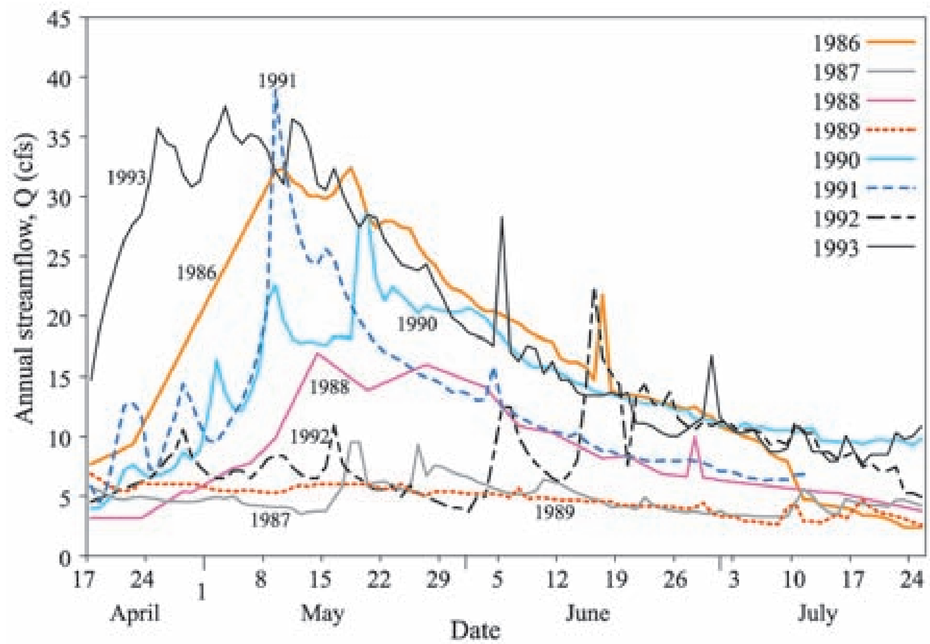


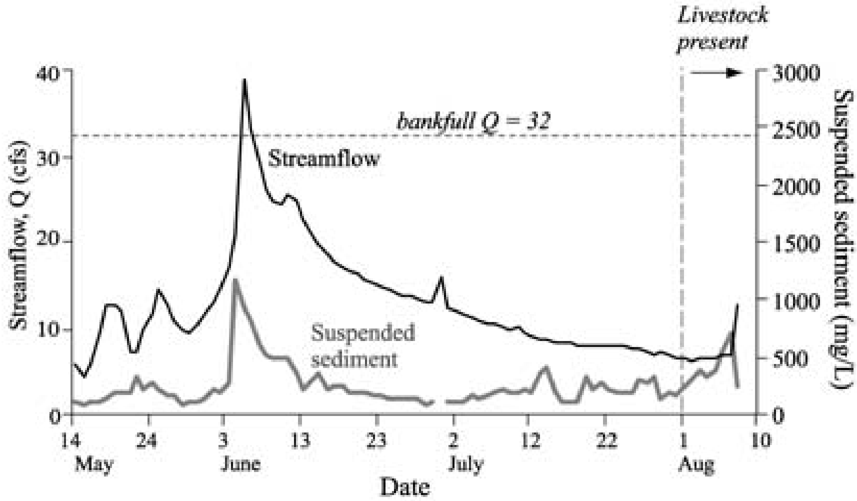

*Table 2. Suspended sediment loading, South Fork Blacktail Creek.*

| Flow Regime | Year | Streamflow (acre-feet per year) | Sediment pre-grazing (tons/ day) | Sediment post-grazing (tons/day) | Total Sediment (tons/day) | Streamflow (cfs) | Sediment pre-grazing (%) | Sediment post-grazing (%) | Livestock Present |
|---|---|---|---|---|---|---|---|---|---|
| Bankfull | 1986 | 3289 | 24.8 | 3.6 | 28.4 | 8.29 | 87 | 13 | No |
| | 1991 | 2165 | 15.3 | 5.4 | 20.7 | 8.51 | 74 | 26 | 11 Aug. |
| | 1993 | 4288 | 41.8 | 25.5 | 67.3 | 9.64 | 62 | 38 | 1 July |
| *Mean* | | *3247* | *27.3* | *11.5* | *38.8* | *8.81* | *74* | *26* | |
| Low | 1987 | 1183 | 3.8 | 2.6 | 6.4 | 4.09 | 59 | 41 | 1 July |
| | 1989 | 1042 | 1.8 | 1.2 | 3.0 | 3.44 | 60 | 40 | No |
| *Mean* | | *1112* | *2.8* | *1.9* | *4.7* | *3.76* | *59.5* | *40.5* | |
| Moderate | 1988 | 1756 | 36.6 | 8.1 | 44.7 | 4.59 | 82 | 18 | 11 Aug. |
| | 1990 | 3518 | 7.4 | 1.6 | 9 | 9.83 | 82 | 18 | 1 July |
| | 1992 | 2032 | 3.6 | 3.9 | 7.5 | 6.7 | 48 | 52 | No |
| *Mean* | | *2435* | *15.8* | *4.5* | *20.4* | *7.04* | *71* | *29* | |

*Table 3. Post-grazing sediment loading.*

| Flow Regime | Year | Livestock Present | Sediment (tons/day) |
|---|---|---|---|
| Bankfull | 1991 | Y | 5.4 |
| | 1993 | Y | 25.5 |
| | *Avg.* | | *15.5* |
| | **1986** | **N** | **3.6** |
| Low/Moderate | 1987 | Y | 2.6 |
| | 1988 | Y | 8.1 |
| | 1990 | Y | 1.6 |
| | *Avg.* | | *4.1* |
| | 1989 | N | 1.2 |
| | 1992 | N | 3.9 |
| | *Avg.* | | *2.6* |

*Figure 2. Streamflow and suspended sediment, 1991. Livestock present after 11 August.*



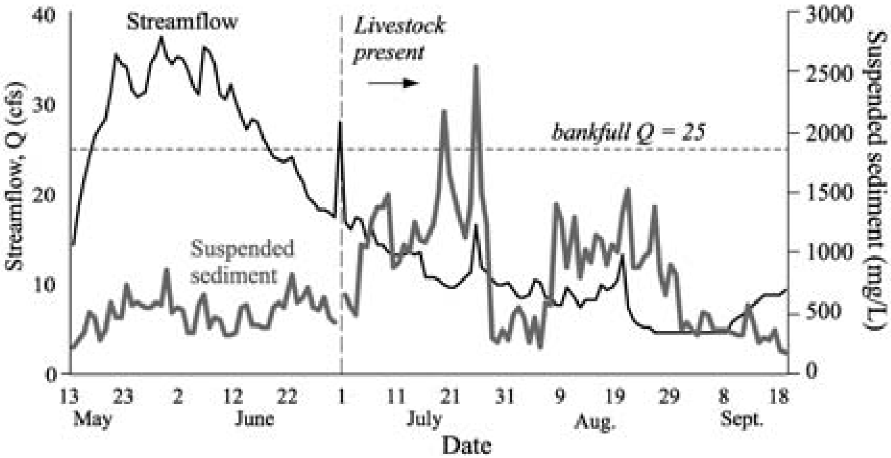
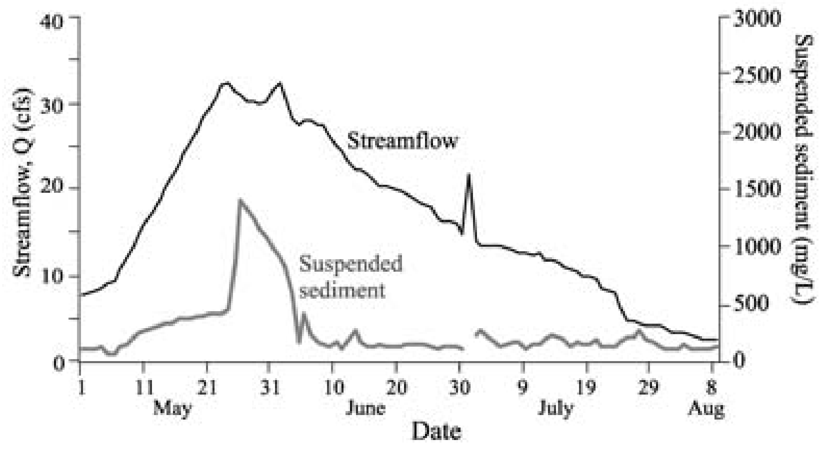




*Figure 3. Streamflow and suspended sediment, 1993. Livestock present after 1 July.*

*Figure 4. Streamflow and suspended sediment, 1986. Pasture rested.*




1993, streamflow was about the same during the post grazing period (1991 = 8.51 cfs [0.24 cms or m$^3$/s]; 1993 = 9.54 cfs [0.27 cms]) but the sediment concentrations are considerably higher when livestock are present (mean post-grazing concentration in 1991 = 241 mg/L; in 1993 = 878 mg/L). During the rest year, post-1 July streamflow approximates the other years (8.29 cfs [0.23 cms]), but sediment concentration is considerably less (154 mg/L).

Figure 5 displays the difference in suspended sediment production when livestock are present after 1 July during bankfull flow years.

When livestock are absent from the pasture (all of 1986, prior to 11 August in 1991), sediment concentrations are generally less than 500 mg/L. When livestock are present (post-1 July 1993), sediment concentrations are considerably elevated. During bankfull years, the falling

*Figure 5. Suspended sediment production (mg/L) for post-1 July during bankfull years.*

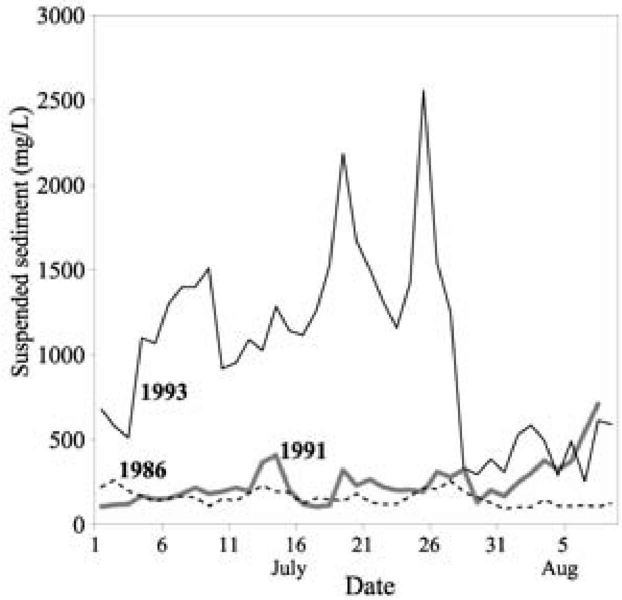



*Figure 6. Streamflow and suspended sediment, 1987. Livestock present after 1 July.*

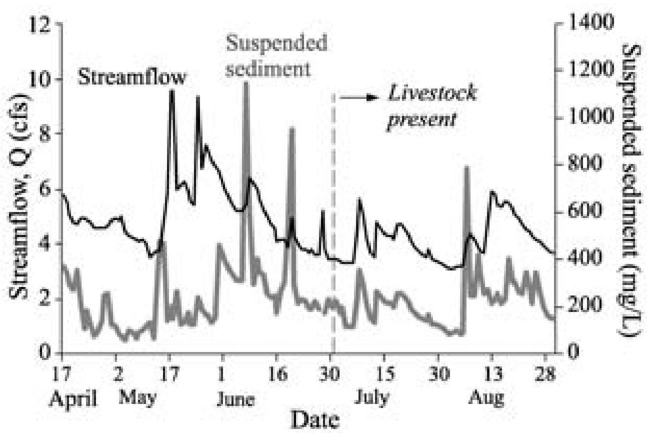
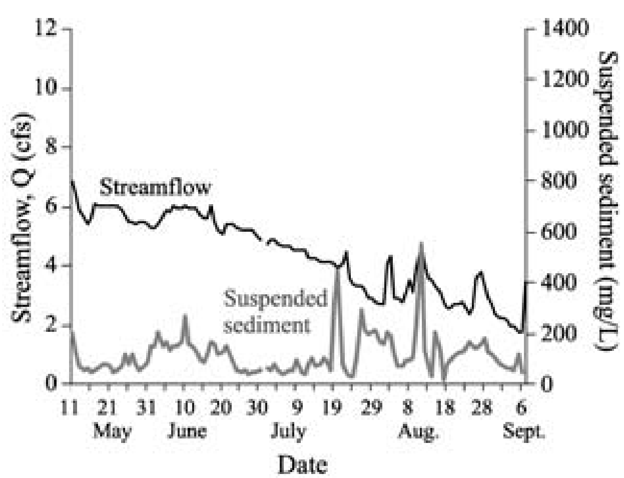



*Figure 7. Streamflow and suspended sediment, 1989. Pasture rested.*




limb of the hydrograph maintains higher flows into the summer. The presence of livestock on streambanks causes soil particles to be directly introduced to the stream, and trampling exposes streambanks to erosion. This combination of effects leads to higher sediment concentrations.

Low flow years show the same trend of similar streamflow levels producing higher sediment concentrations when livestock are present (Figures 6 and 7). During low flow years (1987 and 1989), sediment concentrations mimic streamflow quite well. Streamflows for this period are much the same for both years (1987 = 4.1 cfs [0.12 cms]; 1989 = 3.4 cfs [0.096 cms]), yet suspended sediment concentrations almost doubled when livestock were present (1987 = 216 mg/L; 1989 = 122 mg/L).

Comparing the average sediment production between grazed and ungrazed years (Table 4), we can see that the presence of livestock contributes to a dramatic increase in suspended sediment loading and concentration. Although sediment is clearly flow dependent, with more being produced during the years when bankfull stage was attained, the increase in both concentration and loading during the time that livestock are present shows the influence of grazing as well.

The average sediment concentration for the period after 1 July during rest years is 152.5 mg/L. This can be assumed to be a background concentration for the stream in its current condition. By subtracting this value from the total concentration when livestock are present, it is possible to determine the effect of livestock on sediment concentration, and to then calculate the sediment loading as a result of livestock. Livestock alone produce approximately 5.6 tons (5.1 metric tons) of sediment daily during the post-1 July period (Table 5).

The 5.56 tons per day (5.0 metric tons) that livestock increased sediment during the July through mid-September period from 1986-1993 equates to a total of 2085 tons (1891 metric tons) of suspended sediment for the period of record. The average May through September sediment loading for that period was 12.1 tons per day (11.0 metric tons), or 13,552 tons (12,292 metric tons) for the period

*Table 4. Suspended sediment production for South Fork Blacktail Creek, 1986-1993.*

| | Suspended Sediment | |
|---|---|---|
| Suspended Sediment with: | Sediment loading (tons/day) | Sediment concentration (mg/L) |
| Livestock present (5 yrs.) | 8.62 | 391.6 |
| Livestock absent (3 yrs.) | 2.94 | 152.5 |

*Table 5. Post-grazing sediment production as a result of livestock presence.*

| Year | Flow Level | Post-1 July Accelerated Sediment Concentration (mg/L) | Post-1 July Streamflow (cfs) | Post-1 July Accelerated Sediment Loading (tons/day) |
|---|---|---|---|---|
| 1987 | low | 63.5 | 4.09 | 0.73 |
| 1988 | moderate | 418 | 4.59 | 5.37 |
| 1990 | low | 0 | 9.83 | 0 |
| 1991 | bankfull | 88.6 | 8.51 | 2.11 |
| 1993 | bankfull | 726.1 | 9.64 | 19.59 |
| *Mean* | | *259.2* | *7.33* | *5.56* |

Entrenchment, as defined by Rosgen (1996), is flood prone width divided by bankfull width, and indicates the degree of channel incision. A large entrenchment value describes a narrow, deeply incised stream channel; a small value describes a wide, shallow stream channel.

of record. The sediment produced by livestock during the summer months in five years was 15.4% of the total suspended sediment produced over an eight-year span.

**Stream Survey Data , 1995 - 1999**

The stream survey data do not directly measure sediment in the water column as was done in the above analysis, but instead give a picture of various channel components that directly contribute to sediment production. These data indicate that at the majority of the sites measured in the South Fork Blacktail Creek, channel morphology has been altered by livestock trampling of stream banks, and sources of in-channel sediment have been created and perpetuated.

The stream survey data (Table 6) indicate that the main reason for the impairment of these streams was a change in the entrenchment ratios as a result of livestock trampling [see text box, above right]. For example, the most probable stable form for all the reaches should be E stream types (Rosgen 1996), but trampling along the banks has altered the interface between the top of the bank and the floodplain so the channel has become more entrenched, and shifted to a B stream type. The average entrenchment for E stream types in southwest Montana is 11.0 (Bengeyfield, this volume), while the average entrenchment for the South Fork Blacktail Creek sites is 1.8.

The presence of a reference reach in a tributary to South Fork Blacktail Creek that is adjacent to the Southwest Corner Allotment provides an opportunity for comparison of a number of parameters between reaches. The reference reach is in a neighboring allotment, and appears to be seldom grazed. All reaches have similar valley characteristics (valley bottom width, valley slope, and drainage area, Table 7).

An example of the increase in entrenchment at these reaches is demonstrated in Figure 8 by comparing the cross-section of the Bonita Up reach with that of the reference reach. It can be seen from the bankfull and floodplain indicators that streamflows at Bonita Up are less likely to reach their floodplain than those of the reference, South Fork Blacktail Trib Down. Hence, more stream energy is contained at high flows, leading to accelerated bank erosion and sediment entrainment.

*Table 6. Entrenchment, stream type and functionality of survey sites, South Fork Blacktail Creek*

| Stream | Entrenchment | Stream Type | Function |
|---|---|---|---|
| SF Up | 8.9 | E | FAR |
| SF Mid | 2.0 | B | FAR |
| SF Down | 5.3 | E | F |
| Bonita Up | 2.0 | B | NF |
| Bonita Mid | 2.5 | E | FAR |
| Bonita Down | 1.8 | B | NF |
| Dukes | 1.3 | G | NF |
| Greys | 11.2 | E | F |

*Table 7. Valley bottom characteristics of South Fork Blacktail tributaries.*

| Stream | Valley Bottom Width (ft) | Valley Slope (%) | Drainage Area (acres) |
|---|---|---|---|
| Reference | 235 | 3.2 | 546 |
| Bonita Up | 110 | 4.6 | 288 |
| Bonita Down | 150 | 3.8 | 300 |
| Greys | 140 | 1.3 | 648 |

An effect of excessive trampling of streambanks is an increase in overall stream width. By comparing the cumulative width distribution of Bonita Up, Bonita Down, and Greys Creek with South Fork Blacktail Trib Down, the reference reach, we can see that this effect has occurred on the tributaries of South Fork Blacktail Creek (Figure 9). All of the tributary reaches are considerably wider than the reference reach throughout their length. For example, the mean width of the reference reach is between 1.5 and 2.0 feet (0.46 to 0.61 m), while the mean width of Bonita Up is between 4.5 and 5.0 feet (1.4 and 1.5 m).

*Figure 8. Cross sections of Bonita Up and South Fork Blacktail Trib Down.*

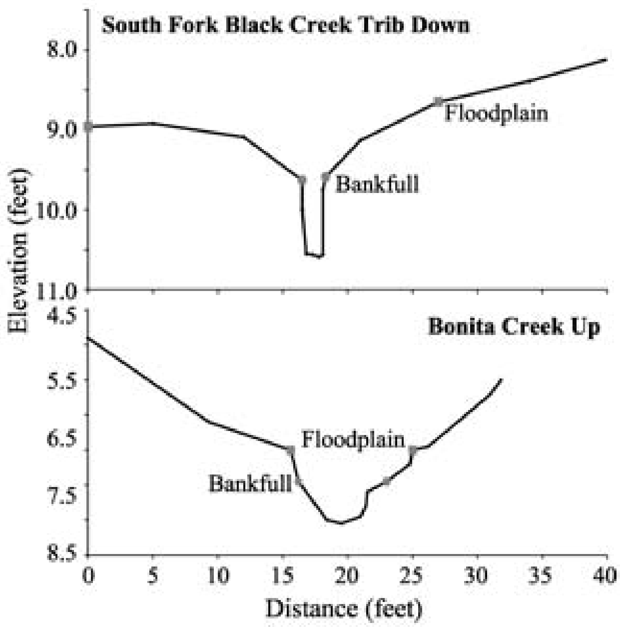



*Figure 9. Cumulative width distribution for tributaries to South Fork Blacktail Creek.*

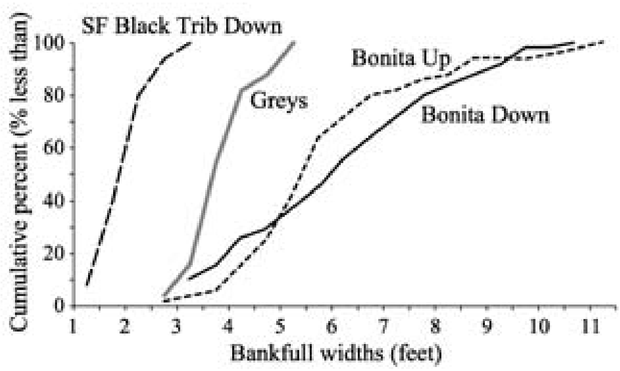
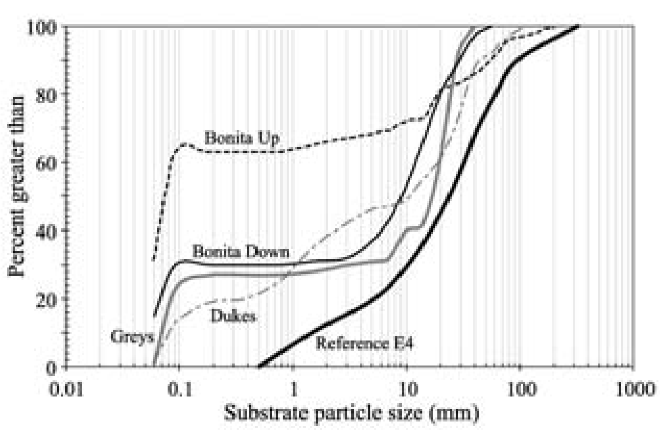



*Figure 10. Substrate distribution for survey sites in South Fork Blacktail Creek.*




Another effect of livestock trampling is to increase sediment in the stream channel. As fine sediment is deposited in the channel, it causes the substrate distribution to be more heavily weighted to smaller sizes. The survey sites in South Fork Blacktail Creek, as compared to a reference distribution for E4 stream types in southwest Montana, show a pattern that supports this change in substrate size (Figure 10) (Bengeyfield, this volume). All reaches show a shift to a finer substrate when compared to reference conditions. For example, about 12% of the reference reaches have fines under 2 mm in size, while about 30% of Dukes and Bonita Down are less than 2 mm.

## Allotment Notes

The Southwest Corner Allotment was grazed by sheep until 1974, when it was converted to cattle. Notes in the allotment file indicate heavy sheep grazing had an adverse effect on vegetation along ridge tops, and that the channel stability of Blacktail Creek was rated as Poor. It was speculated however, that cattle were likely to cause more damage to stream banks than sheep, and that observations of utilization should be taken in the riparian area to determine the allowable AUMs (W. Page, personal communication, 1974). Cattle were managed under a rest-rotation system from the outset, but annual inspection notes indicate that their distribution across the allotment was often poor. A 50% utilization standard was most often employed as a trigger to move livestock to the next pasture. It appears that the allotment was generally inspected once a year, towards the end of the grazing season. Inspection notes reveal that the utilization standard was seldom reached in the uplands, but often exceeded in the stream bottoms. Some excerpts from the notes underscore this point:

- “Cattle concentrated in bottom of Greys Fork. Light use on upper slopes and ridges. Utilization 24%. (14 August 1974)
- “Still cows in bottoms.” (4 September 1974)
- “Cattle pretty well used bottoms. Most of use is where cattle were dropped in drainages.” (12 October 1975)
- “95% of cattle were between forest boundary and Dukes Fork. All of these cattle were in the stream bottom.” (16 July 1981)
- “Need to keep rider to move cows out of bottoms.” “The creek bottoms are used enough for this year, however cattle are scheduled to stay for one more month.” (14 August 1987).
- “Inspected utilization in riparian areas and adjacent benches. The cattle should be removed from the allotment.” (26 September 1988)

- "Bottoms averaged 60-70% use. 31% average streambank disturbance." (11 October 1991)
- "Dukes Fork and Greys Fork are at or beyond riparian guidelines with very little use in the uplands." (1994)

## Discussion and Conclusions

Livestock grazing has been shown to adversely affect stream channels through the alteration of physical dimensions of the channel and by adding sediment (Kaufman and Krueger 1984; Clary and Webster 1990). This effect has been demonstrated in a number of case studies (Platts 1983; Clifton 1989), and literature reviews (Skovlin 1984). Overton (1994) compared reference and grazed conditions to show effects on physical channel attributes. Because of its effects on spawning gravels, the amount of fine sediment in a stream channel has been used as an indicator the quality of salmonid habitat (Duncan and Ward 1985).

A major factor that contributes to sediment loading is the condition of the channel and riparian area. Channels in poor condition will have more sediment sources, and annual disturbance by livestock is more likely to make that sediment available for erosion and transport, both during the low flow and high flow periods. Data from around the South Fork Blacktail watershed indicate that much of the riparian area/stream channel network in the watershed is in poor condition with high levels of fine material in the channel. Of the eight stream surveys located on the South Fork Blacktail Creek and its tributaries above the stream gage, six are either non-functioning or functioning-at-risk, and seven were judged to be in a downward trend (Beaverhead-Deerlodge National Forest, unpublished data).

The percentage of fine sediment is consistently much higher than for reference levels for E4 stream types. The average values for all survey sites in the watershed yield a Bank Erosion Hazard Index (Rosgen 1996) of Moderate, and a Channel Stability Evaluation (Pfankuch 1975) of Poor. Reference conditions for the same protocols rate Low and Good respectively. Streambank alteration by livestock was measured at three of these sites, and averaged 73%. All of the ten reference E reaches in the Gravelly Mountains of Montana in geologies similar to those at South Fork Blacktail Creek are E3 and E4 stream types (Rosgen 1996). In reference E4 stream types the amount of material less than 6 mm in size is 22%. For the eight sites in South Fork Blacktail Creek the average is 49% of the substrate less than 6 mm. The only management activities in the watershed are livestock grazing (109 AUMs per square mile) and dispersed recreation, which has a negligible effect on sediment production. There is one road in the watershed, with two stream crossings. In reviewing these data describing existing conditions and land use, it can be concluded that livestock grazing has created unstable stream channels that contain excessive fine sediment. It seems that conditions exist on the ground that would support the above analysis of suspended sediment concentrations and loadings.

It is the presence of livestock in the riparian area that leads to both changes in channel morphology and increases in sediment production. Trampling of stream banks increases width/depth ratios, while at the same time weakening stream banks, making them more susceptible to erosion. Additionally, hoof action on stream banks directly introduces sediment to the channel, and livestock walking in the channel disturb and entrain already deposited sediment. The analysis concerning the post-grazing time period demonstrates that the combination of these activities appreciably increases both concentration and loading of suspended sediment. During that period, sediment concentration is more livestock dependent than flow dependent (Figures 2-4). However, when livestock are present and flows are bankfull or greater, increased shear stress leads to particle detachment and higher loadings. It is likely that during the post-grazing period in low flow years, most of the sediment being entrained is generated by livestock moving in the channel and disturbing the bed and banks. When stream power increases with higher flows, more of the available sediment is entrained by erosion throughout the channel area.

Although most of the annual sediment load (68%) is created when livestock are not present, the stream bank alteration and bed disturbance by livestock during the grazing season create nearly continuous sediment sources that are available when stream flows rise in the spring. That these sources do indeed exist is evidenced by a comparison of physical channel parameters with reference conditions in similar valley bottoms. Increases in entrenchment, stream width, stream bank erosion hazard, and fine substrate material, coupled with a decrease in channel stability, all indicate changes in stream bank composition and sediment supply. Consequently, a high percentage of the 16.8 tons (15.2 metric tons) of sediment produced daily during the pre-grazing time period is attributable to livestock. These data enable us to assess the effectiveness of management on the allotment in terms of maintaining riparian condition and reducing sediment.

Notes taken prior to and during the period of measurement support the sediment data collected in the 1980s, and the stream surveys conducted in the 1990s. It is apparent that even with a rest-rotation system employed from the inception of cattle grazing, distribution of livestock was poor and use in the riparian area was excessive. In this case, simply implementing a rest-rotation system was not enough to protect riparian areas and stream channels from experiencing accelerated stream bank alteration and its associated sedimentation.

Combining the management history of the watershed with the suspended sediment data collected from 1986-1993, and with the stream survey data collected in 1995-1999, provides a comprehensive picture of the effect of livestock grazing on sediment production. The following conclusions can be drawn.

1. The presence of livestock during the summer months increases suspended sediment concentrations and loading. The increases are greater during years when bankfull flow is attained because more sediment sources are available and the increase in shear stress caused by higher flows leads to particle detachment. During bankfull years, post-grazing suspended sediment was increased by 430% during years when livestock were present. During low-flow years, post-grazing suspended sediment increased 157% over livestock-free periods. Livestock are responsible for about 5.6 tons per day of additional sediment during the post-grazing period.

2. Livestock trampling of streambanks has led to an increase in both channel entrenchment and the percent of fines in the channel. Comparing measurements of these parameters with reference data from within the South Fork Blacktail watershed shows large discrepancies between reference conditions and those surveyed reaches on the Southwest Corner Allotment. High levels of streambank alteration by livestock were measured at each of the surveyed reaches, suggesting a cause-effect relationship for the changes in entrenchment and fine sediment

3. The instability along streambanks created by livestock trampling provides sources of sediment available for in-channel erosion during periods of high flows. Because of the variability of peak flows, and the general flow dependency of sediment loading, this situation could well produce more sediment than the direct effect of livestock during low-flow periods.

4. The rest-rotation grazing system is not adequate by itself to prevent livestock damage to stream banks and the resulting increases in sediment. The Southwest Corner Allotment has been managed under a rest-rotation system since 1974, but has had relatively little successful livestock management within the pastures when cows are present. To maintain acceptable sediment levels in streams, effective herding is needed when livestock are present.

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# Using Multiple Fine-Sediment Size Classes to Evaluate the Condition of Trout Spawning Habitat

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Trout biomass and substrate samples from potential spawning areas were analyzed from 36 streams throughout the Monongahela National Forest, West Virginia to determine if trout biomass and sediment relationships on the forest were consistent with what is reported in scientific literature, and whether the data could provide additional insights into those relationships. Graphs of trout biomass plotted against various size fractions of substrate sediment show fairly large variability in the data, suggesting that fine sediment is only one of many factors that controls trout populations. Trout biomass did not change significantly as the percent of fine sediment < 4 mm diameter increased, showing that this more traditional metric is not applicable for the small sized trout found in this forest's streams. By contrast, trout biomass decreased significantly as the percentage of sediment < 1 mm diameter increased. The most important size class for predicting trout biomass was the < 1 mm fraction. Once sediment < 1 mm diameter comprised 45 percent of the < 4 mm fraction, trout biomass was almost always less than 20 kg/ha. Analyses of other individual particle sizes indicate that "good" spawning materials contain a mix of particle size classes. Consequently, we propose that the traditional single-size classification approach be replaced by an evaluation of multiple particle sizes. This approach, particularly when combined with data about other factors that could affect trout productivity, would provide a more thorough understanding of how management activities could affect trout or whether mitigations could improve stream conditions for trout.

Keywords: *sedimentation, stream substrate, trout, monitoring*

## Introduction

A wealth of literature supports the effects of sediment on salmonids in the North America. Unfortunately, much of that research has been performed in the laboratory or in controlled environments, such as flume experiments. There is a need to examine sediment relationships using field data, to determine how well results under controlled conditions compare with those in the field.

The Monongahela National Forest in West Virginia has conducted aquatic monitoring for more than two decades, including the routine collection of substrate sediment and fish data. The forest traditionally has evaluated stream conditions by classifying fine sediment as those < 4 mm diameter (Chapman 1988), as this size class is widely accepted as the critical one for salmonids. However, the < 4 mm diameter class was established primarily based on studies of western salmonids larger than those typically found in the eastern U.S., especially the salmonids of the inland East. Regional and local studies in the East have suggested that smaller particles are more important in affecting smaller fishes and their habitats. For example, Hausle and Coble (1976) and Argent and Flebbe (1999) reported a negative relationship between brook trout (*Salvelinus fontinalis*) egg and fry survival when fine sediments comprised 20-25 percent of the bed substrate. Hausle and Coble (1976) defined fine sediment as < 2 mm diameter, while Argent and Flebbe (1999) defined them as 0.43 to 0.85 mm. Peterson and Metcalfe (1981) showed that Atlantic salmon (*Salmo salar*) eggs had poorer survival in fine sediment defined as 0.06 to 0.5 mm diameter, when compared to fine sediment defined as 0.5 to 2.2 mm

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diameter. Hakala (2000) showed that sediment between 0.063 mm and 1 mm diameter had a negative effect on spawning substrate quality and brook trout populations in West Virginia.

Consequently, we wanted to examine data collected from the Monongahela National Forest's routine monitoring procedures to determine: 1) if they show relationships between trout biomass and sediment that are consistent with the literature; and 2) if the data already available from the monitoring program can provide additional useful insights. These questions are of more than just academic interest. For years the forest has used the literature to make statements about relationships between trout and sediment in a variety of documents, but it has not substantiated that those relationships apply to streams in the Monongahela National Forest. Being able to confirm some of the most basic relationships would strengthen the validity of statements in those documents. In terms of the second point, too often monitoring simply is done to fulfill a legal or institutional requirement without consideration of the long-term value for land management decisions. With the limited resources available for monitoring, it is critical to ensure that monitoring actually provides useful information.

## Methods

### Sites and Field Procedures

Forty-one streams across twelve land type associations on the Monongahela National Forest (Figure 1) were selected for fish sampling in 1999 because: 1) few data existed for these streams, 2) there was interest in examining the productivity of these streams, or 3) projects were planned in the watersheds in which they exist. While some data were available for several years since 1990, only the data from 1999 were used in this analysis; this data set was large enough for analysis without interjecting variability from multiple years of data collection with potentially greatly different streamflow conditions. In each stream, a 91.4-m representative reach was electrofished. Two passes were made moving upstream and two crewmembers netted shocked fish. Each fish was identified to species and weighed prior to returning them to the stream. Biomass was expressed as kg/ha of stream surface area.

Five streams (Beaver Creek of the Greenbrier River, Fox Run, Ken's Creek, Little Laurel Creek, and Mill Run, a tributary to Taylor Run) had either no fish in the sampled reaches or only non-game species of fish. The other 36 streams contained either native brook trout only or mixes of brook trout and non-native rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*) or both. In this paper we report only on the trout (both native and non-native) that were captured, though the relationships for all trout mirrored those of only brook trout. None of the sampled streams are stocked with fish, so the rainbow and brown trout originated from migrating individuals from off-site stocking.

During the same site visit, spawning gravel substrate were sampled from the same reach using shovel sampling (Grost et al. 1991). Shovel sampling entails pushing the blade into the desired location in the streambed to about half way up the length of the blade. The handle of the shovel then is pushed downward to lever the blade out of the bed. The shovel blade then is slowly lifted from the stream, and water is allowed to drain from the sample before storing it in a zipper-lock plastic bag. During extraction and transference to the bag, care is taken to avoid losing the smallest fraction of the sample.

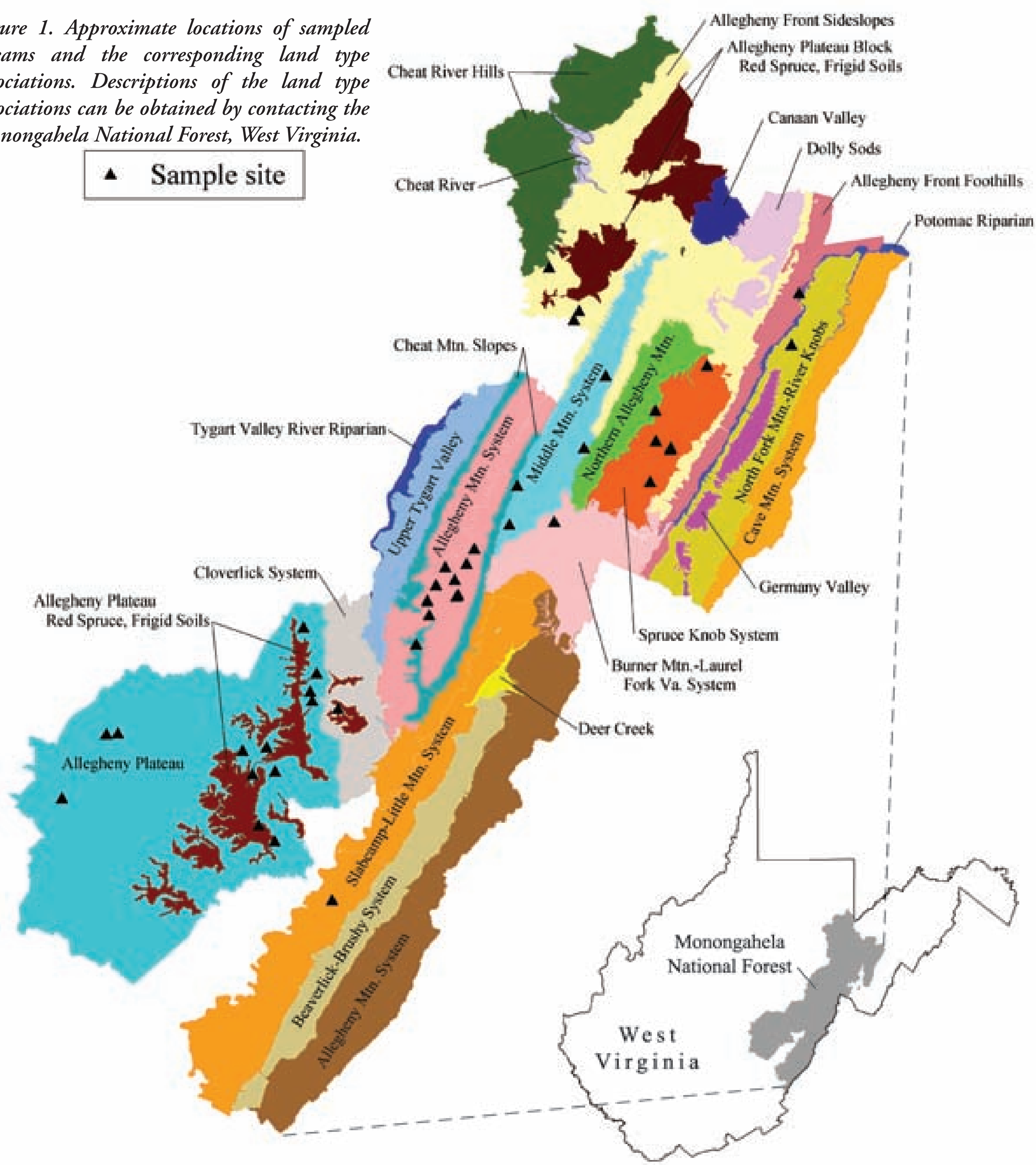
Six shovel samples were collected from six separate sites considered by the forest's fisheries biologist to have suitable characteristics for spawning. Suitable spawning materials were defined in terms of adequate substrate size (predominantly gravel to small gravel) and position in the channel (typically, but not exclusively, pool tails). Each shovel sample was placed in a separate zipper-lock plastic bag and processed individually. Samples were oven-dried at 100°C until they reached a constant weight. Each oven-dried sample was mechanically shaken through a nest of sieves [mesh sizes: 53.8 mm, 38.1 mm, 8 mm, 6.3 mm, 4 mm, 2 mm, 1 mm, and < 1 mm (i.e., pan)] for 7 minutes. The sample weight in each sieve was determined gravimetrically to the nearest gram.

Percent fine sediment of each sample was defined in two ways: < 4 mm diameter (cumulative weights of the materials in the pan, 1-mm, and 2-mm sieves), which is the procedure that the forest traditionally has used to define fine sediments, and < 1 mm diameter (the pan fraction). The latter was considered because a recent study by Hakala (2000) showed sediment between 0.063 mm and 1 mm diameter was most detrimental to brook trout in Monongahela National Forest streams. For the purposes of percentage computations, total sample weight was determined from the cumulative sample weights in only the 8-mm and smaller sieves, because the fisheries staff on the Monongahela has defined spawning materials as particles < 38.1 mm.

### Data Analysis

Mean fine sediment weights were determined for each stream reach based on the six samples. Mean percentages then were determined and are used in the analyses in this paper.

*Figure 1. Approximate locations of sampled streams and the corresponding land type associations. Descriptions of the land type associations can be obtained by contacting the Monongahela National Forest, West Virginia.*




To describe the general relationships between trout biomass and mean fine sediment values for all the sampled sites, trend lines were developed using locally weighted regression with Locfit software (Loader 1998). Locally weighted regression was used because this approach does not assume an a priori defined form of the fitted equation, such as linear, quadratic, etc. Thus, it can be used to provide a trend line that better describes the overall pattern of the data than one that has a more stringent user-defined form, particularly for trends that are difficult to determine visually. The degree value of the local polynomial and smoothing parameter for the locally weighted regressions were selected using procedures outlined by Cleveland (1994), in which the residual pattern was examined to assure the values of both parameters were appropriate and not over-fitted.

Because locally-weighted trend lines do not have associated slope and intercept coefficients, tests of significance were performed on the data, not on the trend lines. Mann-Kendall tests (Mann 1945) were run to determine whether the increases or decreases in the data were statistically significant. Because the data were relatively widely spread and there are other factors that can affect productivity, statistical significance was defined at p ≤ 0.10. Where trend lines showed a change in direction in trout biomass from increasing to decreasing or from increasing to leveling off, the data set was separated into two data sets at the inflection point and both were analyzed for significance.

Stepwise regression was used to determine the size classes that were most important to controlling trout biomass levels (SAS Institute Inc. 1988). Nonparametric correlation analysis (Spearman correlation analysis) was performed (SAS Institute Inc. 1988) to verify if the size classes that were identified as important were directly or indirectly related to trout biomass.

## Results

Trout biomass from all the sampled streams except one, Strader Run, fell within a wide, but well-defined range of 4.48 kg/ha to 99.7 kg/ha (Figure 2). The broad range of trout biomass found across the forest suggests, not surprisingly, that fine sediment is only one factor controlling fish productivity. For unknown reasons, Strader Run appears to be an anomaly for streams on the Monongahela, with a biomass of 168.1 kg/ha. Because of its atypical, extraordinarily high biomass and the potential for that single stream to bias the trend and statistical results, Strader Run was removed from the data set for all subsequent analyses.

Trout biomass relationships for the < 1 mm and < 4 mm fine sediment fractions are similar (Figures 2a and 2b, respectively). Most data are clustered and bounded by the dashed lines we inserted to better illustrate the common range of the data. If these streams are representative of streams throughout the forest, the lower and upper boundaries in Figures 2a and 2b suggest that few streams in the Monongahela have less than 4 percent of spawning materials composed of < 1 mm diameter fractions or less than 12 percent composed of < 4 mm particles, and greater than 18 percent composed of < 1 mm diameter fractions or greater than 45 percent composed of < 4 mm particles.

The general relationships between trout biomass and the percentages of sediment < 1 mm and < 4 mm diameters are illustrated by the trend lines fitted to the data (Figure 3a

*Figure 2. Relationships between trout biomass and fine sediment in potential spawning materials for fine sediment defined as (a) particles < 1 mm diameter and (b) particles < 4 mm diameter.*

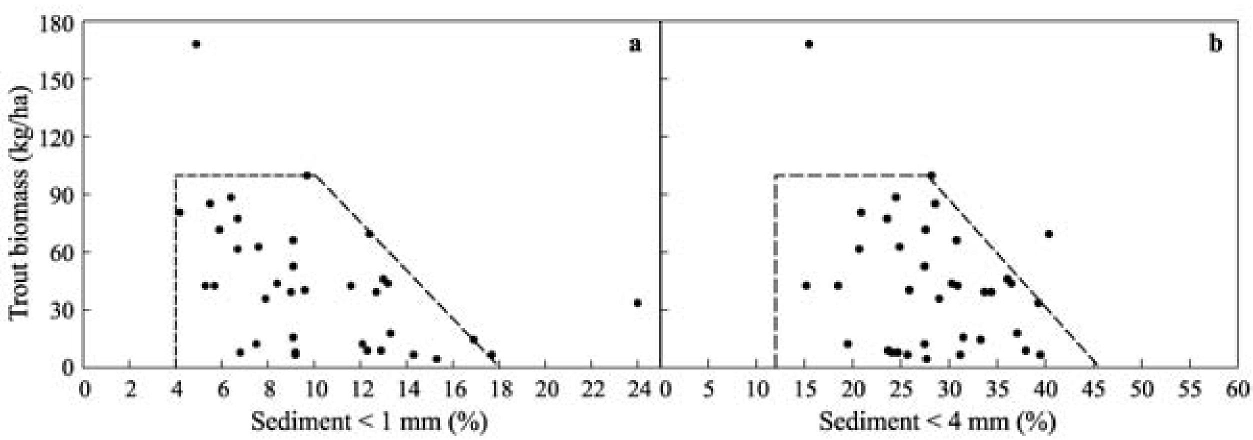
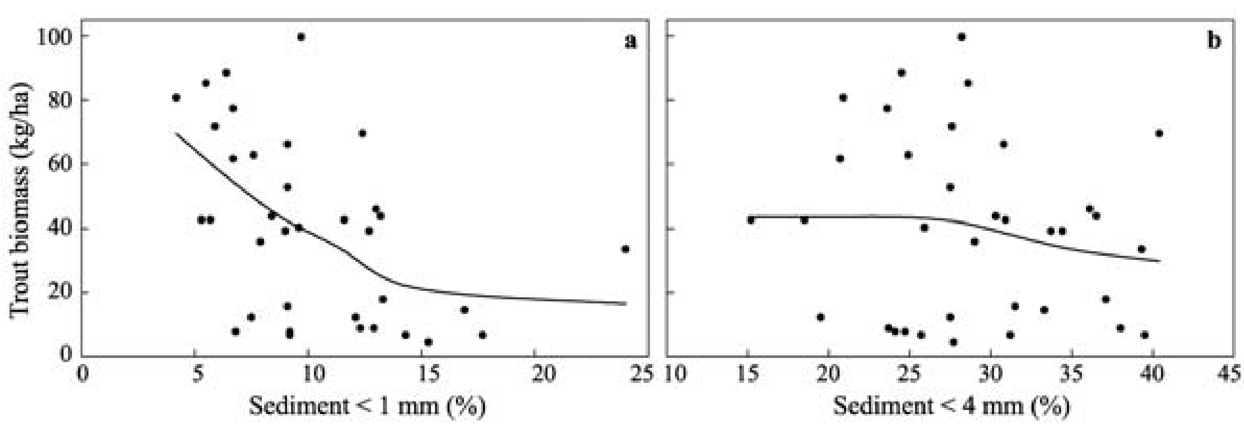
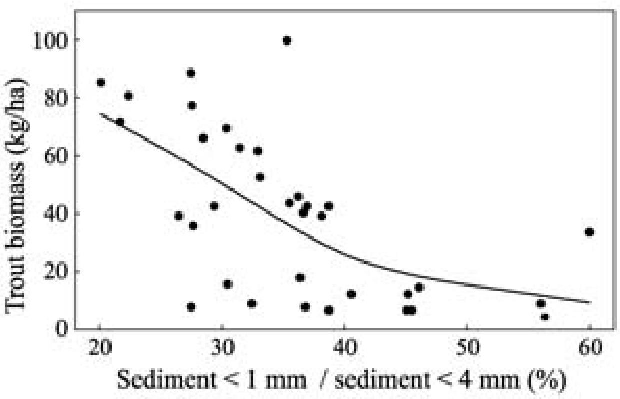



*Figure 3. Locally-weighted regression lines show trout biomass responses to increasing fine sediment in potential spawning materials for fine sediment defined as (a) particles < 1 mm diameter and (b) particles < 4 mm diameter.*



and 3b). Trout biomass decreased significantly (p = 0.002) as the percentage of < 1 mm sediment increased (Figure 3a). By contrast, trout biomass showed a much less distinct and not statistically significant response (p = 0.378) in relation to particles < 4 mm diameter (Figure 3b). Not surprisingly given the relationships in Figures 3a and 3b, as the percentage of < 1 mm particles increased relative to total fine sediment (i.e., < 4 mm) there was a corresponding significant (p = 0.000) reduction in trout biomass (Figure 4). When approximately 45 percent of total fine sediment was made up of < 1 mm materials, trout biomass was almost always less than 20 kg/ha.

*Figure 4. Trout biomass responses as < 1 mm particles in potential spawning materials become an increasing larger percentage of the < 4 mm fraction. The trend line was determined using locally-weighted regression.*




The distinct differences in trout biomass patterns between the individual < 1 mm size class compared to the cumulative < 4 mm size class illustrates the potential importance of considering size classes individually rather than cumulatively. Consequently, to obtain a clearer understanding of how individual sediment size classes are related to trout biomass, we examined trout biomass relative to the percentage of materials in each individual sieved particle size class (except for the < 1 mm size, which is presented in Figure 3a).

The trend line for the 1 to < 2 mm size fraction indicates that trout biomass increased and then decreased with increasing percentages of particles in that fraction (Figure 5a); however, the data are widely distributed and the probabilities of significance on both sides of the inflection point were not significant (p = 0.239 increasing trend line side; p = 0.779 decreasing trend line side). For the next two larger size fractions (2 to < 4 mm and 4 to < 6.3 mm), the trend lines for trout biomass increased with increasing percentages of these particles, and then reached a plateau (Figures 5b and 5c, respectively). The probabilities for the increasing portions of the 2 to < 4 mm and the 4 to < 6.3 mm fractions were significant (p = 0.008 and p = 0.092, respectively), but as the trend lines suggested, the data on the plateaus did not change significantly (p = 0.806 and p = 0.721, respectively). The point at which the trend lines leveled off occurred at a greater percentage than where the inflection point occurred for the 1 to < 2 mm fraction. This shift suggests these slightly larger particles are less deleterious to trout than the smaller ones. While the trend line for the 6.3 to < 8 mm fraction shows similar leveling off after increasing, it is difficult to say how trout are affected when the percentage of particles in the 6.3 to < 8 mm size class becomes large, because there was only one mean value that exceeded 12 percent. Consequently, the data were not separated into different sets for analysis of significance, and the data did not show any significant increase (p = 0.221). Trout biomass for the largest size spawning materials (8 to < 38.1 mm) returned to the same pattern as that exhibited by smaller sized particles, first increasing slightly then decreasing in response to increasing sediment (Figure 5e). The pattern of the trend line was not strong, and the analyses of the data indicate no significant changes in biomass on either side of the inflection point of the trend line, though the probability was approaching significance for the data on the increasing portion of the trend line (p = 0.127). Data on the decreasing portion had a significance of p = 0.272.

Obviously, these trend lines represent only the overall responses of the available data; they do not represent predictions of fish biomass for a specific sediment level in an individual stream. Indeed, one reason for using locally-weighted regression was to focus on the trends rather than inappropriately predicting biomass responses from sediment values based on a small data set. The shape of the trend lines is the important feature here, and the points of inflection should not be used as thresholds for defining the ideal allowable percentage of sediment in any size class. There simply is too much variation in biomass data because of the myriad limiting factors to use an inflection point derived from analysis of a single variable as a threshold.

The trend lines and statistical results do provide some useful preliminary information and insights, which should be validated further as more monitoring data become available. First, the < 1 mm particle size data are consistent with the general findings in the literature that fine sediment is detrimental to trout (Argent and Flebbe 1999; Hausle and Coble 1976; Phillips et al. 1975; Tappel and Bjornn 1983; van den Berghe and Gross 1989), and the more specific findings from a small set of streams in the Monongahela National Forest that particles of < 1 mm diameter have the most demonstrable negative effect on trout biomass (Hakala 2000). Second, defining fine

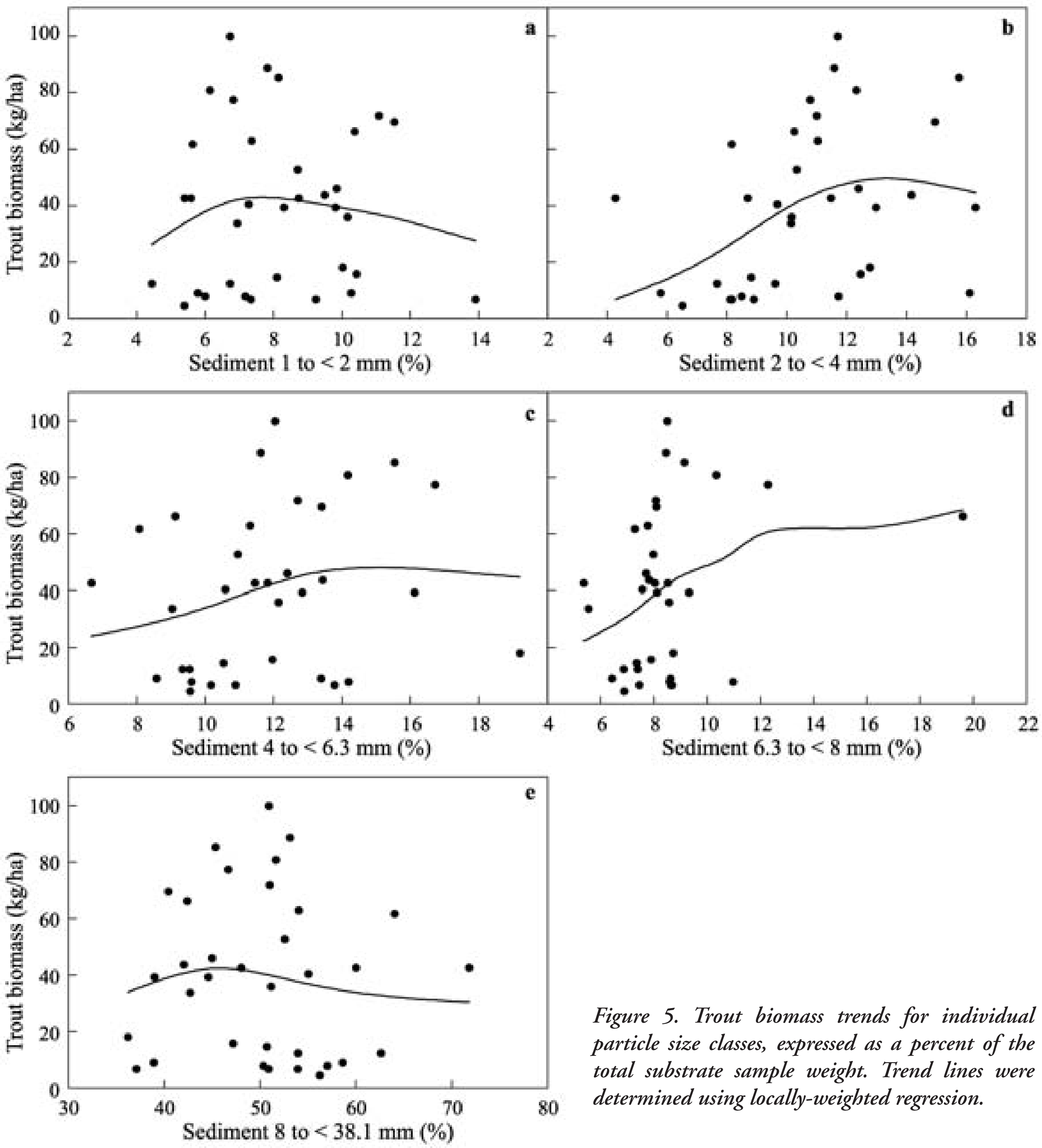



*Figure 5. Trout biomass trends for individual particle size classes, expressed as a percent of the total substrate sample weight. Trend lines were determined using locally-weighted regression.*

sediment as materials < 4 mm in diameter does not seem to be a useful metric for determining the suitability of spawning materials for the relatively small-sized trout found in the Monongahela National Forest. And third, the increasing and then decreasing or flattening patterns of the data and/or trend lines for particle sizes ≥ 1 mm suggest that the best spawning materials are ones that contain a mixture of particle sizes and are not dominated by a single size. Again, this is a general trend, and other conditions, such as water chemistry, habitat availability, and fishing pressure, will influence how well trout succeed in any individual stream.

As a result of these three findings, we propose that the traditional single-size classification approach be replaced with a multiple particle size analysis approach to evaluate the condition of spawning habitat or the extent to which sediment may be a limiting factor in a stream. Without knowing much else about a stream (which often is the case for many streams on public lands), simply determining the mix of particle sizes may indicate if sediment is a limiting factor for trout. A good mix of particle sizes seems to be one in which the intermediate class sizes (2 to < 4 mm, 4 to < 6 mm, 6 to < 8 mm) have percentages similar to each other and greater percentages than the smaller size classes, the < 1 mm size class is only a small percentage of the total spawning material, and the 8 to 38 mm diameter particles make up about half of the spawning material by weight.

Results from stepwise regression support the idea that a mixture of substrate size classes is important for trout success. This procedure is parametric and assumes each of the individual sediment size classes is independent of the others, which is not wholly true, but the results are illustrative nonetheless. In the model, the most important size class for predicting trout biomass was the < 1 mm fraction ($p = 0.0039$); this is not surprising based on the fairly strong (i.e., less variability in the data around the trend line than for other size classes) inverse relationships in Figures 3a and 4. The only other variable that was statistically significant in the stepwise regression was the 2 to < 4 mm fraction ($p = 0.0396$). Nonparametric correlation analysis showed trout biomass to be positively and significantly correlated with this fraction ($r = 0.42$, $p = 0.0114$), meaning that trout biomass generally increases with increasing percentages of 2 to < 4 mm materials, consistent with Figure 5b. The other intermediate size fractions (4 to < 6.3 mm and 6.3 to < 8 mm) and the 1 to < 2 mm fraction each were positively and significantly correlated to the 2 to < 4 mm size fraction ($r = 0.76$, 0.49, and 0.52, respectively, and $p \leq 0.0001$, 0.0026, and 0.0011, respectively). The high degrees of correlation explain why these other fractions were not significant in the stepwise regression; i.e., the contributions of each fraction to predicting trout biomass would have been duplicative with the 2 to < 4 mm class. The high degrees of correlation also support the idea that balanced percentages of these size classes provide the mixes of particle sizes that are conducive to trout success.

## Discussion

As stated earlier, our findings are only empirical, so we only can speculate about the mechanisms driving the responses. Since the samples were collected in potential spawning materials, it is perhaps most intuitive to make conclusions related directly to sediment effects on spawning, redd conditions, and egg development. Thus, the interpretation would be that very small particles hinder oxygen diffusion to eggs laid in redds and fry emergence (Chapman 1988). More-intermediate sized particles provide better conditions in terms of oxygen supply, better substrate for spawning use and success, or both.

However, the composition of spawning material in any reach is an index of the overall sediment composition throughout the reach, not just the spawning areas. Thus, one could reasonably assume that if very small sized sediment dominates spawning materials, other habitats in the reach also are affected by high percentages of very fine sediments. This parity simply could mean that poor physical conditions are ubiquitous in the stream reach and contribute to a lack of habitat variability, which would affect trout during all portions of their life cycle, as well food sources for the fish (Suttle et al. 2004).

The empirical relationships between trout biomass and the very smallest sized mineral materials also have implications relating to current on-the-ground activities-for example, selection of road-surfacing materials. Research by Kochenderfer and Helvey (1987) in the Monongahela National Forest found that 38.1-76.2 mm clean limestone gravel provided a stronger roadbed and less surface erosion than crusher run limestone gravel (0-76.2 mm). Finer materials, including crusher run types of gravel, are usually recommended on older, well-established roads because they create a smoother riding surface, but they are more apt to experience washing (Kochenderfer and Helvey 1987) and "kicking" off of the driving surface by vehicles. Consequently, the combination of our findings and this road research suggest that fine-sized road surfacing particles should be avoided on new road construction, particularly around stream crossings and their approaches, and around water diversion features, such as cross drain culverts and broad-based dips. In addition, on established roads, small-sized, angular stone (to improve packing) composed of stable material (e.g., limestone rather than friable sandstone) would be less detrimental to streams than stone that grades down to very fine-sized particles.

The deleterious effects of even low levels of the finest-sized sediment also may mean that sediment delivery to streams needs to be controlled much more vigorously than is often done. Implementation of sediment control practices that extend beyond those routinely recommended in forestry best management practices may be needed to control the introduction of very fine sediments, as these can be dislodged and transported by even small amounts of water, such as those encountered during small storm events. Installation of silt fences, straw bales, geotextiles, or other sediment retention methods immediately around stream crossings or other sensitive areas may be required in all cases, not just in some cases or at the equipment operator's discretion.

We believe the general relationships we observed between trout biomass and the very small sediment particle sizes, and between trout biomass and the mixture of more intermediate particle sizes probably apply to other streams in the Appalachians that hold similar communities of similarly sized fish. Of course, given the broad range of biomass occurring with the various sediment size classes, it is important to re-emphasize what may be obvious.

Sediment may not be, and probably is not, the only limiting factor in many stream systems, but sediment should be one of the variables that is evaluated when reviewing overall stream conditions. A thorough understanding of stream conditions and potential limiting factors is necessary to determine if a proposed project or a routine activity will significantly affect stream health, or if dollars spent on mitigation to improve conditions will target important factors or be wasted because other factors are equally or more important in controlling fisheries health.

## Conclusion

Trout biomass and associated particle size data from likely spawning materials in reaches from streams across the Monongahela National Forest were examined. The results indicated that the traditional classification of fine sediment as materials < 4 mm in diameter is not a useful metric by which to evaluate spawning materials conditions for small-sized trout on the forest. Instead, we recommend a simultaneous analysis of all available size fractions, paying particular attention to the percentage of materials in the < 1 mm fraction and the percentages of more intermediate particle sizes. The best spawning materials likely are ones that contain a mixture of particle sizes and are not dominated by a single size. Of course, combining information about other stream conditions or limiting factors in the assessment of spawning conditions should further improve any conclusions made, help identify the need for and types of mitigation strategies used during forest management activities, or suggest how routine on-the-ground procedures can be modified to positively affect stream health.

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# Water Quality Effects of Blue-Green Algal Blooms in Diamond Lake, Oregon

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In 2001, a serious bloom of potentially toxic cyanobacteria (blue-green algae) developed in Diamond Lake, a popular recreational lake in the Umpqua National Forest (UNF), Oregon. Toxins produced by cyanobacteria have been implicated in human health problems ranging from skin irritation and gastrointestinal upset, to death from liver or respiratory failure. Blooms have continued at Diamond Lake since 2001 and prompted a call for action to control the problem. In the interim, a strategy was developed to deal with the public health threat posed by cyanobacteria. UNF staff, working with private and government organizations, developed a plan to monitor the lake. Results from the monitoring program were interpreted in light of the World Health Organization (WHO) guidelines for toxic cyanobacteria species. We describe this effort and offer lessons learned to other lake managers faced with similar issues.

Keywords: *aquatic ecosystems, paleoecology, history, water quality, lakes, recreation, public health, cyanobacteria, blue-green algae, aquatic/riparian habitat*

## Introduction

Diamond Lake is a 1300 ha lake located at an elevation of about 1600 m in the central Oregon Cascade Range (Figure 1). This relatively shallow lake (maximum depth 15 m) is located immediately north of Crater Lake National Park in the Umpqua National Forest. The lake watershed is wholly contained within the national forest and national park. Diamond Lake was probably fishless before 1910 when rainbow trout (*Oncorhynchus mykiss*) stocking began. In a typical year, the Oregon Department of Fish and Wildlife (ODFW) stocked as many as 1,000,000 trout fry from a hatchery at the lake. A lodge, 100 summer homes, and three Forest Service campgrounds were built from 1920 to the 1960s. A successful trout fishery was interrupted when tui chub (*Gila bicolor*) were introduced, likely as bait fish, and caused the sport fishery to collapse in the 1940s.

In 1954 the lake was treated with rotenone and rainbow trout were restocked the following spring. The trout fishery was successful and remained so until the 1990s when tui chub were discovered in the lake once again. Efforts began to respond to the tui chub and the decline in the trout fishery, but no one was prepared for the apparent effect of the chub on water quality in Diamond Lake. In 2001, following a routine sampling of the lake, we discovered that the lake contained a high density of *Anabaena flos-aquae*, a potentially toxic species of cyanobacteria.

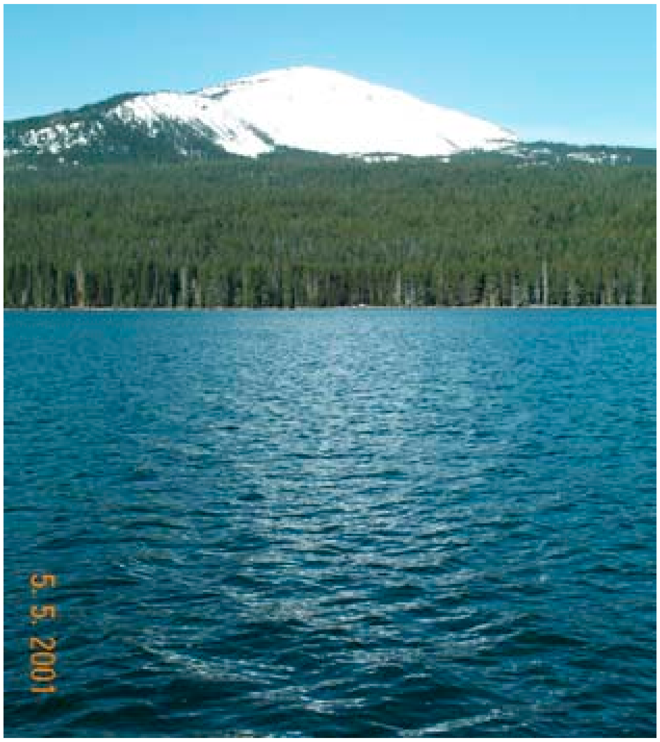
This paper describes Diamond Lake, Oregon, and potentially harmful blue-green algae blooms. We recount the public health actions taken during dense blooms of the blue-green alga *Anabaena flos-aquae* during the summers of 2001-2004, and the role water quality monitoring played in recognizing and responding to the public health risk. Finally, we list some lessons learned by the UNF that may apply to other water bodies.

## Diamond Lake Description and History

Diamond Lake is a popular recreational site in the Umpqua National Forest (Figure 2). The primary attraction in summer has always been the abundant trout fishery, although the proximity to Crater Lake, the spectacular scenery, and hiking opportunities draw many other visitors. At the height of its use in the late 1970s, Diamond Lake drew over 780,000 visitors per year. With the collapse of the trout fishery, that use is now a fraction of its peak.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

*Figure 1. Diamond Lake, Oregon (photo by Joseph Eilers).*




Efforts have been made to expand other uses, including water skiing.

The lake experienced algal blooms during the 1960s, and in 1998 Diamond Lake was placed on the Oregon 303(d) list of water bodies not meeting water quality standards for pH and nuisance algae. Earlier investigations indicated that the lake was productive either from natural inputs of phosphorus (Lauer et al. 1979), or from human development of the shoreline (Meyerhoff et al. 1977). Subsequent investigations also reinforced the notion that the lake was becoming culturally eutrophic (Salinas and Larson 1995). A sediment core collected in 1996 (Eilers et al. 2001) indicated that there might be a link between the fish populations and water quality in the lake, but no one was prepared for the rapid change in 2001 (USDA Forest Service 2004a, 2004b).

**History of Diamond Lake, Oregon, 1910-2001**

1910s - Fish stocking begins and fishery is highly successful
1920 - 1950 - Lodge, campgrounds and 100 summer homes built
1950s - Tui chub population explodes
1954 - Lake is treated with rotenone
1990s - Tui chub return and recreational fishery crashes
2001- Severe *Anabaena flos-aquae* blooms begin

The UNF routinely sampled Diamond Lake monthly each summer, beginning in 1992. The sampling included in-situ measurements of pH, dissolved oxygen and collection of zooplankton and phytoplankton samples (Table 1). During June 2001, the lake water appeared noticeably chalky and blue-green, but no attempt was made to expedite the analyses of the biological samples. An ad hoc sample collected in July was analyzed privately and the results revealed the presence of a dense population of *Anabaena flos-aquae* (JM Eilers, MaxDepth Aquatics, Inc., Bend, Oregon, personal communication, 2001). As of 25 July 2001 the bloom had a density of about 100,000 cells/mL and by early August the density reached 575,000 cells/mL. Samples analyzed by Wright State University, Dayton, Ohio, confirmed the presence of the algal toxins anatoxin-a and microcystin from 6 August through 28 August. Maximum anatoxin-a concentration was reported as 310 µg/L and represented a risk to human health from water contact and accidental ingestion (Eilers and Kann 2002). The 2001 peak anatoxin-a concentration was determined from a phytoplankton sample obtained by towing an 80-micron mesh net. The value was later revised to an estimate of 15.0 µg/L (Kann 2005). In previous sampling from 1992 to 2000, the highest estimated density of *Anabaena flos-aquae* was 8,540 cells/mL. The summer

***Table 1 - Water quality and lake morphometry for Diamond Lake, Oregon (Eilers et al. 2001; Johnson et al. 1985; Salinas and Larson 1995).***

| Parameter | Median | 1992-1995 | 1967-1995 |
|---|---|---|---|
| pH | 8.6 | 7.16-9.23 | 7.1-9.8 |
| Chlorophyll a (µg/L) | 6.8 | 2.6-8.3 | 1.0-39.8 |
| Total phosphorus (µg/L) | 45 | 17-62 | 17-62[a] |
| Total inorganic N (µg/L) | 64 | <16-88 | <16-322 [b] |
| Silica (mg/L) | 3.8 | 1.9-3.7 | 1.9-6.5 |
| Conductivity (µS/cm) | 39.8 | 38.3-40.9 | |
| Alkalinity (µeq/L) | 412 | 396-421 | |
| **Morphometry** | | | |
| Lake area (ha) | 1,300 | | |
| Watershed area (ha) | 13,600 | | |
| Maximum depth (m) | 15.8 | | |
| Mean depth (m) | 7.3 | | |
| Lake volume(hm) | 95.1 | | |
| Hydraulic residence time (yr) | 0.6[c]-1.6[d] | | |
| Lake elevation (m) | 1,580 | | |
| Max. watershed elevation (m) | 2,799 | | |

*[a] excluding one observation of 140 µg/L 1976.*
*[b] excluding one observation of 385 µg/L 1967.*
*[c] estimate based on precipitation volume inputs for the topographic watershed.*
*[d] estimate based on surface discharge from the lake outlet (Johnson et al. 1985).*


*Figure 2.. Diamond Lake, Oregon map.*

of 2001 was the first time since the UNF began systematic sampling of Diamond Lake, that potentially harmful blue-green algae made up 80 percent of the biomass of any given sample (Eilers and Kann 2002).

## Public Health Issues

The chalky, aqua-green appearance of the lake provided a visual clue that something was amiss with the lake, making it easier to communicate with the public and professionals alike (Figure 3). The UNF had to address several issues. These included:

1. What was the significance of the phytoplankton data, with respect to the public health threat of *Anabaena flos-aquae*?
2. If the blooms did present a public health concern, what action should be taken by the Forest Service and other agencies?
3. How should the UNF communicate with the public?
4. How should the UNF determine when the public health concern has abated?

First we needed to interpret the data. Forest Service hydrologists are not usually familiar with toxic cyanobacteria. At the time this issue arose, neither the State of Oregon nor the U.S. Environmental Protection Agency provided criteria or guidelines dealing with water pollution threats from cyanobacteria. To understand the problem, we turned to experts in the field of cyanobacteria (Dr. Jacob Kann) and cyanobacteria toxins (Dr. Wayne Carmichael). Their advice was to use the guidelines provided by the World Health Organization (WHO) regarding public health risks associated with cyanobacteria and their toxins.

The World Health Organization and American Water Works Association (Chorus and Bartram 1999; Yoo et al. 1995) recommend that blue-green algae densities exceeding 500 cells/mL should be monitored closely. This is Alert Level 1, where greater sampling frequency and


*Figure 3. Diamond Lake, Oregon cyanobacteria bloom. Photo by Joseph Eilers.*

spatial coverage may begin. Alert Level 2 occurs when cell densities reach 2,000 cells/mL and warnings are posted for the general public. Alert Level 3 occurs when density reaches 15,000 cells/mL and people are warned to avoid contact with lake water. Alert Level 4 is reached when blue-green algae density exceeds 100,000 cells/mL. At Alert Level 4 lakes all uses should be curtailed, including boating and fishing (Table 2). These human health guidelines are relatively conservative with respect to toxin concentrations expected at the above alert levels. However, because dense wind-driven shoreline accumulations can occur as these buoyant algal cells rapidly rise to the water surface, a sample of toxigenic algae may have a cell density from 100 to 1,000 times higher an hour later or a even few hundred yards away (Eilers and Kann 2002). Thus, these guidelines provide discrete levels of response to minimize the risk of exposure to toxic cyanobacteria.

During this investigation period we learned that there are multiple toxins produced by various species and strains of cyanobacteria, and that other countries are also coping with this threat (Chorus and Bartram 1999). The science of blue-green algae is complicated and evolving. Some species never produce harmful toxins, and some species produce toxin only at certain times. Sunlight, calm water, and warm temperatures often produce high densities of algae near the surface. Blue-green algae are most likely to produce toxin when cell density is high. The species dominant in Diamond Lake, *Anabaena flos-aquae*, most commonly produces anatoxin-a, a neurotoxin with a toxicity rivaling that of cobra venom on a mass basis (Table 3). However, *A. flos-aquae* is also capable of producing microcystin, a hepatotoxin with cumulative long-term effects. Symptoms of neurotoxin exposure include skin irritation or rash, diarrhea, nausea, cramps or general tiredness, sensations of numbness, dizziness, tingling and fainting, dermatitis and gastroenteritis (Douglas County 2004).

Occasional human illness and deaths occur around the world from cyanobacteria toxins in water. In Oregon, several dogs have died along the John Day River since 2001, and a young man died in Wisconsin in 2002 after swimming in a golf course pond (Wisconsin State Journal 2003). Toxins produced by blue-green algae can have acute and chronic effects. Mammals are vulnerable

*Table 2. Guidelines for water contact and monitoring during cyanobacterial blooms (Chorus and Bartram 1999; Yoo et al.1995).*

| Alert Level | Cyanobacteria (cells/mL) | Advisory | Monitoring |
|---|---|---|---|
| 1 | 500 | None | Weekly phytoplankton only, increase shoreline sites |
| 2 | 2,000 | Avoid scums | Weekly phytoplankton and toxin at one site of maximum phytoplankton density |
| 3 | 15,000 | No swimming, waterskiing, or pets in water | Weekly phytoplankton and toxin at all sites with phytoplankton density greater than 15,000 cells/mL |
| 4 | 100,000 | Lake closed to all uses | Weekly phytoplankton and toxin at all sites with phytoplankton density greater than 15,000 cells/mL |

*Table 3. Comparison of toxins. Cyanobacteria toxins are in bold. From Skulberg et al.(1984).*

| Toxin | Source | $LD_{50}$ (μg/kg) |
|---|---|---|
| Muscarine | Amanita mushroom | 1,100 |
| **Anatoxin** | **Anabaena** | 250 |
| **Microcystin** | **Microcystis** | 60 |
| Neurotoxin | Cobra snake venom | 20 |
| **Aphantoxin** | **Aphanizomenon** | 10 |

to toxins, but less is known about immediate effects and bioaccumulation in fish. In 2004, the Oregon Department of Human Services advised people not to consume fish from Paulina Lake when *Anabaena flos-aquae* density was greater than 1,000,000 cells/mL (Oregon Department of Human Services 2004).

## Response to the 2001 Bloom

At Diamond Lake, it became clear that a real public health threat was present. The Forest Service asked for help from the Douglas County and State of Oregon health departments, the Oregon Department of Environmental Quality (ODEQ), and other scientists who had experience with blue-green algal blooms. The UNF established an incident management team with public communications, lake management, water quality and public health specialists. A plan was quickly developed and implemented based on the WHO guidelines. Water contact warnings were posted at the lake.

In order to increase the likelihood that the public response would comply with warnings, the team developed a public communications strategy. Communications involved the Diamond Lake Ranger District, Diamond Lake homeowners, and the Diamond Lake Lodge. The Forest Service and Douglas County posted signs at boat ramps, campgrounds, and entrance roads around the lake. Press releases were distributed to local and regional newspapers, television and radio. The blue-green algae bloom and the potential public health risk at Diamond Lake became well known.

The Umpqua National Forest and Douglas County Department of Health and Social Services closed two swimming beaches on 10 August. All swimming, water skiing and boating were prohibited from 17 August until 27 August, when *Anabaena flos-aquae*, anatoxin-a, and microcystin tests results showed that lake water was safe (Figure 4).

Once the public was warned, we focused our attention on monitoring cyanobacteria, in order to determine when the threat had diminished sufficiently to allow full use of the lake. Fortunately, Diamond Lake is not a public drinking water supply and monitoring only needed to address recreational contact. A monitoring program was designed (M. Jones, Umpqua National Forest, Roseburg, Oregon, personal communication, 2004) that linked the intensity and frequency of sampling to the density of the cyanobacteria. Although *Anabaena flos-aquae* density fell below 1,000 cells/mL by mid-August, water contact was restricted for 10 more days because toxins produced by cyanobacteria remain harmful after the cells have died and lysed. This additional period of safety is required during the post-bloom period. The incident management team met throughout the summer to manage water quality monitoring, public health measures, recreation activities and public information. No documented cases of human health effects from blue-green algae at Diamond Lake are known. Public health measures limited human exposure to blue-green algae during part of the bloom in 2001.

## Beyond 2001

Although the end of the bloom in 2001 provided a welcome relief from the work of responding to the

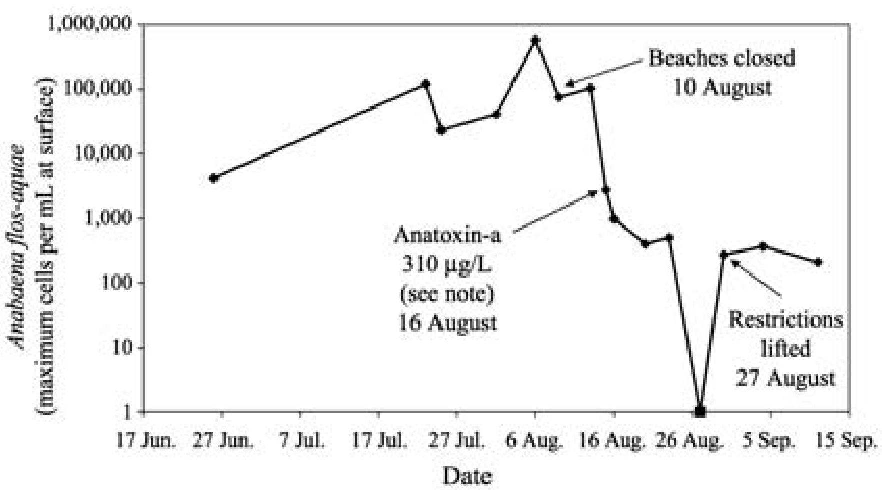



*Figure 4. Cyanobacteria bloom, Diamond Lake, Oregon 2001. Anatoxin-a peak later revised to 15.0 ug/L (see text).*

*Table 4. History of management actions at Diamond Lake, Oregon, 2001-2004.*

| Alert Level | Action | Cyanobacteria (cells/mL) | Date Alert Level Reached in Each Year | | | |
|---|---|---|---|---|---|---|
| | | | 2001 | 2002 | 2003 | 2004 |
| Level 1 | Begin sampling | 500 | 26 June[a] | 6 May | 28 May | 10 May |
| Level 2 | Warning | 2,000 | 10 Aug. | 27 June | 27 June[b] | 16 July |
| Level 3 | Water contact restriction | 15,000 | 10 Aug. | 23 July (to 7 Aug.) | 1 July (to 8 Aug.) | None |
| Level 4 | All uses (boat) restricted | 100,000 | 17 Aug. (to 25 Aug.) | None | None | None |
| All Alerts Lifted | | | 27 Aug. | 31 Aug.[b] | 28 Aug.[b] | 27 Aug.[b] |

*[a] Sampling began after Alert Level 1 (500 cells/mL) blue-green algae density was reached.*
*[b] Date is approximate, based on blue-green algae density records.*

cyanobacteria bloom, a number of questions needed to be answered before the summer of 2002. These included:

1. What was the cause of the cyanobacteria bloom in 2001?
2. Was this an isolated event or could another bloom be expected?
3. How should we monitor for blooms in the future?
4. What was the level of risk to the public?

To answer these and other questions, we needed a systematic way to organize the data collected in 2001 and earlier years. From 1992 to 2001, the UNF contracted to sample the lake about three times per summer. During 2001, the lake was sampled much more frequently and additional short-term investigations were conducted to evaluate spatial and temporal aspects of the cyanobacteria and associated water quality. These efforts by the Forest Service staff, ODFW, ODEQ, and contract scientists produced a tremendous amount of data that had not been organized. These data and others were arranged into a Microsoft Access®[1] database and interpreted in light of the questions listed above (Eilers and Kann 2002). The Access® database made it possible to both review the conditions associated with the bloom in 2001 and provide a framework for organizing data in the future. The data could then be easily shared among interested parties and researchers studying Diamond Lake.

One conclusion from the analysis of the 2001 data was that lake monitoring needed to begin earlier in the spring during rapidly changing conditions. We sampled more frequently in 2002, using pre-assigned stations for shoreline sampling when the bloom occurred. We made arrangements with phycologists for rapid analysis of the phytoplankton samples. We searched for information on cyanobacteria and prepared information sheets to answer frequently asked questions. Paleolimnological analysis of a sediment core collected in October 2000 (in a study funded by ODFW related to the effect of the tui chub) showed a strong linkage between fish populations and the abundance of cyanobacteria in Diamond Lake (Eilers et al. 2001). The serious cyanobacteria bloom in 2001 made it possible to accelerate several research projects on the lake. The result was a new bathymetric map of the lake, a map of the macrophyte beds, the discovery of ebullition zones (depressions with bubbles emerging), a substrate map of the lake, and a hydroacoustic analysis of fish abundance (Eilers and Gubala 2003).

By the time of ice-out in April 2002, new monitoring and communications plans were ready. Research was underway to better understand the relationship between fish populations and cyanobacteria blooms at Diamond Lake. The Diamond Lake Lodge cooperated by conducting daily measurements of lake transparency with a Secchi disk This low-cost information helped track phytoplankton population trends with immediate results (Figure 5).

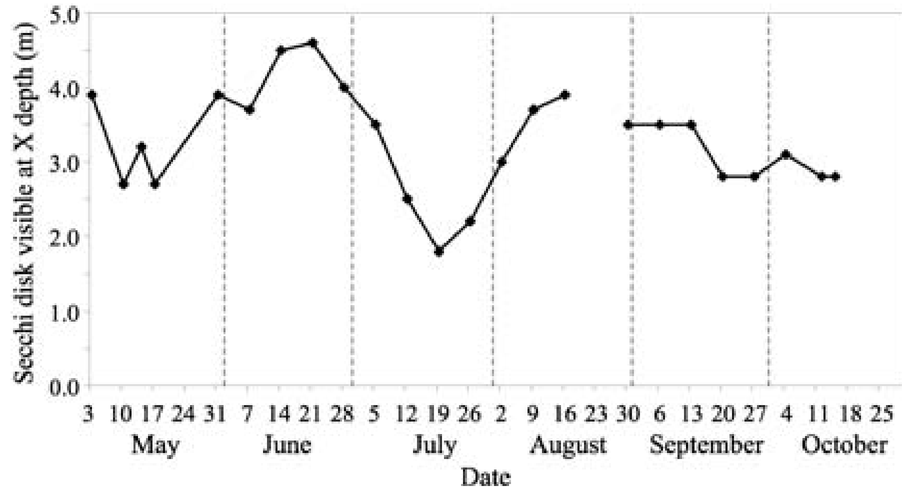
Dense blue-green algae blooms have occurred on Diamond Lake every summer since 2001. Three of four summers, *Anabaena flos-aquae* densities were higher than 15,000 cells/mL, and water contact by people and pets was prohibited for two to five weeks (Table 4).

## Current Protocol for Toxic Algae Monitoring and Alerts

From May through September Diamond Lake Ranger District collects phytoplankton samples from the center of the lake on Monday of each week. These samples are sent overnight to Aquatic Analysts laboratory for analysis of species composition and density. The results arrive the following Thursday. If *Anabaena flos-aquae* densities exceed 500 cells/mL, two additional shoreline sites are sampled the following week. If densities exceed 2,000 cells/mL, one sample is sent to Wright State University for toxin analysis.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

*Figure 5. Secchi depth visibility, Diamond Lake, Oregon, 2004.*




Toxin samples are collected from all sites with densities greater than 15,000 cells/mL (Table 2). Together, the Umpqua National Forest and Douglas County Department of Health and Social Services decide whether to change alert levels for the upcoming weekend.

The marina manager at Diamond Lake Lodge measures Secchi depth, water temperature and wind speed weekly, so we know quickly if algae density is increasing or decreasing.

All lake management decisions are based on blue-green algae densities, rather than specific toxin levels, because tests for phytoplankton identification and density cost about $100-250 per sample and results are available the same week. Toxin results can take as long as six weeks, and cost about $500. These samples are used to document whether toxin was present when swimmers were in the water. Cyanobacteria do not always produce toxin, even during a dense bloom. Lake managers can err by keeping people out of the water when no toxin is present, or by failing to issue warnings when toxin is present. Both errors have consequences. In the first case, people will be disappointed and business will suffer when there is little risk. In the second, people or pets may be harmed if they're exposed to algae toxin. Toxin tests are used to document whether water contact was restricted appropriately.

In order to avoid sending conflicting or complicated messages to the public, it's important not to change alert levels often. Health alerts and restrictions are the most useful when they are clear and consistent. At Diamond Lake, Level 2 advisories are usually posted June to August each summer, and a Level 3 water contact restriction issued once during the peak blue-green algae bloom. A Level 4 restriction on all lake uses, including boating, was used only once after *Anabaena flos-aquae* cell densities reached several hundred thousand cells/mL in the summer of 2001.

## Water Quality Monitoring

Water quality monitoring can help recognize changes in lake ecology. In 1992, there was no reason to expect algae or water quality problems, but not much was known about Diamond Lake. The Umpqua National Forest and Rogue Community College, Grants Pass, Oregon, sampled Diamond Lake in June, July and August every summer from 1992 to 2002. Occasional March, April, May and September profiles in the deep lake center and other, shallower locations (including under-the-ice spring sample dates) were sampled in some years. Similar monitoring continues to the present.

Measurements taken in the middle of Diamond Lake in July 2004 are typical of the summer blue-green algae bloom. A Secchi disk was visible to only 1.8 meters, the surface water temperature was 20°C, and pH was 8.9. Dissolved oxygen at the surface was almost saturated at 9 mg/L (Raymond 2004). Lake pH is increasing, the lake bottom is increasingly anoxic, and algal blooms are changing nitrogen and phosphorus levels in the lake (Table 5). Algae consume the high natural phosphorus, and nitrogen fixation by blue-green algae adds organic nitrogen.

Lake biology is changing too. Introduced rainbow trout, and millions of tui chub, are feeding on invertebrates and zooplankton. Large benthic amphipods are declining, with a shift to smaller invertebrates. The lake is experiencing a loss of the large zooplankton taxa. Large cladocerans that fish prefer have disappeared. Fewer than 10 percent of the individual zooplankton in Diamond Lake in the 2003 summer were edible by planktivorous fish. The lake is now dominated by very small rotifers that are not effective phytoplankton grazers and provide little food for fish (Table 6). Phytoplankton samples also show that *Anabaena flos-aquae* are dominating the July and August algae bloom for the first time since 1992.

*Table 5. Diamond Lake chemical changes.*

| Parameter | 1900[a] | 1975 | 2003 |
|---|---|---|---|
| Lake $PO_4$ phosphorus | ~30 µg/L | 15 µg/L | 0-5 µg/L |
| Lake TKN organic nitrogen | low | moderate | high |
| Surface pH | 8.0 | 9.0 | 9.5 |
| Anoxic hypolimnion | probably rare | 50% of years | annual |

[a] *Speculation based on paleolimnological data.*

*Table 6. Diamond Lake biological changes.*

| Parameter | 1900[a] | 1975 | 2003 |
|---|---|---|---|
| Benthos | amphipods | chironomids + amphipods | chironomids |
| Zooplankton | copepods | cladocerans | rotifers |
| Phytoplankton | chrysophytes + centric diatoms | mixed | cyanobacteria + pinnate diatoms |
| Macrophyte depth | ~ 9 m | 8 m | 6 m |
| Fish | none | trout | tui chub |

[a] *Speculation based on paleolimnological data.*

The experience acquired from 1992 to 2000 helped the Umpqua National Forest expand monitoring activities at Diamond Lake. We had already consulted knowledgeable limnologists, hydrologists and laboratories. We knew how to collect samples for physical and biological analyses, preserve the samples and interpret the results. When it was obvious that *Anabaena flos-aquae* presented a health risk to swimmers, we were able to collect algae and toxin samples and get results quicker.

## Lessons Learned

Dense blue-green algae blooms have occurred on the Diamond Lake every summer since 2001. In three of four summers, *Anabaena flos-aquae* densities were higher than 15,000 cells/mL, and water contact by people and pets was restricted. Visitors to Diamond Lake Lodge and Forest Service campgrounds, and 100 summer home owners accommodate these restrictions by avoiding water contact, fishing from docks and boats, and following press releases to decide what activities are safe. The Umpqua National Forest and the Douglas County and Oregon health departments work together each summer to keep Diamond Lake open for all uses except when there is a risk to public health. Together, the agencies restricted swimming for up to five weeks during the summer since 2001 and no human health effects were documented.

The Umpqua National Forest now has a clear monitoring scheme and guidelines for swimming restrictions, so we can tell visitors quickly when there is a potential risk from cyanobacteria toxins. In 2001, we learned the value of recognizing a problem quickly, working with health officials, and using clear guidelines to tell the public what we knew.

Blue-green algae blooms can appear suddenly, and can be a serious health risk. We offer the following advice to others with potentially harmful blue-green algae blooms:

- Give lake managers the information they need to make good decisions in the midst of controversy. Blue-green algae blooms in water bodies that are used for drinking water may present the highest risk of exposure to toxins.
- Get help from experts, and work together with state and local health departments. Use the incident command system in emergency situations.
- Use clear guidelines. Health departments are trained to handle public health situations. Develop standard signs, warnings, and press releases.
- Increase sample frequency and sample locations as risk increases. If you have a routine monitoring program, you'll know where to send samples and what the results mean. Write a monitoring plan and document the research you used.
- Develop monitoring protocols, use quality control procedures, and manage your data. That includes keeping a record of when warnings were issued and when they were lifted.

Our experience at Diamond Lake is one example of how water quality monitoring can help recognize water quality problems and protect public health on National Forests.

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# Delineation of a Karst Watershed on Prince of Wales Island, Southeast Alaska

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Karst systems have developed in the extensive areas of carbonate bedrock underlying portions of the Tongass National Forest, southeast Alaska. Karst development includes losing streams, sinks, caves, grikes, and resurgence streams. Many of the resurgence streams maintain productive salmon populations important to local culture and economics. Identifying source areas of resurgence streams is crucial to protecting water quality and watershed planning in karst ecosystems. Historically, watershed assessments have only considered topographic boundaries when defining various watersheds. This method is difficult in karst areas where surface waters are rare. Two projects on northern Prince of Wales Island, part of the Thorne Bay Ranger District, have employed tracer dye studies to illustrate the complexity of karst systems, and help redefine watershed boundaries to assist in watershed planning efforts. Through dye trace tests we were able to identify subsurface flow pathways, identify downstream effects, and better assess cumulative effects on a watershed scale. Success of groundwater tracing efforts hinged on locating the springs that feed coastal streams. This required careful inventory of shorelines and margins of the carbonate outcrops. Activated charcoal packets were anchored within these streams and springs to absorb dye. Tracer dye injection points were generally discrete karst features where surface waters enter the systems. The charcoal packets were recovered at intervals to allow time for the dye to move through the systems. Tracking the locations of dye injection and recovery helped identify specific subsurface water flow pathways and measure minimum flow velocities. Identification of these subsurface pathways enabled us to delineate karst watershed boundaries, understand the downstream effects of proposed management, and better manage karst areas.

Keywords: *karst, insurgence, resurgence, dye trace, watershed delineation*

## Introduction

Karst is a geomorphologic term describing the topography resulting from the chemical dissolution of carbonate bedrock. In southeast Alaska, karst refers to areas where this distinct geomorphology has developed from the dissolution of limestone or marble bedrock. Karst characterization includes grikes, caves, insurgence and resurgence streams, and extensive areas where runoff does not exist on the land surface. Instead, these waters infiltrate into the subsurface environment (insurgence) and may re-appear many miles away (resurgence). This process of surface waters appearing and disappearing is just one of the distinct features of karst watersheds.

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Southeast Alaska has over 869 square miles (2,228 km$^2$) of known karst (Figure 1). Of this area, 731 square miles (1,874 km$^2$) are on national forest land as part of the Tongass National Forest. Within the Thorne Bay Ranger District, 283 square miles (725 km$^2$) of karst are located on northern Prince of Wales and surrounding islands (Baichtal and Swanston 1996) (Figure 1). The development of karst is dependent upon many influences such as volume of precipitation, water temperatures, water chemistry, vegetation, soils, and in the case of southeast Alaska, elevation relative to past glaciations.

The coastal temperate rainforest environment of southeast Alaska is essential to the development of karst. With annual precipitation ranging from 100 to 200 inches (254 to 508 cm), and average annual air temperatures of around 45°F (7.2°C), the climate is ideal for carbonate dissolution. In addition, the role of glaciers in modifying existing karst features and depositing glacial till has a significant effect on karst development. Where glacial till was deposited, infiltration is limited, peatlands have

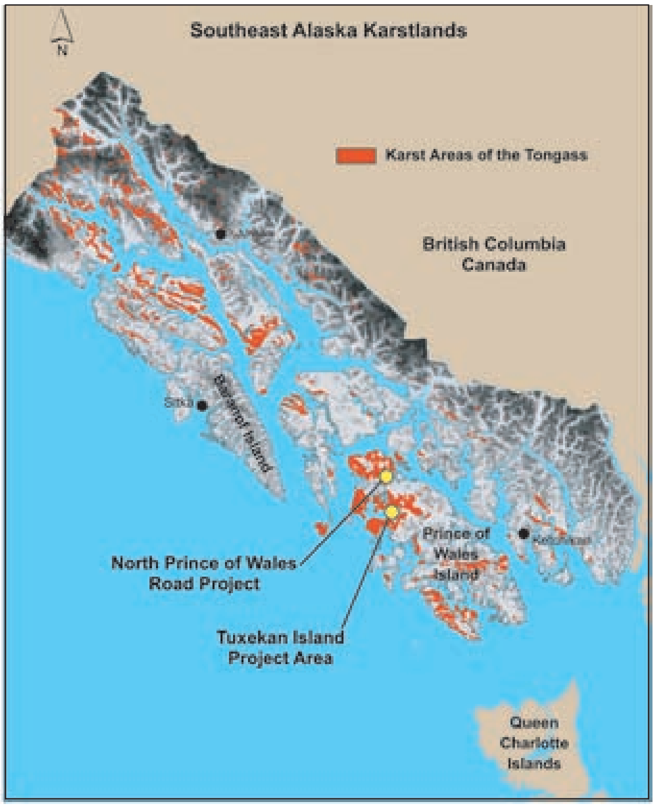



*Figure 1. Project area locations in the Prince of Wales Island area, southeast Alaska.*

developed and hence acidic soils are present. With the development of the peatlands on poorly drained areas and the acidic waters that flow from them, a system of vadose caves and vertical shafts have developed. These have combined with pre-existing subsurface conduits and cave systems to form the current drainage networks.

The carbonate that underlies the study areas consist of Upper Silurian aged (419-423 million years old) Heceta Limestone of the Alexander Terrane. This unit consists of light gray, massive, sublithographic limestone, with abundant amphiporoid corals, dasycladacean algae, oncoids, and brachiopods. Limestone also contains subordinate stromatoporoids, gastropods, pelecypods, bryozoans, trilobites, graptolites, conodonts, and aphrosalpingid sponges. Algal, coralline, and microbial buildups are interpreted to represent platform margin reefs, with carbonate turbidites, debris flows, and slump deposits that accumulated in deeper water off the shelf margin (Soja 1991). Contact with underlying Ordovician to Silurian aged Descon and Luck Creek Breccia Formations is generally conformable, but limestone detritus resembling the Heceta in polymictic conglomerate that conformably underlies Heceta in several places indicates that carbonate sediments were deposited, lithified, and eroded in the Early Silurian prior to the main period of Heceta Limestone deposition. The Heceta Limestone is overlain by the Early Devonian aged Karheen Formation, composed of sandstone, shale, and pebble, cobble, and boulder conglomerate, characterized by redbeds, calcareous cement, and crossbedding (S. Karl, USGS, personal communication).

Structural features within the Alexander Terrane are complex. These structures consist primarily of northwest-to-southeasterly strike slip faults and shear zones and secondary faulting and shearing in a east-to-westerly direction. These formations have been further modified by extensive thrust faulting and localized folding. Dissolution in limestone is accelerated along fault and shear zones, therefore solution channels and lineaments are common along the major and secondary fault zones.

The project areas (located on northern Prince of Wales Island [NPOW] and Tuxekon Island) were last glaciated during the Wisconsin glacial advance from the north and northeast 21,000 to 14,000 years ago. Karst existed on Prince of Wales and surrounding islands prior to the last glacial advance. Recent phreatic passages in two pre-Wisconsinan caves have dissolved through Tertiary paleokarst breccias (Aley et al. 1993). Older passages have been plugged or collapsed by debris from past glacial episodes. Most caves predate the most recent glaciation, based on the presence of glacial clays, glacial sediments, wood, Pleistocene vertebrate remains, and possibly ancient ice. Such evidence clearly suggests that glaciation modified a pre-existing karst landscape, collapsing some passages and systems, gouging into others, and filling some with sediments. The epikarst (surficial karst), which is exceptionally well developed at higher elevations, has been destroyed at lower elevations by the scouring of the most recent glaciation.

## Methods

The methods used to delineate watersheds in karst are drastically different from those methods used in non-carbonate environments. Surface water runoff in non-carbonate environments flows across the ground surface and is ultimately controlled by topography. However, in carbonate environments where surface waters are rare, insurgences and resurgences must be located on the ground, and where possible, these waters must be traced through the subsurface environment, to identify flow paths, and hence watershed boundaries. Although runoff in both carbonate and non-carbonate areas generally flows down gradient, those waters in carbonate environments don't necessarily flow downhill relative to surface topography. The following methods describe ways to determine flow paths using both geomorphic and dye trace methods.

## Mapping of Hydrogeologic Features

Success of tracer projects in karst areas hinges on the ability to identify and map all features that influence runoff. These mapped features include streams, significant sinkholes (those that are open to the subsurface), insurgences, resurgence caves and springs, and any other features where runoff flows into or out of the subsurface environment. Aerial photo interpretation, contour maps, field reconnaissance, and a general understanding of the bedrock geology, are essential in successful identification and mapping of features. All features identified on the ground or through map or photo interpretation were mapped, labeled, and characterized regarding feature type and characteristics (Figures 2 and 3). In some cases, water quality parameters, such as pH, temperature, and conductivity, were collected and used in planning the dye trace.

Aerial photographs were used in this study to identify runoff features and track runoff patterns. Streams, sinkholes, lineaments, geologic contacts, and large closed basins can be identified through aerial photo interpretation. Depending upon the scale and degree of forest canopy, karst features can be more or less evident through a stereoscope. In some cases sinkholes and karst lineaments can be very obvious from aerial photos.

Contour maps were also used to determine where surface drainage features were located on the landscape. Closed depressions, or large internally drained basins, can be identified as areas that contain no drainage outlet. In some cases, digital imagery such as LIDAR can be used to color-code negative contours for identifying sinkholes and closed depressions (Baichtal and Langendoen 2001; Langendoen and Baichtal 2004)

Extensive field reconnaissance was performed to confirm features identified from map or photo work, and to explore for additional drainage features. Surface water streams were walked to determine contributing area, or source at the headwaters, and to determine if the waters dissipated or disappeared into the subsurface. Karst lineaments and geologic structural boundaries were investigated in the field for potential insurgence or resurgence features. Bedrock contacts are logical locations for water to appear or disappear, depending upon the bedrock and the nature of surface runoff. Features identified along these contacts were characterized and mapped. All wetland boundaries proximal to carbonate bedrock were also scouted to determine drainage and to identify additional karst features.

## Planning Dye Traces

Dye trace methods used in this project followed those outlined in Aley and Fletcher's Water Tracers Handbook (1976). These methods use several different fluorescent dyes for tracing. The methods also describe the use of activated charcoal packets for adsorption and the laboratory analysis process for detection.

Planning is a crucial element in a successful dye trace, and in delineating watershed boundaries. Both the NPOW and Tuxekan project areas were separated into five distinct sets of insurgence locations that were chosen for dye introduction. For NPOW, the introduction points were determined according to their location relative to each other and proximity to a proposed road project. Points were far enough separated that two of the five traces could be done simultaneously using the same dyes. On Tuxekan, the five distinct areas were structurally separated, and were capable of handling five sets of four dye introductions all at once. Generally, the dye trace plan must separate out insurgences according to the number of dye tracers available, and the geologic, or structural boundaries between areas, to limit contamination between traces. Where clusters of insurgences are in close proximity, one or several of the more significant features were chosen for dye injection.

## Collection of Background Data

To ensure that no prior trace of the proposed dyes existed in the drainage system scheduled for tracing, background water chemistry information was collected. A set of charcoal packets was placed in all resurgence locations for seven to ten days to collect baseline water chemistry. Packets were placed under rocks within the normal flow section of stream, were bound by a cord, and tied to the stream bank. All packets were placed for easy access during all flow levels, and placed to ensure packets would remain underwater during low flows, yet not be moved, or carried away, during high flows.

## Dye Introduction

After all background packets had been replaced with fresh packets, dyes were introduced into designated insurgences. Transport and introduction were undertaken with care to prevent contamination of the injector's body or clothing by the dye materials. There was no handling of charcoal packets following dye injection without full cleansing of hands and a change of clothing. The dyes used in this study were purchased from Ozark Underground Laboratories Inc. , and included Rodamine

WT, Fluorescein, Eosine, and Sulferodamine dyes. Each of these dyes is characterized by a distinct wavelength when placed in a fluorophotospectrometer; therefore each can be chemically distinguished. The packets contain activated charcoal enclosed in a mesh pouch and anchored to the streambed of a resurgence stream. As runoff in the resurgence zone flows through the dye packet, the charcoal adsorbs the dye and retains the chemical trace for analysis. These tracer packets were recovered from the resurgence area and sent to Ozark Underground Laboratories for analysis. Laboratory reports state the concentration of each dye that is recovered for each site.

The time provided between dye trace introductions is dependent upon the volume of water that is available to flush the dyes. When a dye is introduced into a system, it must be fully flushed before introducing that same dye into the same drainage network. In this study, dye traces were performed between August and November when large storms are generally back-to-back, soils are saturated, and flushing of the drainage networks is rapid. Times between dye tracer introductions ranged from one to three weeks, depending upon flow volumes and access opportunities. The process of packet replacement for the NPOW project generally took a day with two groups of two people, and an additional day for dye introduction. The Tuxekan project required several days for packet replacement and several days for dye introductions.

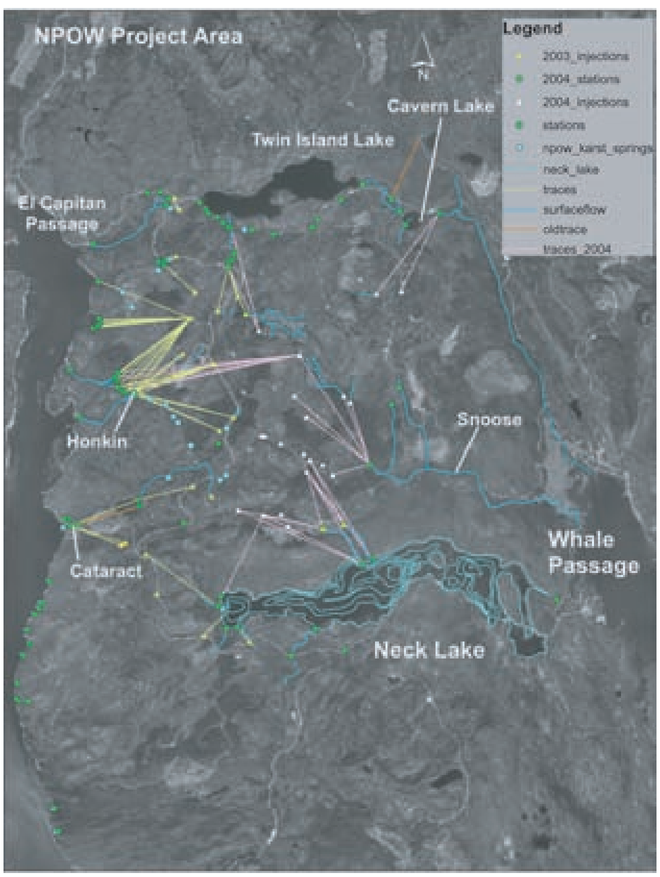



*Figure 2. North Prince of Wales Island project area, insurgence and resurgence locations, and dye trace results.*

**Plotting Dye Trace Results and Modifying Remaining Traces**

When performing a multi-year dye trace, there is opportunity to adjust dye traces according to results of previous work. In the case of the NPOW project, the results of the work performed in 2003 led to increased investigation and an expanded project area for 2004. Because there were no east-west watershed divides identified in the 2003 work, additional field work was done prior to the 2004 work to identify insurgences that might lend information to this question. Trace results in 2004 provided insight to the watershed divide, which better defined the watershed boundary.

## Results

Ozark Underground Laboratories performed charcoal packet analysis for both of these studies. The results of the analysis included type and concentration of each dye recovered. The NPOW project area covered approximately 36 square miles (93 $km^2$). Over a two-year sampling period, 38 dye traces were introduced. Thirty-six of these traces were recovered at 65 springs (Figure 2). In the smaller Tuxekan project area, covering approximately 28 square miles (72 $km^2$), 14 dyes were introduced during one sampling season. Thirteen of these dyes were recovered at 20 springs (Figure 3).

**North Prince of Wales Island**

Dye was recovered at resurgence areas near Neck Lake and Snoose Creek in the southern portion of the project area, Honkin Spring and Cataract Spring in the western portion of the project area, and Twin and Cavern Lakes in the northern portion of the project area (Figure 2). All source areas, where dye was introduced, were located along the high karst plateau of the project area. Resulting dye paths trended northeast, northwest, southeast, and southwest, with no dominant trend direction.

The 2003 dye introduction points were largely along the mainline road system (National Forest System Roads 15 and 20). This road is located along the western flank of the high plateau, trending north-south. The 2004 dye introduction locations were concentrated along the eastern flank of the high plateau and dispersed in a northern, central, and southern trend, focusing on key insurgence features.

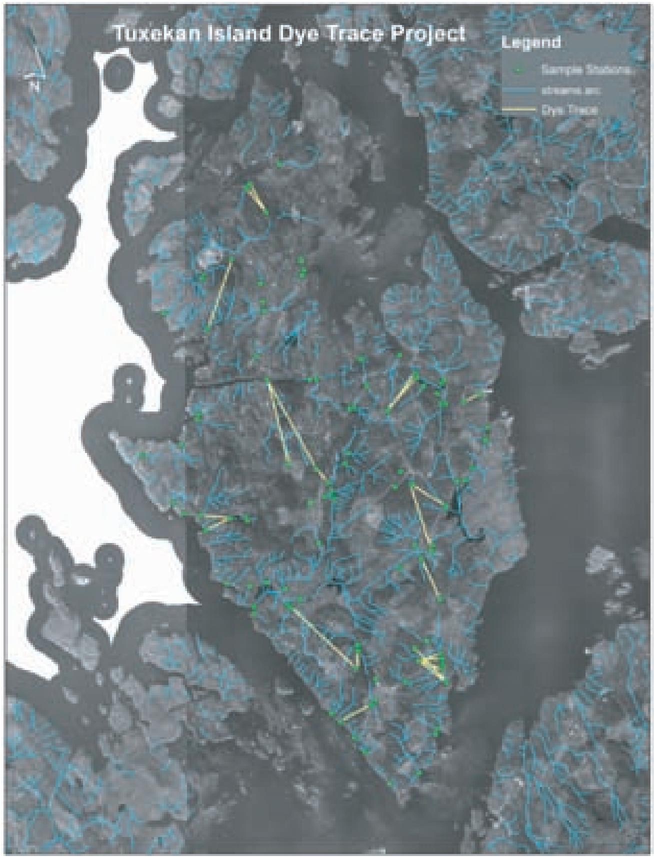



*Figure 3. Tuxekan Island project area, insurgence and resurgence locations, and dye trace results.*

All but three of the 2003 dye introductions eventually entered El Capitan Passage. Most of the 2004 dye introductions eventually entered Whale Passage. The few dyes that crossed this trend were used to delineate the east-west boundary along the high karst plateau. All springs in the western portion of the project area, including Cataract and Honkin, flow into El Capitan Passage, along the western shoreline of Prince of Wales Island. Twin Island Lake flows into Cavern Lake, which flows into 108 Creek, and eventually out into the estuary of Whale Passage. Snoose Creek, a significant drainage in the central portion of the project area, also flows into Whale Passage. Snoose Creek enters Whale Passage slightly south of 108 Creek and within the estuary. Neck Lake outfalls into Neck Creek, which flows a short distance before entering Whale Passage.

A large percentage of the 2003 dye was recovered at Honkin Spring, centrally located along the western portion of the project area. The Honkin Spring Cluster, a series of springs proximal to Honkin Spring, gained source waters from four different insurgences in 2003, and an additional insurgence in 2004. All these source waters are located along the western flank of the high Plateau in 2003, and with the exception of a small sink located in the northern portion of the eastern flank of the project area in 2004. Dye from this small sink (84) was the only dye recovered along the eastern resurgences in 2004. Neck Lake received dye from the southern portion of the eastern flank of the project area in 2004 and received one hit of dye from along the road in 2003. Snoose Creek collected dye from the central portion of the eastern flank of the project area in 2004. Dye recovery was not monitored in the Snoose Creek area in 2003. Twin Island Lakes received dye from the Beaver Falls area, in the northern portion of the eastern flank of the project area. Cavern Lake is downstream of Twin Island Lake and received dye from upslope within its topographic watershed, insurgences 91 and 92.

Several significant resurgences did not receive dye in either year of sampling. For example, resurgences 86 and 87 located in the central portion of the project area, which flow into Snoose Creek, were monitored during the 2004 season and received no dye. The resurgences in the southwestern portion of the project area, 35 to 38, were monitored during the 2003 season and received no dye.

### Tuxekan Island

The Tuxekan Island project area was more linear in shape than the North Prince of Wales project area and a greater number of significant structural features separated the areas of delineation. This allowed a single dye to be introduced in numerous locations within the project area without contaminating adjacent watersheds. Of the 14 dyes that were introduced, 13 were recovered in 20 springs (Figure 3). Similar to the North Prince of Wales project area, Tuxekan resulted in no significant trend for dye recovery. Dye traces follow northwest, northeast, southwest, and southeast flow paths.

Most dyes were recovered less than a mile (1.6 km) away from and within topographic boundaries of, the introduction points. The few exceptions include I-2, which was recovered southwest at 87; I-5, which was recovered northwest at 60; and I-12, which was recovered northwest at 12; all greater than a mile in distance from introduction points. Topographic boundaries were crossed at introduction point I-12, where dye was recovered in two separate watersheds; I-6, where dye was recovered across a topographic boundary to the southeast; and I-2, where dye was recovered across a topographic boundary to the southwest.

## Discussion

Results of these dye traces revealed underlying flow paths. These subsurface flow paths are combined with surface water flow paths to delineate watershed boundaries. The complexity of delineating watersheds is confirmed in the results of these two projects. This complexity lies in the inter-relationship and processes controlling topography, structural geology, and runoff, or flow volume.

### Topography

Topography played a large role in the runoff patterns of both project areas. Many of the topographic watershed boundaries remained unchanged. Those boundaries that did change resulted from dye trace information. Delineation of watershed boundaries must be an iterative process in karst areas because of the influence of subsurface flow paths, and hence dye trace results. Prior to dye tracing, karst watershed boundaries followed topographic divides. With each additional dye trace, the boundary can change to reflect source area. In some cases, the source area of the introduction point became the watershed boundary. In other cases, the watershed boundary was altered, just slightly, to reflect additional source areas.

### Structural Geology

Outcrop pattern, bedrock contacts, structure, and glacial deposits and scouring control landform development and the subsurface flow paths. Spring locations are associated with fault and shear zones, bedrock contacts, and sea-level stance associated with isostatic adjustment after the last glacial advance. In both study areas, the large northwest-southeast faults control the individual drainage basins and the associated east-west shear zones tend to control groundwater flow pathways. Bedrock geology and generalized fault patterns are shown in Figures 4 and 5.

### High and Low Flows

The volume of runoff affected the direction of flow in at least one location on both project areas. On NPOW, dye from insurgence location 87 was recovered at the Honkin Spring cluster and at Headwaters resurgence (Figure 2). Honkin Spring flows west into El Capitan Passage, while Headwaters Cave flows east into Snoose Creek, and eventually Whale Passage (Figure 2). This evidence indicates a watershed that extends the entire width of Prince of Wales Island. On Tuxekan Island, I-5 flows north to Scott Lagoon and south to Karheen Lake (Figure 3). The geology and dye trace results suggest that normal flow in these cases would be in one direction. Overflow during larger storm events would then flood the

*Figure 4. Bedrock geology, structure, and dye trace results, North Prince of Wales Island project area.*

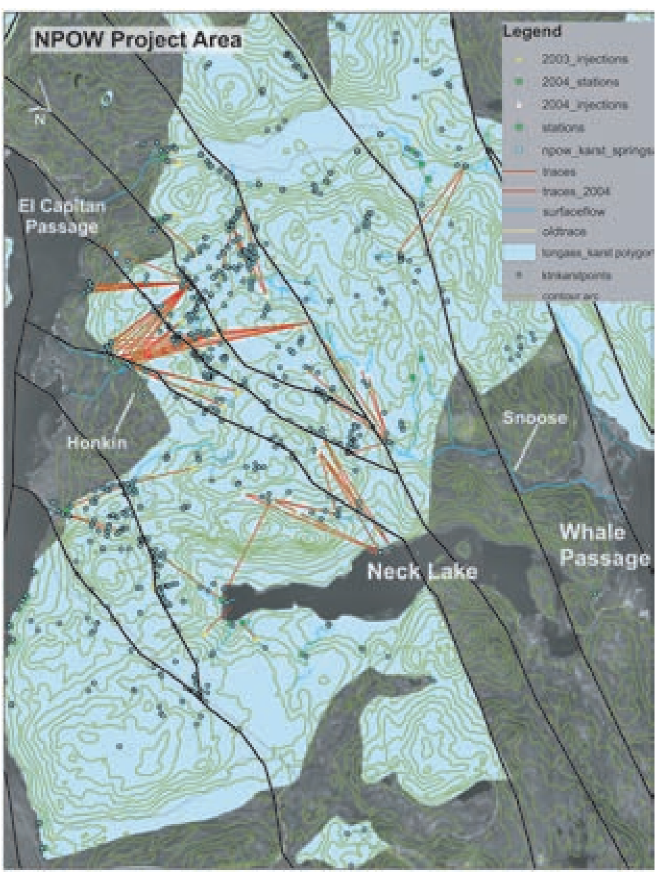
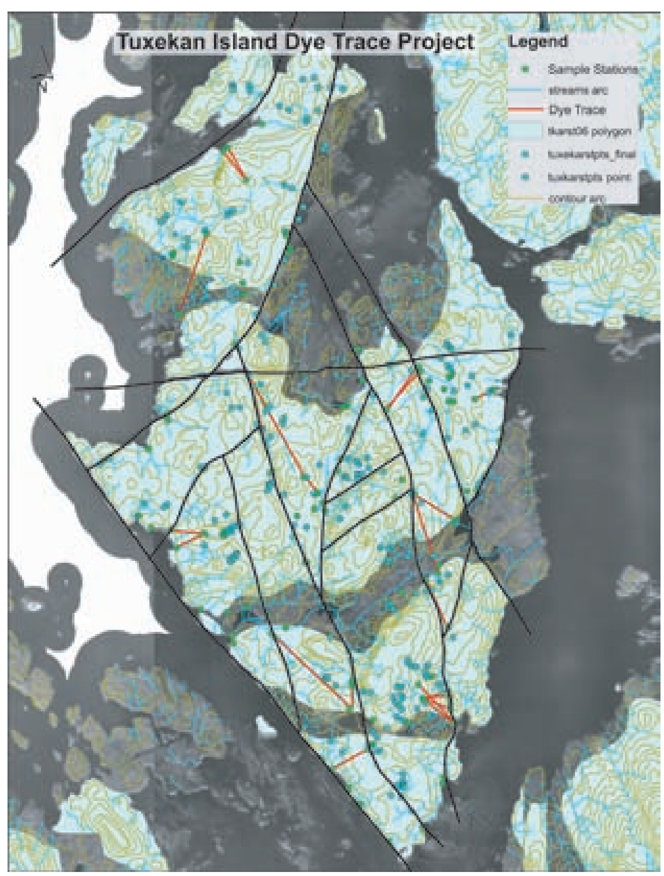



*Figure 5. Bedrock geology, structure, and dye trace results, Tuxekan Island project area.*



dominant passages and spill over into a secondary set of flow passages. Additional dye traces aimed to measure flow velocity may suggest dominant flow paths, and at what flow volume the dominant flow paths are exceeded.

## Conclusions

Tuxekan and NPOW project area watershed boundaries were delineated using the usual tools available for surface topographic watershed boundaries, while also incorporating dye trace results. Topography was the dominant characteristic in the delineation of the boundaries; however, structural geology and flow volume played a large role. Studies with dye tracers revealed subsurface flow paths and helped account for the majority of runoff in the study watersheds. Dye tracers are valuable in delineating karst watersheds and identifying subsurface flow paths in complex geologic structures. Now that the primary karst groundwater basins have been established for these areas, more in-depth studies are planned to determine high and low flow velocities and dominant flow paths.

***Acknowledgements.*** Many thanks to Tom Aley and the staff at Ozark Underground Laboratories for their extensive laboratory analysis that enabled the high level of detail attained in the dye trace results. And huge thanks to the hard working field crew including Dustin Walters, Marika Gertz, Brandy Prefontaine, Adam Cross, Brian Raper, Marsha Gillis, Dan Nolfi, Johanna Kovarik, and many others that endured wet, cold, windy, and seldom sunny, weather conditions to access dye trace packets throughout the project.

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# An Examination of References for Ecosystems in a Watershed Context: Results of a Scientific Pulse in Redwood National and State Parks, California

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Characteristics of reference sites for stream and riparian ecosystems were examined and discussed during a 'pulse' (a short, interdisciplinary field-based inquiry) that visited three pristine streams in old-growth redwood forests in northern California. We concluded that useful reference sites need not be pristine, but must be rich in data linking physical and biological processes, and must frame conditions in a watershed context. Not requiring pristine conditions allows data-rich watersheds with a spectrum of conditions to be incorporated into a regional reference framework. We describe and exemplify three types of references: 1) Reference sites (e.g., watersheds) offer real-world examples of how ecosystems function over time; 2) Reference parameters measured in a region offer first-cut comparisons that can lead to deeper, more contextual analyses; 3) Analytical references can reveal disturbance-related departures from conditions predicted with simple assumptions about some aspects of system behavior. Each type has strengths and weaknesses, and used in combination they can effectively inform management decisions.

Keywords: *environmental references, stream ecology, fluvial geomorphology, watersheds*

## Introduction

Ecosystem management requires interdisciplinary problem solving and an expanded scale and scope of analysis, particularly in lotic and riparian ecosystems that are integrated by the flux of water, sediment, organic material, organisms, heat, and dissolved constituents through watersheds. The need to address interactions between physical and biological processes over the landscape is perhaps greatest at the scale and organization of a watershed, where each point responds to cascading influences from upstream, upslope, and upwind over a range of time scales. Now, with the growing appreciation that biological functions are embedded in physically dynamic landforms (e.g., Minshall 1988; Fausch et al. 2002; Benda et al. 2004), the underlying problem for land managers is, how do physical and biological processes interact in a watershed, or, how does a living watershed function? With incomplete information about these complex systems, resource professionals commonly seek references to serve as benchmarks of functioning systems, asking 'What does a properly functioning watershed look like?'

Managers, regulators, and scientists commonly use relatively pristine systems as references against which to compare other sites of the same type or region that have comparable management issues (USGS 2004). Conditions are evaluated by comparing data for a set of quantitative parameters from pristine and managed systems. The assumption is that human effects account for significant departures from reference conditions and can be analytically separated from variations due to climatic events (e.g., hurricanes) or state variables (e.g., geology, topography), which are assumed to affect the site independently of human influence.

References other than pristine systems are available in the land-management arena, as suggested by Webster's broad definition of reference, '…taken or laid down as standard for measuring, reckoning, or constructing'. Nevertheless, reference conditions are usually associated with pristine or desired states – the "best" sites a region has to offer. In some

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cases "reference condition" is defined based on a specific reference site and becomes the target for restoration efforts, and later, for the evaluation of restoration effectiveness (Jungwirth et al. 2002; SER 2002). For example, a 'desired future condition' can be based on some perceived pristine or near-pristine condition that enhances a valued resource, e.g., productive fish habitat, without being tied to specific reference sites (Salwasser et al. 1996).

Any use of reference conditions should include an analysis of spatial and temporal variability. 'Historic range of variability' (Landres et al. 1999) describes the variability of ecological conditions particularly in the period before and after European settlement in North America. The concept that ecosystems are disturbed and recover from natural occurrences such as floods (Wolman and Gerson 1978), volcanic eruptions (Franklin et al. 1995) and wildfire (Minshall et al. 1997) emphasizes that all systems are in some stage of evolution from major events (Reeves et al. 1995).

Scale is a primary consideration in spatial variation. In some areas of the United States, ecoregions (Omernik 1987) have been divided into sub-regions as a framework for establishing ecological expectations – reference conditions – that are based on the sampling of many minimally impaired reference sites within the sub-region (Ohio EPA 1987). Physical, chemical, and biological data have been used to establish a database of reference conditions for the sub-region. In some cases, a reference framework is based on statistical analysis of a set of sites interpreted to represent reference conditions (e.g., Clarke et al. 2003). Ordination and principal component analyses have also been used to establish reference sites from large regional data sets. However, qualitative "best professional judgment" criteria are still used to select from the array of data the sites that should serve as references (e.g., McIninch and Garman 2002). Comparisons of such reference sites with those judged to be impaired encounter statistical problems of pseudo-replication (Stewart-Oaten et al. 1986) and fail to account for the inherent succession of ecosystems (Loehle and Smith 1990)

These considerations lead to the question, 'Is there something inherent in the reference sites, perhaps complexity or diversity, that sets them apart from others across regions regardless of temporal variability?' To examine this problem, a pulse study conducted by multi-disciplinary teams was held in the old-growth redwood forests of Redwood National and State Parks (RNSP) in north coastal California in June, 2003. Discussions during and following the Redwood Pulse resulted in a re-evaluation of, and some new proposals for, the use of various forms of references in the management of watershed ecosystems.

## The Redwood Pulse

The Redwood Pulse was modeled after the procedure established by Dr. Jerry Franklin (USDA Forest Service, Pacific Northwest Research Station, now at University of Washington), whereby multi-disciplinary teams of scientists focus their collective wisdom and insights on ecosystem functions at a specific site during short, field-based inquiries (Franklin 1982). Hence the term pulse.

The goal was to arrive at new insights about linked aquatic-terrestrial ecosystems. In the leadup to the Redwood Pulse, a framework for inquiry was developed concerning the notion of 'reference condition' as applied in watershed studies. The discussions centered on the importance of natural variability in the parameters selected to characterize a site, whether at the reach or the watershed scale. A collective interpretation was that this variability gives those sites less modified by human activities much of their resilience to natural disturbance. In this view, parameters in pristine sites could exhibit high variance at any point in time, and human disturbance could lead to a reduction in variance. As a consequence, reference sites might actually be more variable than disturbed ones. Thus, the motivating question for the Redwood Pulse was, 'Would reference sites, here defined as most-pristine, exhibit more variation in selected parameters than would be expected in disturbed sites in the same region?' This relative variability was anticipated to be distinguishable to the attendees who collectively had wide-ranging field experience in the Redwood and similar regions.

The pulse participants represented a range of disciplines, including geomorphology, hydrology, fisheries biology, aquatic ecology, plant ecology, entomology, social science, soil science, and natural resources management. (A list of participants is available on request from the corresponding author.) We did not visit disturbed sites nor collect data with the intention of testing an hypothesis. Instead, we used the question of ecosystem variability as a springboard to discuss reference concepts in a field setting. During the pulse, teams from the larger group of twenty-one participants worked side by side, focusing their particular expertise on each site in turn and continuously exchanging perspectives as they made observations and some measurements. During the evening, these separate insights were discussed, integrated, and recorded around the campfire in the Franklin tradition.

In this paper, we report the results of the discussions and propose that the richness of data on influential abiotic and biotic processes can qualify a site as an ecosystem reference, in addition to its condition. Our initial focus on variability led to a conclusion that data richness is an important criterion for selecting reference sites. We also

*Table 1. Characteristics of pulse sites.*

| | Site 1: Upper Prairie Creek | Site 2: Godwood Creek | Site 3: Little Lost Man Creek |
|---|---|---|---|
| **Watershed area (km²)** | 10.5 | 4.0 | 9.9 |
| **Stream gradient (%)** | 1.0 | 1.6 | 2.6 |
| **Bedrock geology** | Coastal plain sediments | Coastal plain sediments | Sandstone and mudstone |
| **Dominant riparian overstory** | Old-growth redwood on floodplain | Old-growth redwood on banks | Old-growth redwood high on banks |
| **Sub-dominant riparian composition** | Red alder and big leaf maple[1] | Hemlock, spruce, vine maple, alder[3] | Red alder near edge of stream, big leaf maple |
| **Percent canopy cover** | 80 | 85 | 80 |
| **Bankfull width (m)** | 7 | 5 | 8 |
| **Valley width (m)** | 130 | 83 | 40 |
| **Bed surface grain size: $D_{50}$ (mm), *S.D.* (phi scale)** | 67 (*1.1*) | 18 (*1.3*) | 54 (*2.1*) |
| **Dissolved oxygen** | 94.7% | 97.1% | 97.3% |
| **pH** | 6.65 | 7.36 | 7.37 |
| **Conductivity (µs/cm)** | 61.7 | 90.3 | 52.6 |
| **Trophic status** | Highly autotrophic | Slightly autotrophic | Highly heterotrophic |
| **Salmonids** | coho, Chinook, steelhead, cutthroat[2] | Same | Same |

[1] **Red alder, *Alnus rubra*; big leaf maple, *Acer macrophyllum*.**
[2] **Coho salmon, *Oncorhynchus kisutch*; Chinook salmon, *O. tshawytscha*; steelhead, anadromous *O. mykiss*; cutthroat trout, *O. clarkii***
[3] **Vine maple, *Acer circinatum***

compare the utility of reference sites with two other types of reference: reference parameters and analytical references.

## Observations and Discussions

Table 1 lists some characteristics of the three stream reaches visited during the pulse, all within the Prairie Creek basin and judged to be "pristine" by Park personnel and scientists from local agencies and universities. Their basins are uncut except for Little Lost Man Creek, which contains a 35-year-old, 40-acre patch cut, and Upper Prairie Creek, which is crossed by a paved road. The Yurok people located their villages outside these deep woods and the occasional understory fires that they would light did not harm the large redwood trees (*Sequoia sempervirens*) (Sawyer et al. 2000) Although all three streams flow through old-growth redwood forests with an understory dominated by ferns and salmonberry (*Rubus spectabilis*), the influence of the redwood trees on the stream differed according to the height and width of the floodplain and the proximity of the trees to the channel (Figures 1, 2 and 3). Godwood and Upper Prairie Creeks are underlain by poorly indurated gravel and sand considered to be deposits of an ancestral Klamath River of Plio-Pleistocene age (Kelsey and Trexler 1989). As a consequence, some of the modern bed particles may have been transported and sorted under very different hydraulic conditions than are present today, but the modern channels are apparently adjusted to transport this imposed particle-size distribution. Little Lost Man Creek is underlain by a more competent sandstone unit of the Francisican Assemblage (Cretaceous age) including coherent sandstone with some interbedded sandstones and mudstones. This stream reach was steeper and more confined than the other two.

Although all three sites were considered pristine, participants observed strong differences between them, including species composition of the riparian zone, proximity of old-growth redwoods to the stream channel, abundance of fine sediment, patchiness of light reaching the stream bed, distribution of riffles and pools, and location and size of large wood within the channel and on the streambanks and floodplains. Most notably, the riparian stand characteristics were very different. The pristine site in Little Lost Man Creek exhibited sediment effects that are usually attributed to human disturbance, such as unstable banks, high bed mobility, and a drape of silt over the gravel armor.

The instream biology was correspondingly variable. For example, invertebrate samples indicated that the Upper Prairie and Godwood Creek sites were autotrophic (food sources produced instream), with the former much more so than the latter, while Little Lost Man Creek was strongly heterotrophic (food sources contributed by the riparian area) (e.g., Merritt et al. 2002). All three stream sites exhibited algal development, including some filamentous forms, associated with light gaps. The ratio of invertebrates

Figure 1. (Above) Site 1 is Upper Prairie Creek (photographed March 2004). At Upper Prairie Creek, alders (Alnus rubra) grow close to the channel (foreground), maples (Acer spp.) are found on a 1- to 2-m-high floodplain, and old-growth redwoods grow on a higher terrace about 2 m high (in background). Although the stream drains an old-growth redwood forest, hardwoods and shrubs rather than redwoods influence the channel directly in terms of litterfall, shade and wood. This led to a high 'patchiness' of sunlight reaching the stream channel, and low levels of large in-channel wood (although numerous redwood snags and large down wood exist on the floodplain). The wide floodplain in this area supported an abundance of small back channels, high flow channels and alcoves. Banks were composed of coarse cobbles and boulders derived from ancient Klamath River deposits, so the streambed particles were, in a sense, pre-washed, pre-rounded and deposited under different hydraulic conditions. The channel has well developed gravel bars.

that use periphyton (scrapers) relative to those that use detritus (shredders + collectors) as a food source was used to evaluate autotrophy versus heterotrophy at the stream ecosystem level. The discrepancy between the high penetration of light to the stream bed in Little Lost Man Creek and the very low density of periphyton scrapers was likely due to dense growths of filamentous algae on coarse substrate surfaces. Scrapers are not able to feed efficiently on filamentous algae (Cummins and Klug 1979).

The three sites also differed significantly in abundance of invertebrates that filter fine particulate organic matter (FPOM) in transport (organic portion of suspended load) as their food source and require abundant stable substrates for attachment. Upper Prairie and Godwood Creeks apparently had plenty of stable substrates (large cobbles) but a poor supply of appropriate FPOM for filtering collector food supply. Water clarity at all three sites indicates little suspended load, and the lack of filtering collectors likely further reflects a poor supply of FPOM in suspension. Little Lost Man invertebrates indicate a lack of sufficient stable substrates as well as a poor FPOM supply. Much of the cobble substrate was covered with filamentous algae, which likely rendered their surfaces unsuitable for attachment by filtering collectors or grazing by algal scrapers.

Figure 2. Site 2 is Godwood Creek. (photographed March 2004). Godwood Creek has more cohesive banks than the other sites, so undercut banks and overhangs are common. At this site, redwoods grow on the edge of the banks and channel, most commonly on terraces 2 to 3 m high. Spruce (Picea sitchensis) and hemlock (Tsuga heterophylla) are also components of the conifer overstory at this site. Vine maples (Acer circinatum) overhang the channel in many areas, but alders are not prevalent. This site is the shadiest of the three, with little algae in the stream. Large in-channel wood is abundant, and many point bars and log jam deposits are present in this reach. The channel substrate consists of loosely packed pebbles and small cobbles.

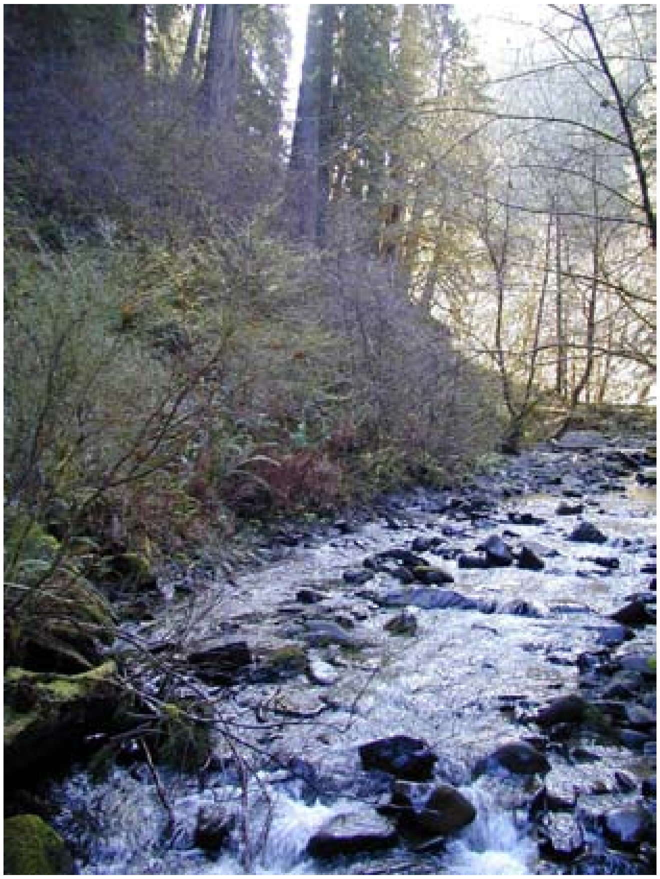


*Figure 3. Site 3 is Little Lost Man Creek (photographed March 2004). Little Lost Man Creek has the coarsest substrate of the three sites, with some 1-m diameter boulders in mid-channel. The floodplain is narrow and point bars are infrequent. Several instances of recent bank failures were noted. Fern-covered streambanks are steep and are devoid of large trees on the lower 7 to 8 m (perhaps indicative of a past debris torrent disturbing the channel banks). However, when trees fall, they commonly reach the stream and large in-channel wood was more abundant here than in Upper Prairie Creek. Alders grow at the channel's edge. Filamentous algae were present during the July visit.*

Our data collection exercises motivated discussions of stream reach variability and reference conditions. A related and recurring question that arose while visiting the sites was, 'How did the site get this way?' (again, in the Franklin tradition). We agreed that a knowledge of the legacy of a site, in terms of long-term state variables (e.g., climate and geology) and the disturbance history (e.g., floods, fires, and landslides), was critical to understanding current conditions and ecosystem processes. This reinforces the conclusion that a key requirement of a reference site is the extent of available data, regardless of where the site might lie along a spectrum from pristine to disturbed.

## Types of Reference

The original question of the characteristics of pristine reference sites evolved into an examination of the types of references (Table 2) and their usefulness in evaluating the condition of aquatic and riparian ecosystems in the context of their watersheds.

***Reference parameters.*** Perhaps the most widely used referencing approach is to directly compare the value of a parameter measured at a site of interest to a reference value, range, or distribution, without considering influencing processes. References can be derived from sites judged to be pristine or representative, or from sites sampled randomly in a region. A single-valued reference parameter can take the form of a sample statistic (e.g., mean, maximum or minimum), a scientifically determined or regulatory threshold leading to a degraded condition, or a desired state. A single-valued reference leaves no ambiguity as to whether a criterion is met, but the variability of natural systems suggests that such a comparison is too simplistic.

*Table 2. Reference types; their expressions as values, models or locations; and examples.*

| Reference Type | Expression | Example |
|---|---|---|
| *Parameter:* | | |
| Single value | Average | Pools per mile |
| | Minimum, maximum | Water temperature |
| | Threshold | Total Maximum Daily Load (USEPA) |
| | Presence /absence | EPT [Ephemeroptera (mayflies), Plecoptera (stoneflies), Coleoptera (caddisflies)] |
| Distribution | Range | Flow regime? |
| | Cumulative percent | Wood volume/channel area |
| Process | Value or distribution | Litter input/area-year |
| *Analytical reference* | | |
| | Budget | Water, sediment, sediment, dissolved constituents, temperature |
| | Distributed models | SHALSTAB (Dietrich and Montgomery 1998). |
| *Site:* | | |
| Watershed | Reference watershed | H.J. Andrews (LTER), Caspar Creek Experimental Watersheds |
| | Reference framework | National Ecological Observatory Network (proposed) |

Even if used merely as a benchmark, it does not provide an interpretation of a deviation from the reference value unless, as a threshold, it triggers some regulatory action.

A comparison against the full distribution of values from a set of data offers a broader use of reference parameters. Here, the distribution of values from a set of reference sites is presented as a range, standard deviation, or cumulative frequency distribution. Comparison of values against the reference distribution provides information on the deviation from the central tendencies of the reference sites. This broader approach is more informative and can reveal the uncertainty in making management decisions. Distributions of environmental parameters (e.g., wood loading, sediment concentrations) measured in managed and pristine systems in the same region commonly overlap (Lisle 2002). Commonly the 'best' reference sites exhibit wide variation in the parameters selected as measures of their condition, making it difficult to define a target for restoration.

A reference can represent a level of achievement of acceptable conditions on a scale that runs from 'not properly functioning' or 'at risk', to 'properly functioning' (NMFS 1996, 1999). However, a reference condition does not need to represent a pristine system or a target, but can be a benchmark for comparison without a predetermined value or decision context. Application of the Webster definition is still appropriate – a standard to compare with a system in order to help guide analyses to better understand how it got this way and what its trajectory is. Nevertheless, a useful reference must contain some meaning in order to allow an interpretation. In this view, a reference can be used to expose extraordinary conditions and be used in the analysis of cause and effect (e.g., stream cleaning, recent debris flow, influences on riparian communities).

However, any reference parameter is limited in its usefulness to understanding causal linkages, and expanding the scale and context of a reference demands new strategies. One strategy is to quantify relations between terrestrial riparian and aquatic conditions by focusing on processes that transfer watershed products between parts of the watershed ecosystem. Because physical and ecological processes occur at a variety of time scales, a meaningful reference for a parameter like wood loading could be the annual or decadal inputs of wood that are governed by rates of mortality from disease, windthrow, bank erosion and landslides and, ultimately, tree growth (Van Sickle and Gregory 1990; Benda et al. 2002). Also, reference processes could include seasonal or annual rates of primary production or nutrient cycling or fluxes of sediment, nutrients, or organisms. A reference could be used to track trends in processes over time at the same site in the same watershed, or to compare processes among different sites or watersheds in a region. Concentrating on rates of movement from one state to another provides insight into the mechanisms resulting in variability in space over time. For example, with regard to invertebrate life cycles, all three of the sites examined in the Redwood Pulse were dominated by those taxa with annual or shorter generation times. These would be populations with the potential for quick response to changes in the physical environment, and their presence is not very compatible with a view of pristine systems as being relatively stable.

***Analytical references.*** Expanding the use of references from reaches to watersheds requires more than just expanding the same site-scale measurements to more places. One strategy is to employ an analytical reference such as a budget, that is, a statement of spatial and temporal variations in inputs and outputs and changes in storage of a watershed product such as sediment (Reid and Dunne 1996), wood (Benda and Sias 2003; Hassan et al. in press), or particulate organic matter.

As an example, inputs of particulate organic matter (POM) were generally in balance with outputs for a small first-order woodland stream in Michigan (Figure 4) as well as for twenty-three reaches in four different watersheds (Figure 5). The amount of detritus in storage in a reach of stream is the result of biological activity (microbial respiration, invertebrate assimilation) and flow-related loading and unloading of storage in the sediments. The majority of the POM is stored in fine particles, which account for the majority of microbial respiration and 80% of the invertebrate assimilation (Petersen et al. 1989).

In the case of large woody debris (LWD), although historic values for volumes lost or gained usually cannot be determined precisely, enough can be learned of past events and conditions to roughly evaluate departures from natural loadings. This allows some basic questions to be addressed:

- What accounts for present wood loading, and more specifically, how much has land use affected riparian sources and input and output mechanisms?
- What is the trajectory in wood loading given the present and future potential of the riparian forest to contribute wood to the stream?
- Which management alternatives are consistent with the desired trajectory?

Another form of analytical reference is the output of a numerical model relating an environmental or ecological variable to a simplified representation of one or more watershed processes that is applied to the conditions and state variables of a target watershed (Power et al. 1998). Thus, the primary purpose of an analytical reference is not to accurately predict actual conditions, but to project what

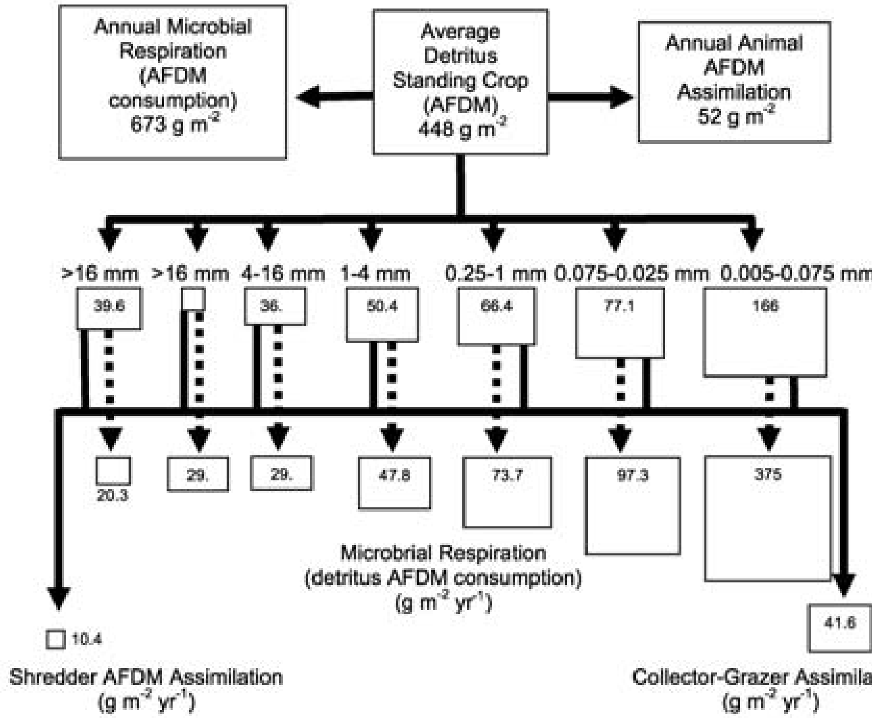



*Figure 4. Summary of annual average ash free dry mass (AFDM) in the benthic detritus (bedload) standing crop and consumption by microbial respiration and animal assimilation. Microbial respiration (hatched arrows) and invertebrate (shredders, collectors, and scrapers) assimilation (open arrows) apportioned by mm particle size categories (16 mm W = wood, bark, twigs – a very resistant fraction; 16 mm L = leaf litter). All particle sizes > 1 mm are defined as coarse particulate organic matter (CPOM) and < 1 mm defined as fine particulate organic matter (FPOM). Data from a first order tributary of Augusta Creek in southern Michigan. Modified from Petersen et al. (1989).*

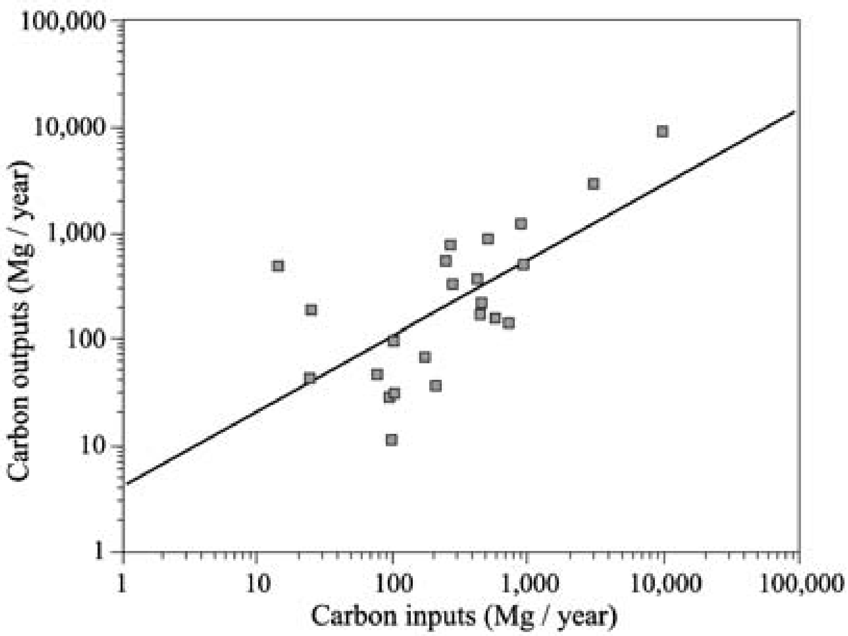



*Figure 5. Generally balanced relationship between annual carbon inputs and outputs for 23 stream locations in four watersheds. Modified from Petersen et al. (1989) and based on data in Cummins et al. (1983).*

would be found if certain assumptions or conditions were met. Deviations from the analytical reference can reveal the relative strength of other influences.

For example, reference particle sizes of sediment on streambed surfaces in a watershed can be computed from drainage area and channel slope of each reach by assuming that a gravel bed should be at the threshold of movement under bankfull discharge conditions (Power et al. 1998). This is a characteristic of active gravel-bed channels that maintain equilibrium with modest sediment loads. A streambed that is much coarser than the reference particle size could indicate sediment starvation or inputs of large material by debris flows or landslides; a much finer bed could indicate large channel-routed sediment loads, particularly of fine material.

Similar theoretically based models are available for referencing stream temperature based on shade (Bartholow 2002), woody debris loading based on topography and riparian stand structure (Van Sickle and Gregory 1990), the occurrence of shallow landslides based on drainage area and slope [SHALSTAB (Dietrich and Montgomery 1998)], and invertebrate communities dependent on the predictable nature of riparian litter inputs (Grubbs and Cummins 1996).

Numerical models provide a site-specific, theoretical framework to examine relations between environmental conditions and controlling processes. They also enable simulations based on a wide range of scenarios and tests of ecosystem sensitivity to stressors. However, the power of numerical models is limited by the very strategy that makes them computationally possible-simplification of the whole suite of processes that determine the functions of ecosystems in the context of their watersheds. In fact, every model can do no more than produce a reference, because none can incorporate all of the conditions and processes that govern the behavior of a natural system.

***Reference watersheds.*** There is a commonly held view that human influences on watershed conditions transcend those due to climatic events or state variables, thus significant departures from reference values within the same region must be due to human activities. Our observations in the Redwood Pulse led us to doubt that view. We found, for example, that geology in a pristine site we examined produced channel conditions that are commonly attributed to human disturbance. It was clear that establishing a local context – 'how it got that way' – is essential to applying a reference approach.

To this end, we conclude that expanding both the context and scale of references would require a database linking processes in an integrated system – a reference watershed. We envision reference watersheds as real-world examples of the full suite of processes that govern the functioning of a living watershed. Watersheds could qualify as references by having comprehensive, long-term data bases. Our vision of reference watersheds is most closely represented in Long Term Ecological Research (LTER) sites and experimental watersheds that are devoted to research and protected from endemic land use, except for controlled experimental treatments. Many, but not all, LTER sites are essentially pristine. Thus our view that data richness, rather than condition, is a primary requirement conforms to an existing system of reference watersheds. Insofar as pristine watersheds in many regions are rare, this expands the number of watersheds that could be used as references.

A reference watershed should be large enough (say, $10^0$-$10^1$ $km^2$) to incorporate important processes linking terrestrial, riparian, and aquatic ecosystems in a network of low-order tributaries. They should be rich enough in data and information to explain the variability in observed environmental parameters and their relation to causal factors (again, "how it got this way"). Although it is important to know how pristine systems work, it is also important to know how cumulative effects occur in disturbed systems and what impacts to monitor. Moreover, both pristine and anthropogenically disturbed watersheds are subject to infrequent large disturbances such as wildfire and floods, and thus a variety of states can exist within and among any number of reference watersheds. Examples of data-rich reference watersheds include LTER sites [including H.J. Andrews, in Oregon (*www.fsl.orst.edu/lterhome.html*); Hubbard Brook, in New Hampshire (*www.hubbardbrook.org*); Coweeta, in North Carolina (*coweeta.ecology.uga.edu/webdocs/1/index.htm*)], many of which were once treated experimentally but are now off-limits to major treatments. Others include watersheds associated with Biological Field Stations. For example, Augusta Creek at the Michigan State University Kellogg Biological Station (Mahan and Cummins 1978) or Linesville Creek at the University of Pittsburgh Pymatuning Laboratory of Ecology (Coffman et al. 1971), and experimental watersheds [e.g., Caspar Creek, northern California (*www.fs.fed.us/psw/topics/water/caspar/*)] that still undergo periodic large-scale treatments.

Ideally, the number of reference watersheds could be expanded to include a wider range of conditions. This would allow conditions in a targeted watershed to be compared to those resulting from a range of disturbance intensities (natural or anthropogenic) and state variables. With extensive data, the causal linkages would be relatively well known in the reference watersheds. Comparisons between watersheds would reveal not only the departure of environmental variables from desirable states, but also the linkages that would suggest how more desirable conditions could be achieved. Moreover, reference watersheds could aid analyses of target watersheds by revealing the strong pathways between watershed condition and environmental variables. Depending on the condition of the target watershed, some reference watersheds may be more useful than others. Reference watersheds in a similar condition could indicate how the target watershed functions now, whereas more pristine references could indicate how it might function in an improved condition, and therefore suggest the most plausible approach to restoration. A broader reference framework would evolve as watersheds that host research or administrative studies accumulate enough data to assume the role of a reference watershed. This could occur naturally as analyses prompted by initial comparisons with the 'founding' reference watersheds expand the information base for other watersheds. Recently developed remote sensing and analytical techniques (LIDAR, GIS) enable rapid accumulation of large-scale data sets for new areas.

***Relative utility of reference types.*** The three types of references vary in the degree to which they address a number of issues important to analysis of watershed ecosystems (Figure 6):

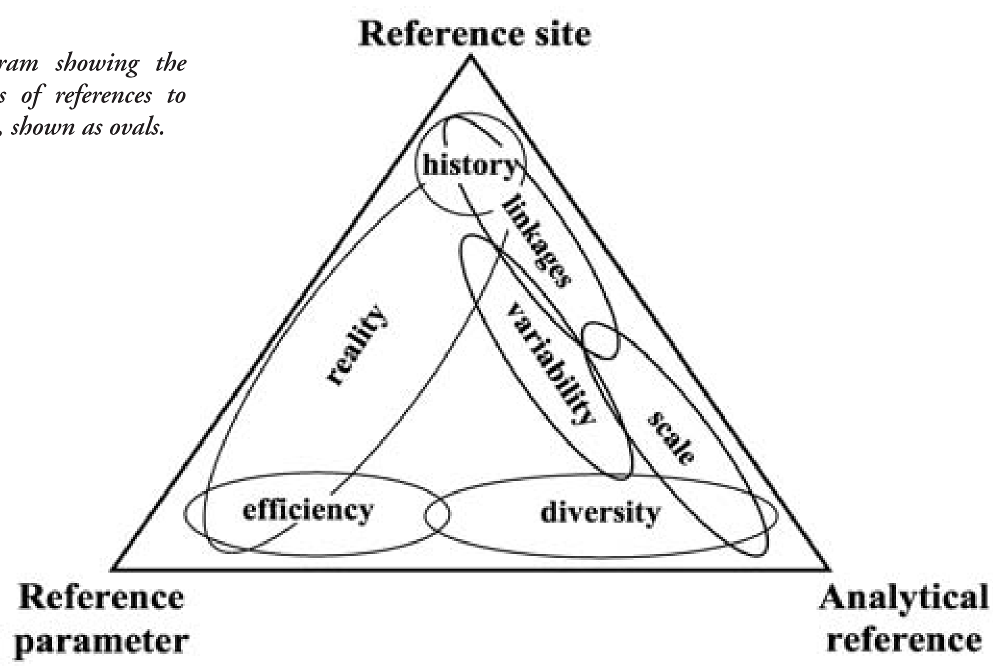
- **Linkages** – A reference should incorporate linkages between processes that determine ecological conditions in order to enable analyses of cause and effect. The complexity of natural systems characterized by cascading fluxes of watershed products through various landforms requires a broad scope of analysis. The capacity to link aquatic biota to the stochasticity of the physical system (such as matching critical life history stages with hydrology and temperature) is a valuable attribute of a reference.
- **Scale** – For many problems, the spatial scale of analysis needs to embrace geographic areas (watersheds) that influence a reach of river, and time periods, that cover major climatic fluctuations (e.g., ENSO).
- **Temporal variability** – Sequences of events and contingencies create a wide range of possible outcomes in natural systems that are conditioned by past events and climatic change.
- **Diversity** – To separate anthropogenic effects on ecosystems, references must address the wide diversity in underlying controls, such as landforms, climate, and geology, that affect ecological conditions and processes in a region.
- **Efficiency** – All of the preceding present complications for arriving at an assessment of the effects and risks of ecosystem management. Nevertheless, references must be understandable and practical for use by managers.
- **Reality** – The real world is the ultimate reference, and references must represent it as accurately as possible.
- **History** – Conditions in watershed ecosystems are the culmination of environmental events and processes played out over time and space. Knowledge of history at local and regional scales provides the background to project reference conditions backward and forward, so that contemporary conditions can be interpreted in the context of environmental trajectories.

Reference sites, such as LTER sites or experimental watersheds, ground us in the functioning of real watershed ecosystems over time. The linkages are there to discover and quantify, although there are technological and institutional limitations on the scope and scale of information that can be gathered. The value of reference sites increases exponentially as records lengthen and the systems become more completely understood. Analyses that employ this information can become more powerful by using data from reference watersheds in other areas that have different controlling conditions, or from less data-rich watersheds in the same region, as described earlier as a reference framework. However, reference sites are limited in their capacity to reveal variability, because they represent one history of an infinite number of possibilities created by climatic variability and disturbance events.

Reference parameters provide real-world information at a regional scale and are often readily available. They provide straightforward comparisons with monitoring data, revealing anomalies and prompting more in-depth analyses. However, without further analysis, interpretations are severely limited because of lack of context with other conditions and processes that lead to cause and effect.

Analytical references are becoming more attractive as references because they can address a wide range of scales,

*Figure 6. Triangle field diagram showing the relative capacity of three types of references to provide qualities of information, shown as ovals.*



stochastic processes, and levels of risk. They explicitly make linkages between various processes and conditions, and can simulate events that have not been observed. In the final analysis, however, they are only as good as their representation of reality, which must be confirmed by examination of real places in real time.

## Conclusions

Redwood Pulse participants examined the nature of conditions of three pristine channel reaches that would commonly serve as references. The resulting discussions led to a reappraisal of what constitutes a valuable reference and an appreciation of the utility and shortcomings of a broad range of reference types.

We concluded that a reference site should be a well-studied system, not necessarily pristine, but rich in data linking watershed and ecological processes. For managers, the great benefit of this approach is that pristine watersheds may not be required to establish workable management goals. A greater emphasis on gathering and integrating significant data sets through time would expand the number of watersheds that could be used to establish references. This opens the possibility of formulating a regional referencing framework whereby data-rich watersheds with a spectrum of conditions provide a context for investigating cumulative effects.

A referencing framework provides a means to determine the causal linkages between underlying conditions, environmental variation, and the functioning of the watershed and its ecosystems. In comparison, stand-alone reference parameters taken out of context of the variety of settings where they are measured or applied offer limited interpretive power. Nevertheless, such parameters are easily available and allow initial comparisons that should motivate deeper analyses. Moreover, the full set of values of a particular parameter in a region offers a wider context for interpretation than a single value, such as a threshold or average. Reference parameters that express process or function, that is, rates rather than state variables, are more likely to capture linkages influencing ecosystem condition.

Analytical models provide formal, explicit organization of our understanding of these interactions and a means to sort out strong influences from weak ones, and anthropogenic effects from natural ones. As analytical tools are developed with new knowledge and techniques, analytical references will provide a new wave of approaches for addressing cumulative watershed effects. However, models are ultimately based on knowledge and data from real systems, and their development should motivate new, interdisciplinary field studies.

Finally, Pulse participants concluded that references are essential tools in management-driven analyses of watershed ecosystems, where biological and physical processes interact in a complex structure of linkages activated by stochastic disturbances. Our discussions revealed a variety of reference types, each with strengths and weaknesses, which can be integrated to support more effective, full-scale analyses. Science-based management decisions will always rely on incomplete understanding of watershed ecosystems, but analyses using data-rich reference sites and valid analytical models, combined with the best professional judgment, will help to achieve the competing goals of the public's interest in resource management.

***Acknowledgments.*** This contribution is a distillation of the collective thoughts of the participants of the Redwood Pulse. Paula Yoon of the Redwood Regional Watershed Center was instrumental in arranging logistical support for the Pulse. Redwood National and State Parks provided the use of an environmental school lodge, kitchen, and cabins for the pulse participants. Thomas Dunklin and Betsy Watson recorded and transcribed notes of summary discussions. Mike Furniss facilitated communication among participants through the establishment of an interactive web site. Insightful comments by Bret Harvey on earlier drafts are much appreciated. All photos by the authors.

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# Section 1. Applied Science and Technology

## Part 3. Surface and Groundwater

Overleaf:
Photo: Torrent sedge (*Carex nudata*) on the North Fork John Day River, Umatilla National Forest, Oregon. Photo by Bruce McCammon.

# Chronic Misapplication of the Relationship Between Magnitude and Frequency in Geomorphic Processes, as Illustrated in *Fluvial Processes in Geomorphology* by Leopold, Wolman, and Miller (1964)

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M.G. Wolman and J.P. Miller's paper, *Magnitude and frequency of forces in geomorphic processes* (1960), examined the long-term work done by erosion. They showed that for processes like sediment transport, where movement of materials is driven by shear stress, a large proportion of the work is performed by relatively frequent events of moderate magnitude. Erosional work as indexed by the product of the rate of movement of an event and its frequency of occurrence reaches a maximum at a relatively frequent event. The relationship between magnitude and frequency as charted in Figure 3-23 in *Fluvial Processes in Geomorphology* (Leopold et al. 1964) is frequently referenced. Through time the abscissa in this chart has often appeared as "discharge" rather than "applied stress" as originally published. This transposition reasonably defines sediment transport in a channel only for flows up to bankfull depth. However, once flows overtop the bank, the rate of increase for in-channel bed shear (γRS) must show an inflection. This relationship is not shown in the incorrect representations of the magnitude/frequency relation and has implications for methodologies that attempt to calculate total sediment transport at flows in excess of bankfull.

Keywords: *channel geomorphology, bankfull discharge, sediment transport*

## Introduction

In their 1960 Journal of Geology paper, *Magnitude and frequency of forces in geomorphic processes*, M. Gordon Wolman and John P. Miller examined the relative importance in geomorphic processes of extreme, so-called catastrophic events and more ordinary events of smaller magnitude. They evaluated the relative amounts of "work" done on the landscape over the long-term by events of all magnitudes. They concluded that a large part of sediment transport by various media is performed by events of moderate magnitude that recur relatively frequently, rather than by rare events of unusual magnitude. Many features of the landscape are formed by frequent events with relatively small applied stress. Notably, and with lasting impact, they found that stream channel dimensions in alluvial channels seem to be molded by flows at or near the bankfull stage.

A conceptual depiction of the relationships discussed in their paper was presented as Figure 1 of the 1960 paper (see our Figure 1). Leopold, Wolman and Miller duplicate that chart as Figure 3-23 in *Fluvial Processes in Geomorphology* (1964). The form of the chart has been frequently duplicated in subsequent papers that purport to reference either that book or the earlier paper.

In many of the subsequent papers, the abscissa of this chart has often been depicted as "discharge," rather than "applied stress" as originally published. We will show a couple of examples, drawn from a target-rich environment, where this has occurred. The fact that discharge and applied stress are not synonymous is obvious and will not be elaborated upon here. Overlooking this distinction has consequences, especially in the estimate of bedload sediment transport at stages above bankfull.

## Shear Moves Bedload Sediment

Gravity is the bus that drives sediment to the sea.

There are multiple modes of sediment transport in streams. Bedload is pushed along by shear stress, while suspended and washload sediment must be maintained in suspension by turbulence and upward velocities that equal or exceed settling velocities of particles.

Figure 2 shows the basic vectors of sediment transport in rivers: gravity, shear stress, normal stress, and friction.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

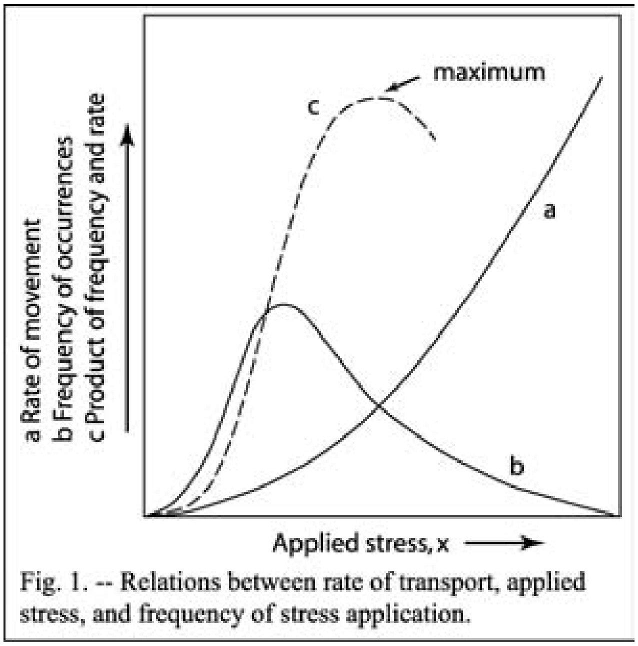



Fig. 1. -- Relations between rate of transport, applied stress, and frequency of stress application.

*Figure 1. From* **Magnitude and frequency of forces in geomorphic processes***, Wolman and Miller (1960).*

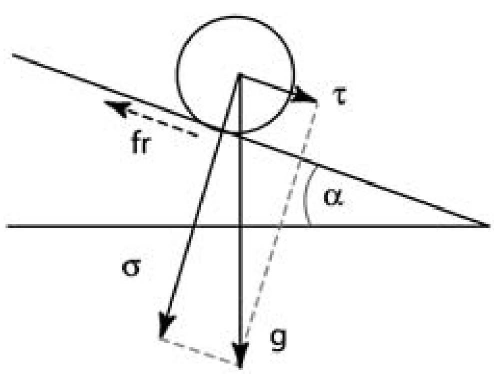



***Figure 2. Forces on a particle; bedload sediment transport. Original figure from a no longer available Internet instruction module from the University of Exeter, Department of Geography, Module 1202/2- "Stream Form and Process".***

Shear is an applied stress. Commonly denoted by the Greek letter Tau, $\tau$, shear is the force applied tangentially to the sediment surface. It is useful to remember that stress and pressure have the same units: force per unit area, $lb/in^2$ or $N/m^2$ .

In *Fluvial Processes*, Leopold, Wolman and Miller describe the relationship between shear and sediment movement in the following terms:

"To the extent that the movement of sediment by water or air is dependent upon shear stress, the rate of movement can be described by the equation

$$\mathbf{q = k}(\tau - \tau^c)^n ,$$

where q is the rate of transport, k [is] a constant related to the characteristics of the material transported, $\tau$ [is] the shear stress per unit area, $\tau^c$ [is] the critical or threshold shear required to move the material, and n [is] an exponent.", p. 79

It is important to remember that shear stress, not discharge, is being described in this equation. The authors' use of the term "q", standard nomenclature for describing discharge, has probably led to some of the later confusion.

This transport relationship is a power function illustrated by the "a" line (Figure 1 in *Magnitude and frequency of forces in geomorphic processes*, also our Figure 1). Applied stress is the independent variable. Figure 3-23 in *Fluvial Processes* is identical. In the text of the 1960 paper and in the subsequent book, Wolman and Miller emphasized that stress must exceed critical threshold values before particles move. Unfortunately, the charts show movement beginning at an implied applied stress just past zero. This, too, has probably led to subsequent confusion.

## The Relationship Shown in Wolman and Miller (1960) Has Often Been Misrepresented

Figure 1, the cornerstone chart from *Magnitude and frequency of forces in geomorphic processes*, has been referenced many times. In many instances, the abscissa has been transformed from applied stress to flow. Figures 3 and 4 are two examples.

### Flow Increases Faster Than Does Shear at Stages Above Bankfull

All erosional processes are driven by gravity. The gravitational force acting on water drives the flow downslope in a confined channel, where the slope of the water surface represents the balance between the energy gradient and frictional resistance from the channel bed and banks.

Shear and flow are partially products of water depth, both increasing as water stage increases. As water levels exceed bankfull stage, water flows out on the floodplain and flow increases considerably faster than does channel shear. Shear, not flow, is moving bedload sediment.

The transport relationship charted in line "a" of Wolman's Figure 1 remains correct above bankfull stage. Transforming the independent variable from applied stress to flow, as in (our) Figures 3 and 4, leads to an incorrect view of the bedload transport rate at stages above bankfull. Bedload transport continues to increase when flows exceed bankfull, but only as shear increases.

It follows that extrapolation of flow/bedload sediment transport rates determined at less than full channel flows,

*Figure 3. Transformation of the abscissa from applied stress to discharge. From Andrews (1980).*

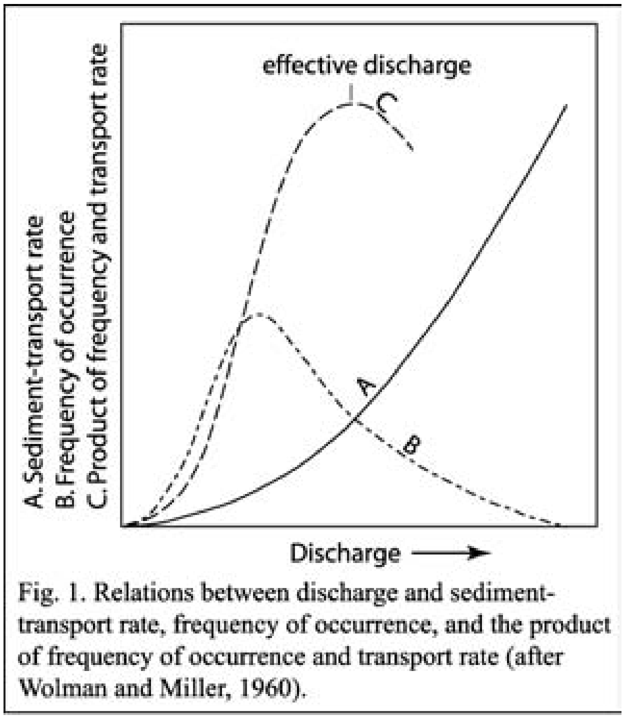
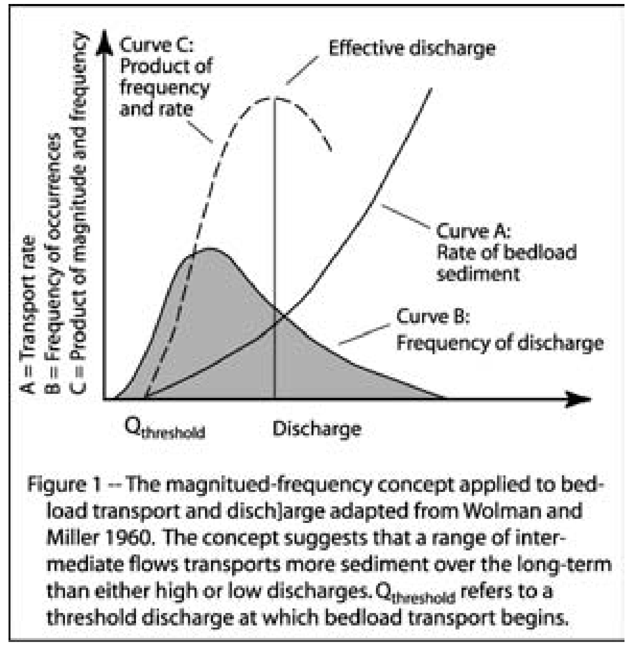



*Figure 4. Transformation of the abscissa from applied stress to discharge: A recent example of the same mistake. From Schmidt and Potyondy (2004).*




to flows in excess of bankfull, can lead to an overestimation of total bedload transport.

## Conclusion

Wolman and Miller's 1960 paper opened innovative lines of inquiry for geomorphology. Figure 1 in that publication has been widely, and often incorrectly, reproduced. The abscissa of that figure is often incorrectly portrayed as "flow" rather than "applied stress" as originally published. Of physical necessity a depiction of bedload sediment as a function of flow needs to show a diminished slope beginning at the stage of bankfull flow.

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# The Evolution of Channel Maintenance Science in the Forest Service

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Channel maintenance instream flows consist of a specified range and duration of flows designed to provide for the self-maintenance of alluvial stream channels. Channel maintenance flows provide for processes that determine the form of the physical channel. Agency scientists placed emphasis on physical channel form to satisfy constraints imposed by litigation in Forest Service reserved water rights claims. The original channel maintenance flow methodology was developed by Forest Service hydrologists in 1982 and the technical basis for channel maintenance flows and quantification approaches has evolved significantly over the last 20 years. Under the original approach, the channel maintenance hydrograph consisted of a rigid stepped hydrograph fixed in time and capped at bankfull discharge. Under current approaches, the flows necessary to maintain channels are seen as a naturally variable range of flows typically beginning at intermediate flows below bankfull discharge and including high flows that inundate the floodplain. While the original approach focused primarily on the need to transport sediment through the stream system, more recent approaches recognize that the required flows must also provide sufficient low and high flows to sustain streamside vegetation. As understanding of gravel-bed streams processes and the linkages between streamside vegetation and streamflows increases, additional improvements and refinements to quantification approaches are likely.

Keywords: *channel maintenance, instream flows, favorable conditions of water flows*

## Introduction

The Forest Service attempted to acquire channel maintenance instream flows in many adjudications throughout the western United States during the 1980s and 1990s. These instream flows claims have generally failed, their failure attributed to hostile state court forums, the stringent test established by the U.S. Supreme Court for implied reserved water rights, and the difficulty of quantifying instream flow water rights for dynamic hydrologic stream systems (Witte 2001). This paper concentrates on the scientific aspects of channel maintenance flows and the extraordinary change in scientific thinking pertaining to channel maintenance that has occurred within the Forest Service and the scientific community between the origination of the first channel maintenance methodology in the 1980s and the present. A brief discussion of the legal framework surrounding the development of channel maintenance instream flow concepts and pertinent court decisions is provided to establish context.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

## The Legal Context of Channel Maintenance Instream Flows

The genesis of the doctrine of federal implied reserved water rights occurred in 1899, but it was not until 1963 that the doctrine was expanded by the United States Supreme Court in Arizona v. California to include national forests, parks, and recreation areas. Prior to the court's decision in 1963, the application of the doctrine (which holds that when Congress reserves land it impliedly reserves water in a quantity sufficient to meet the purposes for the reserve) was widely believed to be restricted to Indian reservations.

Following the expansion of the doctrine to other federal reserves, the Forest Service began filing for instream flows on National Forest System lands. These efforts occurred in state water courts throughout the West pursuant to the limited waiver of federal sovereign immunity provided by the McCarren Amendment (passed by Congress in 1952). This amendment gave state water courts jurisdiction to hear federal water right claims.

Litigation of one of the first claims filed under the federal implied reserved water rights doctrine for National Forest System lands occurred during the adjudication for the water rights of the Rio Mimbres on the Gila National Forest in New Mexico. Instream flow claims for the benefit of fish, recreation, and aesthetics were filed under the authority of the Creative Act of 1891 and the Organic Administration Act of 1897.

These claims were denied in 1978 by the United States Supreme Court in United States v. New Mexico by a narrowly split (5 to 4) decision. The majority ruled that the Forest Service could not claim federal reserved water rights for Multiple-Use Sustained-Yield Act purposes and strictly construed the purpose for which water could be claimed under the doctrine on National Forest System lands to two purposes, "securing favorable conditions of water flows and to furnish a continuous supply of timber."

In an effort to protect stream flows for these narrow purposes on National Forest System lands, the Forest Service defined favorable conditions of water flows to include healthy stream channels. Under the constraints imposed by the Supreme Court, the Forest Service devised a methodology to determine the amounts of water necessary to maintain stream channels in a condition suitable for "securing favorable conditions of water flows." The flows quantified under this approach came to be known as channel maintenance instream flows. Due to the constraints of the federal impliedly reserved water rights doctrine, only the minimum amount necessary to secure favorable conditions of water flows could be claimed (Witte 2001).

Channel maintenance flows are non-consumptive instream flows specifically designed to maintain the physical characteristics of the stream channel (Schmidt and Potyondy 2004). Providing for channel maintenance requires that stream channels support healthy streamside vegetation and have flows of sufficient magnitude, duration, frequency, and timing to maintain channel morphology so that the capacity of the channel to convey natural flows is unimpaired over the long term.

## The Original Channel Maintenance Methodology

The original channel maintenance methodology was primarily developed by Forest Service hydrologists David Rosgen and Hilton Silvey (Rosgen 1982) and are based to a large extent on concepts contained in the classic geomorphology textbook, "*Fluvial Processes in Geomorphology*" by Leopold, Wolman, and Miller (1964). Subsequent personal involvement in Colorado's Water Division One litigation by Luna Leopold, Emeritus Professor of Geology at the University of California, Berkeley, former Chief Hydrologist of the U.S. Geological Survey, and one of the world's leading authorities on river hydraulics and geomorphology, gave credibility to these ideas.

The Forest Service's original channel maintenance procedure was documented in the Forest Service directives system, Forest Service Handbook 2509.17, Chapter 30, "Procedure for Quantifying Channel Maintenance Flows" (USDA Forest Service 1985). In it, channel maintenance flows are defined as, "A range and duration of in-channel flows necessary to maintain the stability and effective function of the stream channel. This includes those flows which are necessary to provide for the self-maintenance of the stream channel network so as to retain its capacity for passing flood discharges and minimize channel erosion and/or sediment deposition associated with instability or disequilibrium conditions. The consequences of not maintaining channel stability include channel aggradation, channel erosion, floodplain encroachment, vegetation encroachment, changes in hydraulic geometry, and reduced channel capacity with resultant increased risk of flooding and associated resource damage."

The channel maintenance procedure was intended for application to snowmelt dominated, perennial, alluvial channels capable of adjusting their dimension, shape, pattern, or gradient, or several of these characteristics, in response to changes in streamflow (Rosgen et al. 1986). Generally accepted concepts used by engineers, hydrologists, and geomorphologists formed the basis for the channel maintenance procedure.

Three basic flow components were considered essential for a channel maintenance flow regime: (1) a peak flow (bankfull discharge); (2) a low flow (baseflow discharge); and (3) snowmelt rise and recession discharges (Figure 1). Bankfull discharges were considered essential because flows near bankfull have been shown to move the most sediment over the long term (Wolman and Miller 1960) and are frequently referred to as channel-forming flows. Baseflows were considered necessary to maintain the "thread of the stream" (the thalweg channel) by migrating sediment from riffles to pools and preventing vegetation encroachment and seedling establishment in the active channel by maintaining high water tables. Gradual rise and recession flows were included to avoid rapid changes in stage which might cause accelerated bank erosion and to allow for a duration of flows that mimics the natural hydrograph. This was accomplished by beginning the claim when average annual flow was first attained during the spring snowmelt hydrograph. Flows were then gradually increased in 10 percent increments between the average annual and bankfull discharges resulting in a stair-stepped hydrograph up to and including bankfull discharge. The recession limb of the hydrograph was constructed in a similar manner except that the duration of recession flows was constrained to one day under the concept of the existence of a hysteresis effect, allowing for a rapid recession. Hysteresis assumes

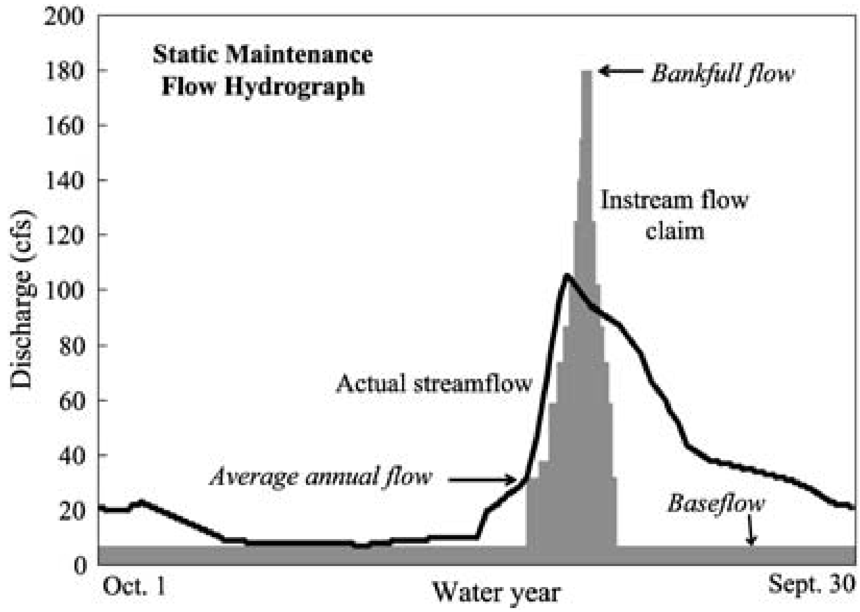


*Figure 1. The original form and elements of the static maintenance flow hydrograph consisting of gradual rising steps, a cap at bankfull discharge, a recession limb, and year-round baseflows.*

that the majority of the sediment is transported during the rising limb and therefore flows during the recession portion of the hydrograph are not as critical for sediment movement and channel maintenance. Therefore, flows after the peak were allowed to decrease rapidly relative to the rise.

A typical static channel maintenance flow hydrograph is constructed using this procedure (Figure 1). The term static is used because the shape of the hydrograph was fixed in quantity and time once it was initiated by the occurrence of average annual flow. A static form was required because the procedure was developed under the assumption that the instream flow claim must meet the basic requirements of State water rights law, that is, in order to provide for certainty in water administration the amounts claimed needed to be precisely stated with respect to time and amount. Details of the procedure for constructing maintenance flow hydrographs can be found in Forest Service Handbook 2509.17, Chapter 30 (USDA Forest Service 1985).

Significant technical points of contention included questions of whether average annual flow was the appropriate required discharge for the beginning of channel-maintaining sediment transport, whether peak flows constrained to no more than bankfull discharge were adequate to maintain stream channels, and whether baseflows played any important role in maintaining physical channel characteristics.

## Development of the Dynamic Hydrograph

Technical problems with the static nature of the channel maintenance flow hydrograph first surfaced during the 1991 trial of an adjudication encompassing the South Platte River and its tributaries, hereafter referred to as Water Division 1. During the trial, experts for the State of Colorado analyzed the entire period of daily flow records for 19 USGS gaging stations and superimposed the static hydrograph to determine how often the claim would actually be met. The analysis showed that actual hydrographs varied from year to year to such an extent that the static claimed hydrograph frequently misaligned with the occurrence of peak flows (e.g., Figure 2). Note that in this example bankfull discharge occurs in the stream, but at the time of its occurrence, significantly lower amounts of water are claimed due to the fixed, static nature of the claim process. Likewise, when bankfull discharge is claimed, natural stream flow for that year has already receded so that water equal to bankfull is unavailable. The net result is that in this high flow year scenario, the bankfull discharge required to maintain the channel would fail to be claimed by the Forest Service.

The pattern from the 19 streams examined showed that the channel maintenance flows claimed would only reached bankfull discharge 15 to 19 percent of the years of record (Gordon 1995). This low occurrence of bankfull discharge was significantly less than the 67 percent of the years (every two out of three years) that Forest Service technical testimony had argued was necessary for the channel to be maintained. The State concluded its testimony by pointing out that even if the claim was granted, the Forest Service would fail to achieve the desired maintenance objective. Conceding, but never refuting the analysis, the Forest Service proceeded to develop the dynamic hydrograph in a span of several weeks to overcome the deficiencies of the static approach.

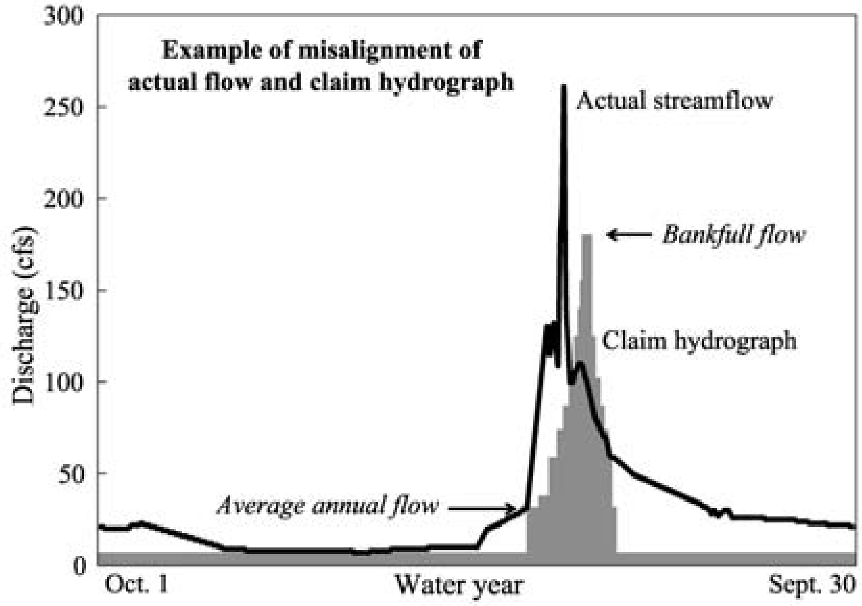


*Figure 2. A typical example of misalignment between actual streamflow and the static maintenance flow hydrograph.*

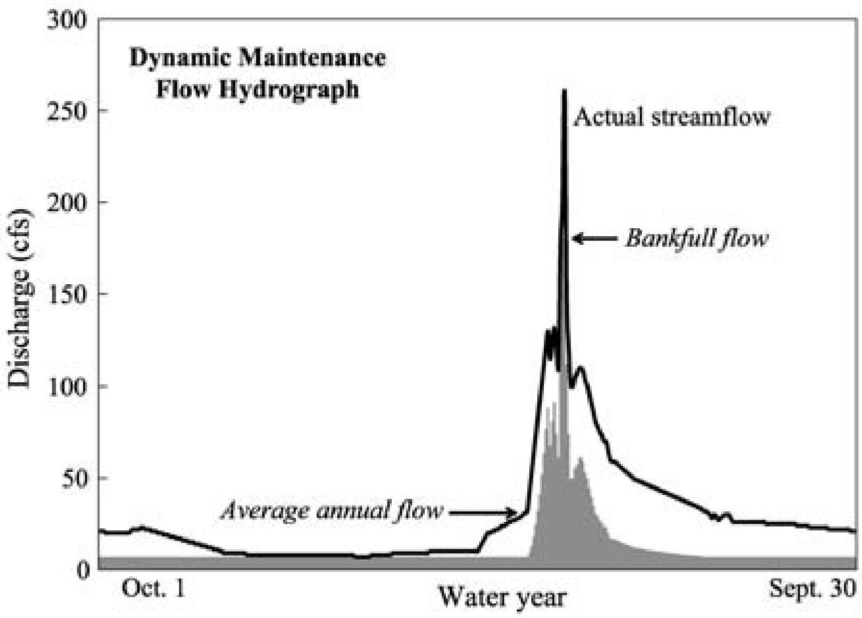


*Figure 3. The form and elements of the dynamic maintenance flow hydrograph structured so that the claim is only made when water is in the channel and claimed flows are proportionally distributed so that more water is claimed at flows approaching bankfull discharge.*

The "dynamic" hydrograph was so named because it rises and falls with natural stream flows. To achieve this, the dynamic claim hydrograph was structured and positioned so that it only claimed flows when water was actually in the stream channel (Figure 3). The dynamic form retains most of the essential features of the static form: claim initiation beginning with attainment of average annual flow, a maximum peak set at bankfull discharge, and a baseflow component. However, instead of the "stairstep" appearance of the static claim, the dynamic form claimed a sliding percentage of the streamflow such that more water was claimed at flows closer to bankfull. Amounts were calculated according to the following formula:

$$\text{Claimed flow} = Ql + \left( (Qs - Ql) \times \left( \frac{Qs - Q\,a}{Qb - Q\,a} \right) \right)$$

where: Qs = actual streamflow, Ql = baseflow, Qa = average annual flow, and Qb = bankfull flow.

Positioning the claim under actual stream flows eliminated a primary deficiency of the static hydrograph by assuring that the claim was active only when flows up to the channel forming bankfull discharge occurred. Scientifically this provided an improved solution of the channel maintenance flow problem. Administratively however, the dynamic solution was complex and problematic because it might not meet fundamental requirements of a water right with respect to time and amount and it would be difficult to administer in practice. In addition, other technical points of contention pertaining to bankfull discharge, the initiation of sediment movement at average annual flow, and the need for baseflow remained.

In the final decision in the Water Division 1 litigation in 1993, Judge Behrman denied both the static hydrograph and dynamic hydrograph based channel maintenance claims. The judge observed that the technical challenges to quantify channel maintenance claims had not been adequately met and noted that it might be impossible to do so (Gillilan and Brown 1997). He further commented that the hurried time constraint imposed on the development of the dynamic hydrograph in particular was not the ideal environment for careful scientific study and suggested that a proposal developed under calmer and more scholarly circumstances would be appropriate (Gordon 1995).

## Current Approaches

The USDA Forest Service Stream Systems Technology Center was established in 1992, in part, to improve the scientific understanding of channel maintenance flows. Since that time, they have consulted with a wide array of scientists in the Forest Service, other agencies, universities, and consultants, with the aim of arriving at a consensus on the best science available to address this issue.

While there is still diversity of opinion on many technical aspects of channel maintenance, initial consultation with the scientific community identified four technical areas that were at odds with then existing Forest Service approaches:

1. Channel maintenance requires a range of flows, including peak flows exceeding bankfull discharge;
2. In alluvial gravel-bed streams, required channel maintenance flows need to periodically move the caliber of sediment making up the bed of the channel (Phase 2 transport);
3. Baseflows, while perhaps necessary for other important ecological functions, play an insignificant role in maintaining the physical form of the channel; and
4. Streamside vegetation plays an important role in maintaining stream channels.

**Sediment Transport**

A major change in scientific thinking beginning in the late 1980s and through the 1990s is the concept that channel maintenance in gravel-bed streams centers around a range of intermediate flows rather than bankfull discharge alone. While Emmett (1976) was the first to propose two distinct phases of transport in armored channels as early as 1976, it was not until the 1980s that others expanded the concept to describe phases of bedload transport in gravel-bed streams (Jackson 1981; Jackson and Beschta 1982; Beschta 1987; Ashworth and Ferguson 1989; Warburton 1992). During the 1990s, numerous other scientists confirmed that intermediate discharges transport mainly sand (Phase 1 transport) whereas discharges near or above bankfull transport coarser bedload (Phase 2 transport) (Church et al. 1991; Komar and Shih 1992; Kuhnle 1993; Carling 1995; Lisle 1995; Wathen et al. 1995; Petts and Maddock 1996; Wilcock and McArdell 1997; Whiting et al. 1999; Ryan and Emmett 2002; Church and Hassan 2002). While there is widespread agreement that movement of coarse gravels beginning at discharges associated with Phase 2 transport and continuing on to higher discharges is important for channel maintenance, considerable uncertainty exists regarding the best manner to identify this initiation discharge and numerous approaches have been proposed (Emmett 1999; McNamara et al. 2000, Ryan et al. 2002, Whiting and King 2003, Schmidt

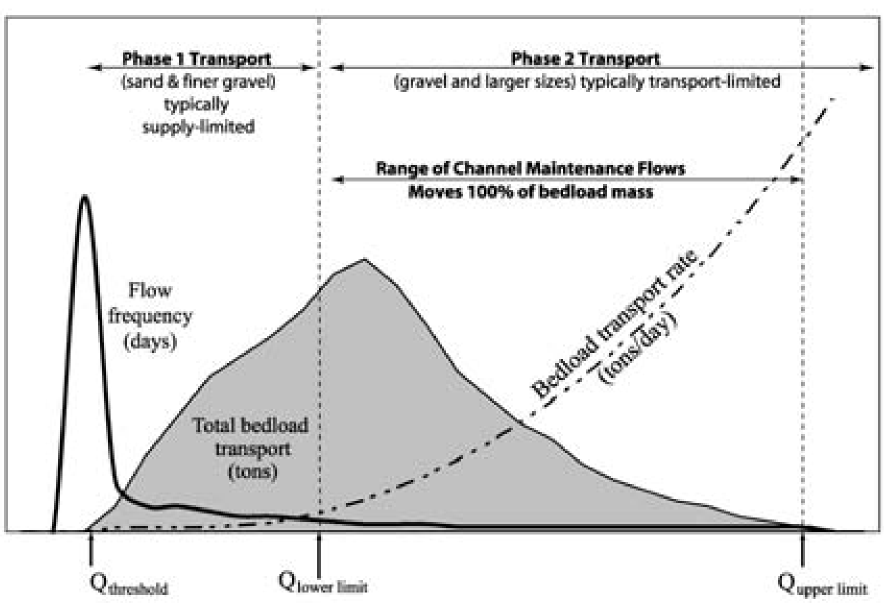


*Figure 4. A conceptual model of total bedload transport that forms the basis for the current proposed approach for quantifying channel maintenance instream flows in gravel-bed streams in the western United States.*

and Potyondy 2004). Regardless of methodology used to identify initiation, investigators generally have found that Phase 2 transport begins at discharges ranging between 60 to 100 percent of bankfull discharge (Jackson 1981; Pitlick 1994; Carling 1995; Petts and Maddock 1996; Ryan and Troendle 1996; Whitaker 1997; Ryan et al. 2002, 2005; Trush et al. 2000).

Schmidt and Potyondy (2004) summarize the current science and develop a conceptual gravel-bed river total bedload transport model (Figure 4) which forms the basis for a proposed approach for quantifying channel maintenance instream flows in gravel-bed streams in the western United States. The approach is appropriate for quantifying channel maintenance flows on perennial, unregulated, snowmelt-dominated, gravel-bed streams with alluvial reaches. Under this approach essential channel maintenance flows begin at a lower limit of discharge associated with the onset of Phase 2 bedload transport (80% of bankfull is used as an example in the diagram) and includes all flows up to an upper limit set at the 25-year flood stage (Figure 5). All flows from the lower limit to the upper limit are claimed as necessary for channel maintenance whenever these flows occur assuring that claims are made only when water actually exists in the stream channel. While all high flows contribute to sediment transport and channel morphology, flows exceeding the 25-year event are excluded as unnecessary for channel maintenance because they are thought to play a role primarily in valley maintenance (Hill et al. 1991). In addition, because extreme high flood flows may cause property damage, they are excluded for practical purposes because it is difficult to characterize these high flows as a "favorable condition of water flow." The current hydrograph structure claims considerably less water than either the static or dynamic approaches because it places greater reliance on short duration flows approaching and exceeding bankfull to accomplish the necessary sediment transport.

A remarkable shift in our understanding of the range of sediment transporting flows needed for channel maintenance has occurred (see Figure 6). The original peak flow structure began with a conservative estimate of when bedload may begin to move in some channels, typically a value of around 20% of bankfull discharge, and was limited to flows no higher than the bankfull discharge contained within the main channel, excluding flows that would spill onto the floodplain. The current peak flow approach begins with the initiation of coarse sediment transport making up the bed of the channel, commonly a value ranging from 60 to 100% of bankfull discharge and having an average of about 80% of bankfull discharge. The flows exceed bankfull to a significant degree and include flows that spill onto the floodplain, recognizing that the floodplain is an extension of the channel that needs to be periodically disturbed in order to maintain floodplain processes and streamside vegetation.

**Streamside Vegetation**

A parallel shift in thinking has also occurred regarding the role of vegetation in channel maintenance flow processes. Under the original approach, vegetation was essentially considered an "enemy" of channel maintenance and the original approach argued that baseflows were necessary to prevent vegetation encroachment within the channel while failing to acknowledge the role streamside

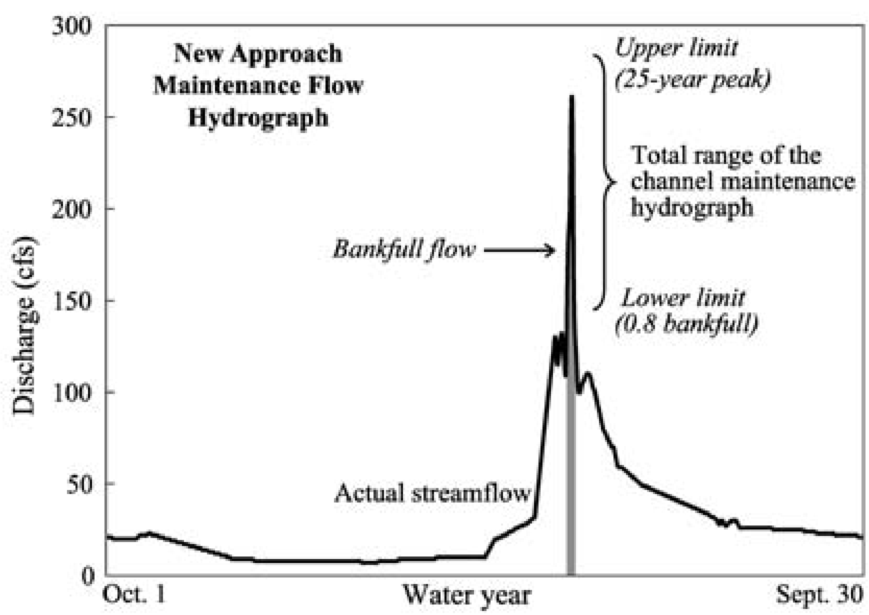


*Figure 5. The form and elements of the maintenance flow hydrograph under the current approach. Channel maintaining flows begin at a lower limit with the initiation of coarse gravel (Phase 2 transport) and include flows up to an upper limit, the 25-year peak flow.*

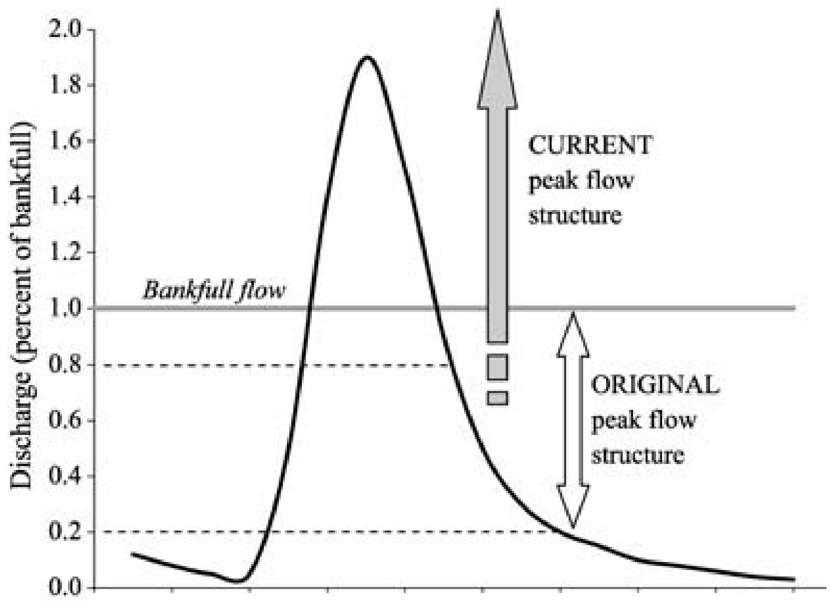


*Figure 6. An illustration of the remarkable shift in the range of flows considered necessary for channel maintenance between the original static hydrograph approach of the 1980s and the range of flows considered to necessary today.*

vegetation plays in providing for streambank stability. The primary concern centered on possible detrimental effects to the channel that might result from in-channel vegetation blocking orderly sediment transport through the system.

The current approach treats streamside vegetation as an essential part of a well-maintained channel by recognizing that a properly functioning channel requires a flow regime that not only conveys water and sediment, but also maintains adequate streamside vegetation to protect the integrity of channel banks and floodplain while at the same time keeping the channel proper free of perennial vegetation (Schmidt and Potyondy 2004). Toward that end, high flows exceeding bankfull stage are needed to provide for periodic disturbance to assure regeneration and to scour vegetation from the channel. These high flows can substantially influence channel dynamics, encourage floodplain scour and sediment deposition, provide for water storage and nutrient cycling and the periodic disturbance required by streamside and floodplain plant communities (Jackson et al. 1987; Gebhardt et al. 1989; Gregory et al. 1991; Stromberg et al. 1991; Jackson and Beschta 1992; Mahoney and Rood 1993).

The association between riparian vegetation and streamflow is particularly evident in arid environments and year-round baseflow may also be needed to sustain protective streambank vegetation in losing reaches in arid and semi-arid regions (Stromberg and Patten 1996). However, in many temperate mountainous environments, adequate soil moisture during the growing season is available to sustain streamside and floodplain vegetation because subsurface flows contribute moisture to riparian soils and mountainous sideslopes contribute water to maintain soil moisture and baseflow making instream baseflows unnecessary (Schmidt and Potyondy 2004).

## CONCLUSION

The goal of this paper is to describe the differing approaches to channel maintenance that the Forest Service has employed over the years. Science by its very nature is dynamic and continually expanding in its understanding. Furthermore, disciplines, especially relatively young sciences such as fluvial geomorphology, operate under accepted paradigms until new paradigms are adopted and this is part of the process that has been especially evident over the last decade (Kuhn 1962). The change implemented by the Forest Service in its channel maintenance technology in response to challenges to its science in legal proceedings and other forums is a positive, rather than a negative attribute.

More hydrologists and geomorphologists work in the field of fluvial geomorphology today than at any time in the past. Numerous papers are being published, research is in progress, and understanding of geomorphic processes is expanding and changing as interest in the disciple continues. By discussing and understanding the strengths, weaknesses, and appropriateness of past methodologies, it may be possible to encourage the development of improved ideas and approaches.

Two specific areas need further research with respect to current channel maintenance science: First, much remains to be learned about sediment transport science in coarse-grained gravel bed channels typically found in the mountainous watersheds of the national forests; Second, much remains to be learned about streamside vegetation and species specific linkages between streamside vegetation and streamflows in mountain streams. As work in these areas continues, we can be certain that the science of channel maintenance will once again evolve in response to this new knowledge and the approach employed today may again need to be refined to reflect the new science.

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# Forest Service Channel Maintenance Flows in the Klamath Basin

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The Fremont-Winema National Forest has filed channel maintenance in-stream flow water rights claims within the Upper Klamath River basin, Oregon. Claims were filed at 31 sites under the 1897 Organic Act, and represent an estimate of the minimum flows necessary to maintain stream channels over time. Data were collected on stream hydrology, the composition of bed-material, bedload transport over a range of flows, and channel characteristics. These data were used to formulate an instream flow claim based on the ability of the stream to move the larger particle sizes composing the streambed and banks, and thereby maintain the channel. Channel maintenance flows were determined to begin when the framework component of the bed-material as determined by the Parker-Klingeman bedload transport model began to be mobilized by the stream. Streambed framework materials consist of gravel-sized particles, and make up the major morphological features of the streambed. Channel maintenance flows are relatively high flow events, and include the range of high but not extreme discharges that are most effective at transporting bedload sediment and thereby maintaining channel capacity. Because this method for quantification of channel maintenance flow claims is calibrated to individual stream characteristics, it can be easily adapted for use in a wide variety of streams and conditions.

Keywords: *channel maintenance flows, Upper Klamath River basin, Fremont-Winema National Forest, Organic Act, bedload*

## Introduction

### Favorable Conditions of Flow and Reserved Water Rights

The Forest Service has filed Favorable Conditions of Flow (FCF) claims at 31 sites under the 1897 Organic Administration Act, 16 U.S.C. § 475, which defined the purposes for which National Forests were originally created. In 1978, the United States Supreme Court (United States vs. New Mexico, 438 U.S. 696, 706-707) reaffirmed the idea that that one of the reasons the National Forests were established was for the purpose of "securing favorable conditions of water flows." Water rights claims for instream flows were prepared by the Fremont-Winema National Forest, and were initially submitted to the Oregon Department of Water Resources in April 1997. The purpose of this paper is to provide detailed information on the concepts and procedures used in developing Favorable Conditions of Flow (FCF) channel maintenance instream flow water rights claims by United States Department of Agriculture, Forest Service, on national forest lands within the Upper Klamath River basin, Oregon. These claims prescribe the minimum amount of streamflow necessary to maintain stream channels over time and thereby ensure the delivery of water to downstream users.

Since the passage of the Organic Act, engineers and natural scientists have become more knowledgeable about the hydrologic cycle and have gained a better understanding of the effect of forested lands on incoming precipitation, runoff patterns, evaporation, and transpiration. The phrase "favorable conditions of flows" has been interpreted to apply to forest management and the hydrologic cycle in the following two ways. First, the forest was thought of as a moderator of runoff and streamflow, where flood flows such as spring runoff were stored. It was generally recognized that forest cover might increase infiltration of precipitation into the ground, reducing runoff and flood peaks and eventually increasing low flow in streams. Secondly, it was important to protect forests and the integrity of stream channels for the conveyance of streamflow so that forest lands could contribute to a sustainable water supply to downstream users.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

If a stream channel has reduced capacity to convey water, flows are impeded, the risk of flooding is increased, and the efficiency of water delivery to downstream users is impaired. The FCF instream flow claims are intended to maintain the physical characteristics of the channel so that the ability of the channel to convey streamflow and sediment is maintained. These non-consumptive claims do not reduce the amount of streamflow available for downstream appropriators and other uses. They are initiated only during periods of high streamflow, and require the minimum amount of streamflow necessary to maintain proper functioning condition of streams by maintaining channel capacity and channel features so that the ability to pass natural flows is ensured.

**Channel Maintenance**

Channel maintenance and the morphology of channels depend on a complex set of watershed physical processes and factors related to stream hydrology and the transport of sediment. A certain quantity of streamflow is necessary to transport the sediment entering the channel and thereby maintain channel form. As well as removing sediments supplied to the channel, higher flows prevent the encroachment of vegetative growth in the channel (Reiser et al. 1989). The amount of streamflow needed to maintain the channel depends on the quantity and sizes of sediment entering the channel. A stream will adjust to streamflow and sediment inputs to maintain a mean equilibrium that reflects the prevailing flow and sediment regimes (Lane 1955; Rosgen et al. 1986).

To maintain a channel's shape, the volume of material transported into the channel reach must be conveyed through the reach over time. Failure to convey the sediment load delivered to a stream reach over time will result in sediment accumulations in the reach and reduction in the capacity to convey flood flows. Channel maintenance flows must account for fluctuations in flow and the quantity and characteristics of the sediment and other debris supplied to the channel. Channel maintenance processes act over time. While sediment may accumulate during one period of time, accumulated sediments are eventually removed. For example, erosion of streambanks or sediment influx from tributaries may locally increase bed elevations, leading to small-scale flooding and flow diversion, with sediments eventually transported and redistributed to downstream areas.

The frequency and duration of moderately higher streamflows, especially flows around bankfull and larger, are particularly important for controlling channel morphology (Hill et al. 1991). Bankfull flows are those flows that fill the channel up to the stage where the stream just begins to overflow into its floodplain. In gravel-bed streams, these relatively high flows result in significant rates of bedload transport (Beschta 1987), because bedload transport rates generally increase rapidly with increasing streamflow. Large floods are very effective at altering channel form as they are able to transport significant amounts of sediment. However, over longer periods of time large events transport a far smaller total volume of bedload (Leopold 1992). In contrast, flows that fill the channel to the level of the floodplain (bankfull flows) are most effective at moving sediment over time, and are the dominant channel-forming flows (Wolman and Miller 1960; Andrews 1984; Leopold 1992) in mobile, alluvial bed channels. The mean recurrence interval of bankfull flows (on an annual flood frequency series) for a large variety of rivers has been found to be about 1.5 years (Dunne and Leopold 1978), but can also vary considerably from the 1.5-year flood (Hey 1994).

**Sediment Transport**

The movement of sediment involves its entrainment, transport, and ultimate deposition. Bedload and suspended load are the two major modes of sediment transport (Graf 1971; Richards 1982). Suspended sediment consists mainly of finer particles such as silts and clays, which are completely supported by the turbulence of flowing water. Bedload usually consists of particles of sand, gravel, cobbles, and boulders that are transported by traction, or roll, slide, and bounce along the streambed.

In flowing water, the smallest particles such as silt, clay, and colloids are held in suspension within the water column. Suspended sediment concentrations typically show considerable variation over time, and respond in a non-linear and highly sensitive manner to changes in flow and sediment availability. Particle settling velocities and fluid forces in turbulent flow work to maintain larger particles such as sand in suspension. As a result, the distribution of sand of 0.01- to 1-mm diameter in the water column is not uniform, and often results in transport alternately as bedload and in suspension (Beschta 1987). The spatial concentrations of these larger particle sizes may continuously shift as flows encounter different channel geometries and hydraulic conditions in downstream transport.

Bedload transport rates in streams vary spatially and temporally, even during constant flow conditions. Generally, bedload transport increases rapidly with increasing discharge. That is, as discharge increases, bedload transport rates increase at an exponentially greater rate than the flow (Gomez 1991).

***Importance of Bedload and Suspended Sediment to Channel Maintenance.*** Bedload is important in the formation of channels. Gomez (1991) points out that a significant portion of river-deposited sedimentary rocks in the geologic column are composed of particles coarser than the maximum sand size transported in suspension in contemporary river systems. Further, he states:

'If river morphology is viewed as the result of interplay between hydraulic conditions and the resistance of materials in the channel perimeter, bedload transport provides the major process linkage between these factors, and virtually all aspects of morphologic change in a river, including bank erosion, are governed by bedload transport.'

Movement of the coarser or larger bedload has been found to be more important in the formation of channel geomorphic features than the finer fraction of the bedload (Leopold 1992). The coarser fraction of the material transported by the stream annually, although it makes up a smaller fraction of the total bedload, determines and comprises the major features of the channel's morphology.

Suspended sediment may be important in channel-forming processes where it is a dominant component of the sediment supplied to the stream. In high energy gravel-bed streams, suspended sediment likely plays less of a role in channel maintenance than bedload. The finer fraction of suspended sediment (silts and clays) can often be transported very long distances within a river system [Fisk (1947), as cited in Chorley et al. (1984)], and may be transported through a reach without significant deposition.

In light of the dominant role of bedload in channel formation and maintenance, the methodology for determining FCF water rights claims should be based on bedload transport rates over a range of flows for a particular stream and the properties of the bed-material sediments to determine the appropriate flows needed to maintain channels. By determining the quantity and size of bedload transported with increasing discharge, a FCF instream flow claim can be established that asks for the smallest amount of streamflow necessary to accomplish the objectives of channel maintenance.

***Estimation of Bedload Transport.*** Physical bedload prediction models are widely used to estimate bedload transport rates where extensive bedload samples and long-term flow information may not exist. These physically-based models rely on the premise that a unique relation exists between hydraulic variables, sedimentological parameters, and the rate at which bedload is transported. They use information including channel dimensions and profile, the size distribution and characteristics of bed-material, stream hydraulics, and energy slope, and bed shear stress (Vanoni 1978; Parker and Klingeman 1982; Dawdy and Vanoni 1986). Bedload transport equations generally assume equilibrium between bedload inflow and outflow. When applying a bedload transport equation, more accurate predictions can be obtained when the model is calibrated against field data from the particular site where it is to be applied (Dawdy and Vanoni 1986).

Bedload transport in the Upper Klamath basin was estimated by the Forest Service using the model developed by Parker and Klingeman (1982). This bedload transport model utilizes bed shear stress to estimate transport. Bed shear stress is measured as the force of flowing water against the bed, and is calculated based on the specific weight, depth and energy slope of the water. The Parker-Klingeman (PK) bedload transport model can be calibrated to the individual hydraulic, morphologic, and bedload transport characteristics of streams.

The subpavement particle size distribution was used as the basis for bedload transport modeling, because over time, the bedload composition more closely resembles the subpavement particle size distribution. Calibration of the model using locally derived hydraulic and bed-material characteristics should greatly enhance the predictive power of a bedload transport formula (Dietrich and Smith 1984). A more detailed description of the application of the PK model is described in Bakke et al. (1999).

**Streambed Characteristics: The Nature of Bed Sediments**

Adequate characterization of bed-material is a fundamental part of establishing Favorable Conditions of Flow instream flow claims, using the approach taken in the Klamath River basin by the Forest Service. Bed-material distributions are used in the bedload sediment transport modeling process, to characterize channel roughness, and to determine initiation of transport of bedload. Bedload initiation information obtained from bed-material sampling is important in the development of water rights claims for channel maintenance.

Bed-material in alluvial, gravel-bed rivers is often observed to be poorly sorted and spatially heterogeneous, and can include a large variety of size classes. This spatial heterogeneity is often more pronounced in streams and rivers in mountain environments. Differences in material sizes on the bed of a stream can be caused by a variety of processes including mass wasting inputs, glacial lag deposits, logs or other debris, tributary inflow, and the migration of channel bedforms. The specific geomorphic and geologic context of a stream will influence the patterns of sediment delivered to the stream, and ultimately its bed-material size distribution.

Bed-material is characterized by a bed surface layer that is often more coarse than the underlying material, especially in heterogeneous sediments (Chin et al. 1994). Below dams or in other areas of diminished sediment supply, this layer has been called a static armor layer (Gessler 1967; Little and Mayer 1976; Bray and Church 1980) and is relatively immobile at ordinary discharges. Mobile armor, in contrast, exists where an upstream sediment supply is present (Andrews and Parker 1987), and is mobile under frequently occurring high flows (Leopold and Rosgen 1991).

The mobile armour layer may also be described as pavement (Parker et al. 1982; Parker and Klingeman 1982), and is approximately equal in thickness to the depth of the larger exposed particles (Andrews and Parker 1987; Andrews and Erman 1986). The layer of generally finer bed-material lying below the pavement layer is called the subpavement layer (Parker and Klingeman 1982), or the sub-armour layer. This layer may act a source of sediment to replenish the surface layer as it erodes (Parker and Sutherland 1990). An understanding of the various processes by which the bed of the stream and the pavement and subpavement layers change with increasing flow is important for the application of bedload transport equations used to predict amounts and size classes of bedload at various flows (Dawdy and Vanoni 1986).

The pavement layer of the stream (Figure 1) has been described as being inherently mobile and dynamic, and interchanges with the bedload. It forms readily on streambeds, and has been found to be present even during floods capable of moving all available grain sizes (Parker and Klingeman 1982). It has also been described by Parker and Klingeman (1982) as being a regulator that forms "just so as to render all available grain sizes of nearly equal mobility." The pavement layer acts to hide the smaller sized bed-material from the flow, and limit its entrainment into the bedload. In turn, larger particles exposed on the bed surface are more exposed to flow, and as a result are nearly as mobile as the finer material (Parker and Klingeman 1982; Andrews and Parker 1987).

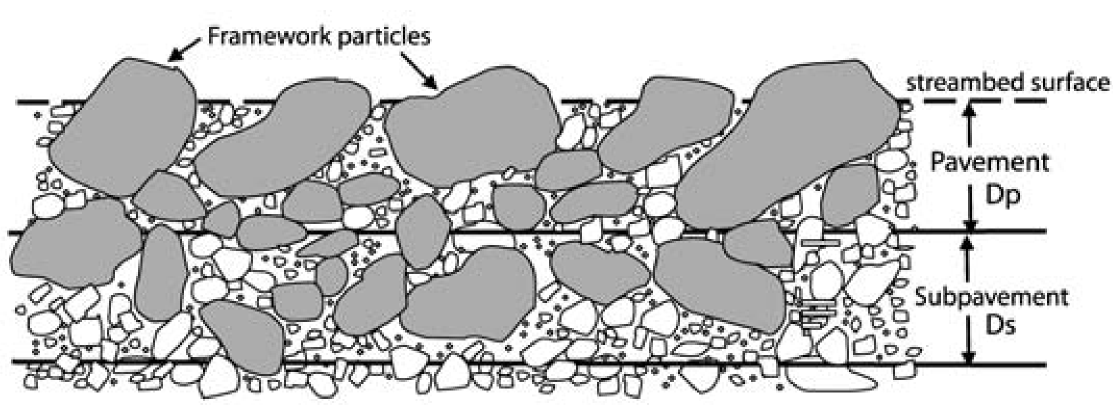
Gravel-bed, alluvial channels are composed of materials deposited by flowing water. In many alluvial rivers gravels deposited by the river consist of a framework of coarse particles or clasts, the voids of which are filled to some degree with finer sediments, which are termed the matrix materials (Miall 1996; Church et al. 1987; Carling and Reader 1982). Framework particles are usually in tangential contact with each other and form a stable, self-supporting structure (Pettijohn 1975). Deposits in which finer material such as sand and silt exceeds 30 percent of the total volume of sediment are called 'matrix supported' gravels. Large framework clasts in these deposits are not necessarily in contact with each other, and the spaces between large particles are filled with finer material.

## Study Area, Channel Maintenance Sites and Data Collected

### Physiogeographic Setting

The Upper Klamath River basin is located in south-central Oregon and northern California. It is bordered on the west by the summit of the Cascade Range, on the north by the Deschutes River basin, on the south by the Pitt River watershed, and on the east by the northwestern margin of the Great Basin. The geology is mostly volcanic, with minor accumulations of alluvium and other sedimentary strata. Precipitation varies from over 70 inches (178 cm) annually in the higher areas of the Cascades, to less than 20 inches (51 cm) annually in lower, more arid areas. The portion of the basin above Upper Klamath Lake is over 3000 mi$^2$ (7680 km$^2$) in area.

*Figure 1. Alluvial gravel deposit, with pavement (Dp), and subpavement layer (Ds). Framework is shown by the darker particles. Matrix is composed of finer material between larger grains, and may consist of small gravel, sand, or finer material.*



The Klamath River flows about three hundred miles (482 km) from its headwaters to the Pacific Ocean. Three major tributaries contribute to the flow of the Klamath River. These are the Sprague, the Sycan, and the Williamson, all of which arise in a mountainous region of south-central Oregon and drain into Upper Klamath Lake. The Klamath River itself begins where the river flows out of Upper Klamath Lake.

**Sites and Data Collected**

Thirty-one USDA Forest Service claim sites were included in the analysis of channel maintenance flows. These channel maintenance sites were located on alluvial channels within the boundaries of the Winema, Fremont, and Klamath National Forests, and were usually located near the national forest boundary. All flow and bedload information was collected at a claim site consisting of a specifically designated cross section, termed the channel maintenance cross section. Selection of the location of this cross-section followed guidelines outlined in Rantz (1982). Information on bedload transport, bed-material, stream discharge, and water surface slope data were collected at all claim sites.

More intensive bedload sampling and discharge measurements were done at ten fluvial process study claim sites (Table 1) to help further understand fluvial processes in the Upper Klamath River basin. These sites were selected because they were located in diverse geomorphic settings, which were thought to represent a variety of hydrologic and geomorphic conditions typically encountered in the Upper Klamath River basin. Information on sediment transport and discharge at these sites increased our understanding of fluvial process in the Upper Klamath River basin. The number of bedload samples at these locations varied from 5 to 26, however all but one fluvial site had more than 11 samples collected. Forest Service personnel collected all bedload samples with the single exception of the Sprague River at Chiloquin, Oregon site, where the US Geological Survey (USGS) collected the bed-material. Two of the streamflow gages were run by other agencies, and had substantially longer periods of record than the Forest Service gages, which ran for 5 to 7 years. All streamflow gages at these sites were recording gages.

Bedload transport samples were collected at 21 miscellaneous sites. Real time stream gages were operated at 10 of these sites. Discharge was measured approximately monthly during the spring, summer, and fall months at the remaining 11 ungaged sites. From two to four bedload samples were collected at each of these sites.

**Methods**

***Discharge Measurements and Rating Curves.*** Discharge measurements were performed and discharge rating curves developed for each site using methods established by the Water Resources Division of the USGS, as outlined in Rantz (1982). Discharge records were adjusted to accommodate shifts in channel controls and bed elevations, and to accommodate ice blockage in the channels during the winter and spring months. Flow duration curves were generated from processed stream data. At sites with data recorders, pressure transducers were used to record hourly water stage. Transducers were housed in a stilling well located near the cross section used for discharge measurements.

***Bed-material Sampling.*** Given the broad spectrum of particle size classes often encountered in gravel-bed rivers, it is difficult to design and implement a sampling program that adequately represents all or most of the material present. Changes in substrate size and condition can vary longitudinally, laterally, and over time. The volume and area of the bed that was sampled must represent the bed-materials well enough to be used in the bedload

*Table 1. Fluvial Process Sites, number of bedload samples collected, and period of record for discharge records used for claims.*

| Fluvial Process Site | Bedload samples collected | Flow data period of record | Number of years of flow record |
|---|---|---|---|
| Annie Creek | 20 | 1991-1999 | 9 |
| Cherry Creek | 26 | 1993-1999 | 7 |
| Fivemile Creek | 12 | 1993-1999 | 7 |
| N. Fk. Sprague River Sandhill | 13 | 1993-1999 | 7 |
| Paradise Creek | 12 | 1993-1999 | 7 |
| S. Fk. Sprague River Brownsworth | 13 | 1993-1999 | 7 |
| Sprague River Chiloquin | 5 | 1921-1999 | 59 |
| Spencer Creek | 21 | 1993-1999 | 7 |
| Sycan River above marsh | 16 | 1993-1999 | 7 |
| Williamson River Sheep Creek | 11 | 1978-1999 | 22 |

transport model and in the calculation of framework bed particles. Our objective was to determine bed-material characteristics in the vicinity of the cross-section used for bedload transport estimates and flow measurements.

A fundamental aspect of accounting for the spatial and temporal variability of bed-material samples is the selection of a sample site. Bed-material samples generally were taken a short distance upstream or downstream of the bedload sampling cross section within the same hydraulic control as the cross-section. If this was impractical, samples were taken in a location with thalweg bed-material characteristics similar to the channel maintenance cross section. For most sites several bed-material samples were collected.

Volumetric samples of bed-material were collected after the methods of Milhous et al. (1995) using a barrel sampler, consisting of an open-ended and shortened steel drum. For most streams a 55-gallon (208-L) barrel sampler was used (diameter 58 cm). However, for streams with bed-material consisting of cobbles, pebbles, and sand sized particles, a 10-gallon (37.8-L) barrel sampler was used (diameter 27 cm). Since most of our streams were relatively shallow, the barrel sampler was generally effective. However, there were concerns regarding the adequate capture of fine material while using the sampler. Polyethylene tarp skirting was used as a flow barrier around the base of the barrel while sampling to prevent currents from washing fine material out of the sample.

The pavement layer depth was defined by the vertically oriented embedded depth of the largest particle exposed within the area of the streambed contained within the barrel sampler. Embedded depth was equal to the distance in the vertical direction of the most deeply embedded exposed particle to the surface of the matrix material (Figure 2). After the pavement layer was removed, subpavement samples were taken to a depth equal to the embedded depth of the pavement layer.

It was common for unequal total volumes of pavement and subpavement to be collected at each site, due to the fact that the pavement depth was measured into the channel bed from the plane of embeddedness. Larger particles embedded in the pavement layer protrude past the plane of embeddedness a short distance, and this increases the volume of the sample collected by an amount equal to the volume of the pavement particles that extend beyond the plane of embeddedness. Thus, in order to compare pavement with subpavement in each size class, proportions by weight were determined for each particle size class.

***Bedload Sampling.*** Bedload sampling must account for spatial and temporal variation in bedload transport rates in order to adequately characterize mean bedload transport rates across a channel cross section at a given flow. Samples were taken at all sites with a 3-inch (7.62-cm) Helley-Smith sampler (Helley and Smith 1971) using methods outlined in Emmett (1981), Klingeman and Emmett (1982), and Edwards and Glysson (1988). The Helley-Smith sampler is a pressure difference bedload sampler developed specifically for use in gravel bed rivers. The hydraulic efficiency of the Helley-Smith sampler is 1.54. This sampler gives adequate information on the amount and sizes of bedload in transport, however since the sampler has a 3 x 3 inch (7.62 x 7.62 cm) opening, there is an upper limit to the sizes of material that it will collect. Sampling at all sites was done at ten equally-spaced points across the channel maintenance cross section, and the sampler was in place for 1 minute at each sampling point. For most samples four passes were made across the stream, thus giving total sample time of 40 minutes. This sampling time was thought to adequately account for temporal variability in bedload transport. Sampling was occasionally done near the upper limits of applicability of a handheld Helley-Smith sampler because of deep water and high flows. At some sites because of high flows and high bedload transport rates, the sampling times were reduced to 15-30 seconds at each vertical point. Sample times were altered because adequate sample volume was collected by the sampler in the shorter amount of time. When at-a-point sample times were reduced, total sample times were reduced correspondingly, since only four passes were made across the stream. Thus total sample times for a single bedload sample ranged from 10 to 40 minutes.

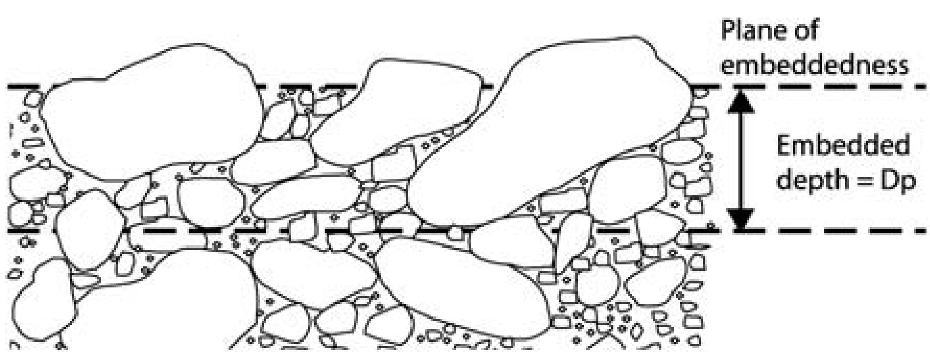



*Figure 2. Pavement depth (Dp) is equivalent to the vertically oriented embedded depth of the largest exposed particle contained within the barrel sampler. Finer material between larger grains is matrix material.*

***Laboratory Analysis.*** Bed-material and bedload samples were dry sieved and weighed in the laboratory. Particles with a median diameter, or b-axis larger than 63 mm were weighed individually and their median diameter determined in the field. The sieve sizes used for bed-material analysis ranged from 0.063 to 64 mm. Sieve sizes used for bedload analysis ranged from 0.25 to 64 mm. Sizes below 0.25 were assumed to consist predominantly of particles transported in suspension.

***Water Surface Slope and Cross-Sections.*** Longitudinal profiles of water surface slope and detailed surveys of the channel cross-sectional profile at the sampling cross section were needed to adequately characterize energy conditions and channel shape at the sampling location. To facilitate this, a permanent benchmark was established at each site, and this was used to determine relative water surface elevations up-and downstream of the sampling cross-section.

A tripod-mounted level was used to determine water surface elevation and bed surface longitudinal profiles and cross-sections at each bedload sampling site. Water surface slope is a good surrogate for energy slope, which is important for estimating the stream power available for bedload transport. Surveys were done adjacent to the streambank upstream and downstream of the bedload sampling cross-section. The elevation of the water surface was determined at closely spaced intervals. Interval length was dependent on the size of the stream and the complexity of the channel. Generally, elevation intervals were more closely spaced for smaller, higher gradient streams, and wider for larger, less steep streams and rivers. Longitudinal profiles were used to determine water surface slope in the immediate vicinity of the sampling cross-section, usually from the upstream to downstream channel controls. A linear regression was applied to the slope survey points, and the median surveyed slope was selected as the representative slope. Several detailed surveys were done of each channel maintenance cross section. Survey points were spaced at relatively close intervals. Particular attention was paid to documenting breaks in slope or high and low points in the channel cross section.

## Determining the Claim Initiation Discharge

The Forest Service claims were initiated when the framework component of the bed-material particle sizes began to be mobilized, as determined by the Parker and Klingeman (1982) bedload transport model. The process for determination of each FCF claim involves several steps:

1. Develop site stage/discharge rating curve and hydrograph
2. Determine stream bed-material and channel characteristics
3. Model and predict bedload transport over a range of flows
4. Develop framework bed-material size distribution
5. Determine lower and upper limits of flow

This procedure was used at all FCF claim sites. The following is an example of the process and data used for determining the minimum flow needed to begin mobilizing the framework material for a fluvial process site.

### Develop Site Stage/Discharge Rating Curve and Hydrograph

The South Fork of the Sprague River fluvial process site is located at the outlet of a 62.1 square miles (161 km$^2$) mostly forested watershed at an elevation of 4540 ft (1384 m), just upstream of the confluence with Brownsworth Creek. The geology is almost exclusively volcanic, with minor accumulations of alluvium near streams. Normal precipitation in the watershed ranges from about 40 inches (~102 cm) per year at the highest elevations to about 20 inches (~51 cm) per year near the gage (Oregon Climate Service 1992).

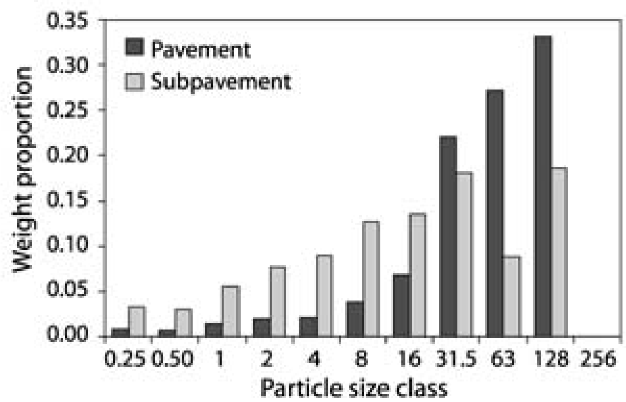
The South Fork of the Sprague River gage has operated from water year 1993 to the present. Discharge records from 1993-1998 were used for developing the FCF claims. A data logger instrumented with a pressure transducer was used to record stage, and observations of stage were made at 30-minute intervals. A stage vs. discharge rating curve was developed (Rantz 1982), and this was used to generate a mean daily hydrograph for the period of record. The hydrograph was inspected for periods of ice blockage of the channel, and mean daily hydrographs from nearby ice-free gages from the same period were used to adjust the hydrograph. Flow records were used to generate a flow duration curve (Dunne and Leopold 1978) representing the water years 1993-98.

### Determine Stream Bed-material and Channel Characteristics

Bed-material data were used to generate size distributions for both the pavement and subpavement layers. Cumulative distributions were used to generate median particle diameters ($D_{50}$) and the 84th percentile ($D_{84}$) for the bed-material (Figure 3).

Weight proportions of bed-material in each particle size class were then determined. Usually several samples of both pavement and subpavement were collected. To calculate the proportions of material in each particle size class, weights of different samples in each size class were added and the proportions calculated from the weight totals in each size class.

*Figure 3. Bed-material distribution of pavement and subpavement, S. Fork Sprague River.*




### Model and Predict Bedload Transport over a Range of Flows

The Parker-Klingeman (PK) model uses bed shear stress to estimate bedload transport. A more detailed description of the application of the PK model is described in Bakke et al. (1999). The procedure consists of calibrating two empirical constants (an exponent and a reference Shield's stress) using site-specific information, including two or more bedload measurements, bed-material and channel cross-section characteristics, and water surface slope. The PK equation can be calibrated for a wide set of conditions. A program called SEDCOMP (Dawdy 1997) was used to optimize the bedload transport equation, and calibrate it to site specific information on bedload transport at each claim site. A separate program FLOWDUR (Dawdy 1997) uses the calibrated parameters and optimized PK equation developed in SEDCOMP combined with an estimated flow duration curve and bedload rating curves to compute thresholds for bedload transport of different size classes of material.

### Develop Framework Bed-material Size Distribution

Mobilization of particle size classes consisting of framework particles is essential for maintaining channel morphology. These particle size classes represent the size fractions which, when mobilized, maintain channel form over time. These materials consist of gravel-sized particles, and make up the major morphological features of the streambed (Leopold 1992). The bed-material framework particles for this study were determined through analysis of bed-material samples that were collected at each bedload sampling location.

As was mentioned earlier in this paper, the pavement layer of the stream-bed is generally coarser than the underlying subpavement layer. The first step in identifying the framework particles is to calculate the weight proportions in each particle size within the pavement and subpavement layers. The framework gravels are determined by subtracting the weight proportion in each size class of subpavement from the respective proportion in each size class in the pavement. This procedure determines the bed-material size classes of the pavement layer that generally have a higher proportion by weight than the material found within those size classes in the subpavement layer. These materials are the framework gravels.

Table 2 provides an example of the calculations used to determine this distribution. The weight proportions of subpavement are subtracted from the corresponding proportions of pavement. Weight proportions were used

*Figure 4. Application of the Parker-Klingeman bedload transport model.*

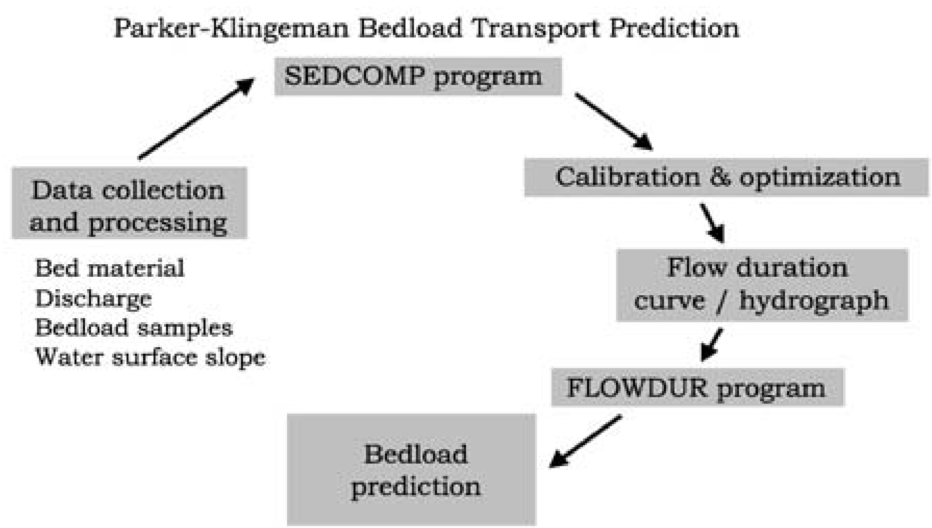


*Table 2. Weight proportions of bed material and determining the framework particle size distribution, S. Fork Sprague River. Proportions of subpavement are subtracted from the pavement to obtain the framework distribution. In this example the framework is from 32 to 126 mm.*

| | Particle Size (greater than, mm) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Layer | 0.25 | 0.50 | 1 | 2 | 4 | 8 | 16 | 31.5 | 63 | 126 | 253 |
| Pavement | 0.008 | 0.008 | 0.014 | 0.019 | 0.022 | 0.038 | 0.068 | 0.220 | 0.271 | 0.331 | 0 |
| Subpavement | 0.032 | 0.029 | 0.055 | 0.077 | 0.089 | 0.127 | 0.136 | 0.180 | 0.088 | 0.187 | 0 |
| Framework (pavement - subpavement) | < 0 | < 0 | < 0 | < 0 | < 0 | < 0 | < 0 | 0.040 | 0.184 | 0.144 | 0 |

because unequal volumes of material were collected in each layer of bed-material. The volume is different between the layers because the pavement depth is determined by the embedded depth of the largest exposed particle. The framework size distribution was determined for the South Fork Sprague River, and is combined with the pavement and subpavement distributions in Figure 5.

The calculated framework distribution for this example ranges from 31.5 to 126 mm in size. The lower limit of the FCF claim begins when the framework distribution of the bed material begins to be mobilized.

### Determine Lower and Upper Limits of Flow

Bedload transport model results can be used to determine the lowest discharge at which a particular particle size class shows appreciable movement. The bedload transport quantities and sizes per unit discharge are quantified by discharge increment, and the relative amount of transport for each particle size class is determined.

Moving framework particles is essential for channel maintenance. The instream flow claim initiates at the flow where 2% of the total bedload by weight is composed of framework particles. This percentage was selected based on comparative observational analysis of bedload transport rates at all claim sites. On average at all the claim sites, these claim initiation flows, based on the mobilization of framework particles, corresponded to about 60% of bankfull flow.

The 25-year flood event calculated using regional flood frequency estimates (Harris et al. 1982) was selected as the upper limit for the claim, because it represented a reasonable upper limit for the channel maintenance claims. These estimates were customized to conditions in the Klamath River basin by EA Engineering (unpublished report 1987).

## Final Claim Structure

### South Fork Sprague River Example

An example of the application of a Favorable Condition of Flow water rights claim for the period 1993-98 is shown in Figure 6. The claim is shown by the shaded region of a mean daily hydrograph for this location. At South Fork Sprague River the instream flow initiates at the claim initiation water flow (140 cfs [3.96 cubic meters per second {cms}]), and is capped at the 25-year event at 926 cfs (26.2 cms). For most years, water is claimed predominantly during higher flows during the late winter and spring months. Water year 1994 was the driest year

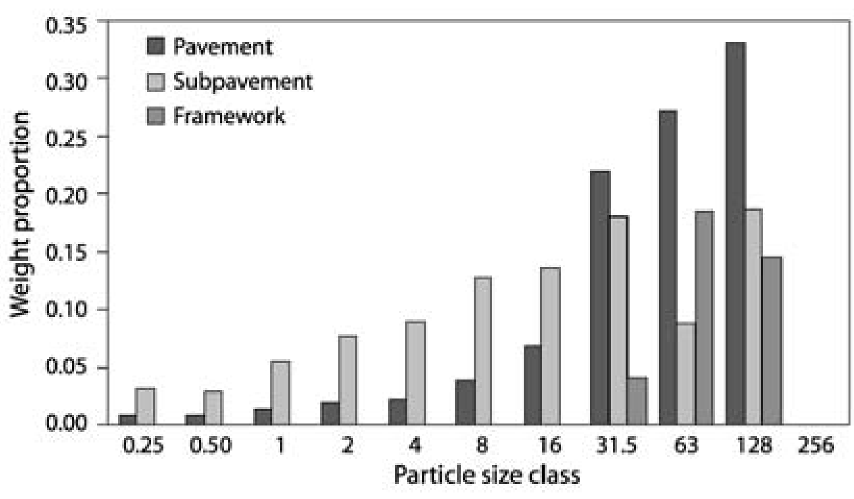



*Figure 5. Framework distribution with pavement and subpavement, South Fork Sprague River.*

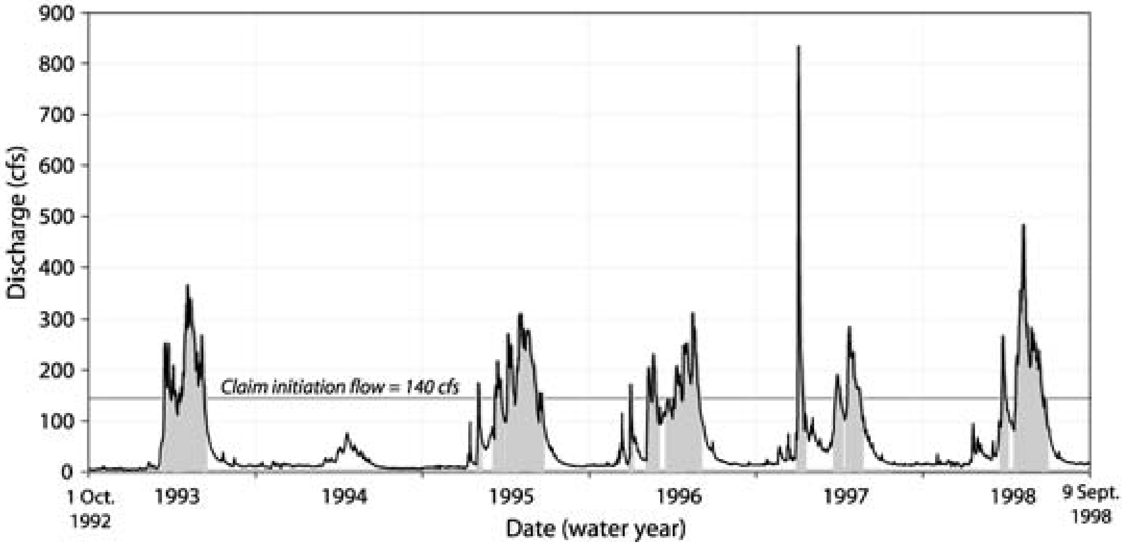



*Figure 6. Mean daily hydrographs from South Fork Sprague River for water years 1993-1998. Favorable conditions of flow claims are the shaded areas of the hydrograph.*

since this site has been gaged, and streamflow remained below the claim initiation flow for the entire water year.

### Discussion

An examination of the hydrographs in Figure 6 reveals that the FCF instream flow claims consist of a series of peak flows with the bulk of the discharge occurring during spring snowmelt runoff. The runoff increases in December and January of 1995 and 1996 are probably early season rain-on-snow peak flows. April through July runoff in water years 1993-1996 for an Upper Klamath River basin gage as percent of average is summarized in Table 3. These data were compiled for the USGS-operated gage on the Sprague River at Chiloquin. The driest year on record was 1994, with runoff predicted at 32% of average. In contrast, 1993 was a very wet year, with runoff predicted at 129% of average. In 1995-96, runoff was at near normal levels. To the extent that the estimate of streamflow at the USGS gage represents conditions at the South Fork Sprague gage, the hydrographs for the years 1995 and 1996 probably are typical of the percent of water claimed during near average projected runoff years. However, the timing of spring runoff and the resulting claim may vary from year to year, despite any similarities in runoff volume.

*Table 3. Percent of average runoff, Klamath River basin, Sprague River at Chiloquin gage.*

| Year | Percent of Average Runoff |
|---|---|
| 1993 | 129 |
| 1994 | 32 |
| 1995 | 90 |
| 1996 | 99 |

Inspection of the hydrographs (Figure 6) also reveals that most of the water volume claimed for FCF in-stream claims occurs during the spring months when potential and existing agricultural irrigation withdrawals are at a minimum. During the period July through September, no water would have been claimed for FCF claims. Exercise of FCF in 1993 and 1994 would have ended in mid-June, and in May of the 1996 water year. It is also important to note that this claim site is located on Forest Service managed public lands in an area where no agricultural activities exist or are likely to occur. However, diversions from the South Fork of the Sprague occur several miles below this location in the upper Sprague River valley.

## Summary and Conclusions

Favorable Conditions of Flow (FCF) in-stream flow claims were developed using extensive knowledge of site hydrology, geomorphology, the sizes and character of streambed-materials, combined with information about the transport of bedload by the stream. They are based on the premise that a certain quantity of streamflow is necessary to transport inputs of sediment to the channel and thereby maintain the channel's form and its ability to convey streamflow and sediment. The claims were developed in five steps. These were:

1. Develop site rating curve and hydrograph
2. Determine stream bed-material and channel characteristics

3. Model and predict bedload transport over a range of flows
4. Develop framework bed-material size distribution
5. Determine lower and upper limits of flow

The FCF instream claims are initiated during relatively high flow events. The lower limit of these claims is determined by the characteristics of the material composing the streambed and the results of bedload sediment modeling. Instream flows are capped by the 25-year flood. The frequency and duration of these higher streamflows are important for controlling channel form and dimensions. The resulting instream flow encompasses the range of discharges that are most effective at conveying bedload sediment and thereby maintaining channel capacity. In light of the dominant role of bedload in channel formation and maintenance, this method uses bedload transport rates over the range of flows observed at a particular stream and the properties of the bed-material sediments to determine appropriate FCF streamflows needed to maintain channels. Further, because bedload transport rates increase rapidly with increasing discharge, and because higher discharges occur relatively infrequently, a high percentage of the bedload can be moved by a relatively small volume of streamflow-the minimum amount of flow necessary to maintain the channel.

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# Keeping Our Streams Flowing: Tonto National Forest Groundwater Policy

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Rapid population growth in central Arizona has increased the demand for water supplies. As surface water sources are fully appropriated, current development efforts are focused on groundwater. The Tonto National Forest has been the recipient of an increasing number of requests to develop groundwater resources from a variety of entities including communities and subdivisions, copper mines, Native American tribes and state agencies. Because groundwater pumping could have an impact on national forest resources, the Tonto National Forest has required development proponents to conduct aquifer tests prior to authorizing long-term pumping. Several of these tests indicated that groundwater removal would have a significant impact on stream flows and associated water-dependent resources. As a result, the forest developed a groundwater policy aimed primarily at protecting National Forest resources. The policy identifies the objectives for managing groundwater and specifies the steps that groundwater development proponents must follow before use of groundwater will be authorized. This paper describes the current groundwater situation relative to the Tonto National Forest. It also illustrates, through a series of case studies, the interdependence between ground and surface water and the dramatic impacts that groundwater withdrawals can have on surface waters. Finally, the primary elements of the forest groundwater policy are discussed. This policy provides managers with an additional tool to protect valuable streams, springs and riparian areas on the forest.

Keywords: *groundwater, water policy, stream flow, riparian, water dependent resources, surface/groundwater interaction*

## Existing Groundwater Situation

Demand for development of forest groundwater resources is increasing. Most of this demand involves the development of water for transport and use off-forest. The increase in requests to use groundwater can be attributed primarily to:

***Rapid Population Growth.*** The population of central Arizona is growing very rapidly. This increase in growth translates into a growing demand for water resources.

***Fully Appropriated Surface Water Resources.*** Most surface waters are fully appropriated by existing users. As a result, groundwater is often the only source of water available for future needs.

***Arizona Water Law.*** Arizona water law is somewhat unique in that there are few regulations governing groundwater resources (outside of several specially designated areas including Phoenix and Tucson). In most areas of the state, the right to develop groundwater rests with the overlying landowner and no water right is required. Thus, all that is required to obtain National Forest groundwater resources is a Special-Use Authorization for well drilling and water conveyance.

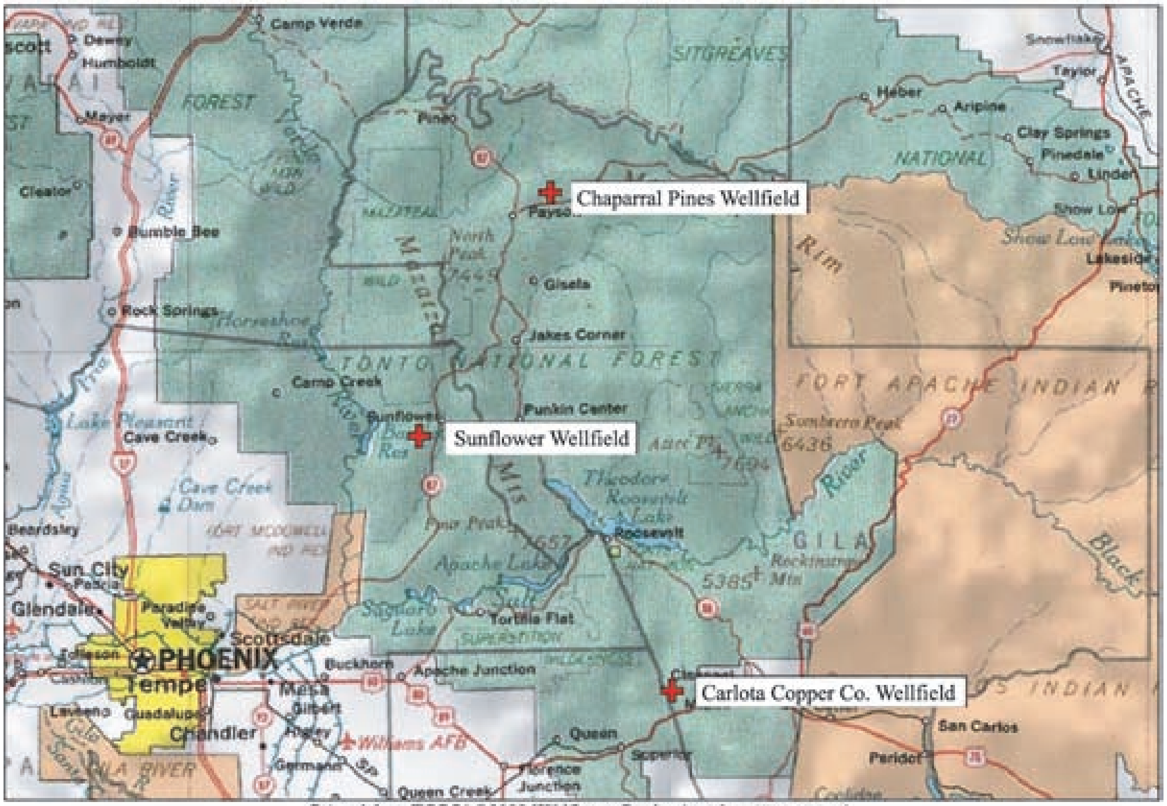
***Cost.*** The Forest Service charges nothing for the water it provides, only for the land use authorization.

## Case Studies

The Tonto National Forest's groundwater policy evolved from our experiences with proposed groundwater development projects. Three of these projects include: The proposed Carlota Copper Mine, a medium sized copper mine partially located on the forest; the Sunflower Well, a well on private land that was proposed to provide water for widening and relocating a highway located on the forest; and the Chaparral Pines pipeline, a water supply pipeline that conveys water from a wellfield on private land across the forest to a subdivision near Payson, Arizona, also on private land (Figure 1). The discussion that follows provides brief descriptions of each of these projects.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

*Figure 1. Groundwater development project locations.*



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## Carlota Copper Company Wellfield

The proposed Carlota Copper Mine is located six miles (9.6 km) west of Miami, Arizona, at an elevation of approximately 3,700 feet (1128 m) in a rugged mountainous semiarid region. Vegetation is composed predominately of chaparral, desert brush and juniper-grassland. The Carlota Copper Company proposes to mine 100 million tons (90.7 million metric tons) of ore from open pits over a twenty-year period to produce 900 million pounds (409 million kg) of copper. The ore would be leached with a sulfuric acid solution in a heap leach process. Water requirements for the mine average 590 gallons per minute (gpm) [1,926 liters per minute (Lpm)] with peak water requirements of 850 gpm [3,217 Lpm] during dry months.

The mine is located in the Pinto Creek watershed, which drains into Roosevelt Lake, a major water supply reservoir for the Phoenix metropolitan area. Pinto Creek, which becomes perennial below the project area, is a valuable resource on the forest, and is a rare perennial stream in the Sonoran desert (Figure 2). Pinto Creek has been designated as an Aquatic Resource of National Importance (ARNI) by the EPA, has been studied for eligibility for inclusion in the nation's Wild and Scenic River System, has been nominated for unique waters status, has been named as one of the ten most endangered rivers in the nation by the American Rivers environmental group, and has been called a "jewel in the desert" by Barry Goldwater. To protect the stream, the forest applied for and received an instream flow water right from the state that seeks to maintain median monthly flows along a nine mile reach of the stream located approximately four miles below the Carlota project area. These flows range from 1 to 2.7 cubic feet per second (cfs) [0.03 to 0.08 cubic meters per second (cms)].

The mining company conducted an extensive search for water that included: acquisition of Central Arizona Project

*Figure 2. Pinto Creek.*

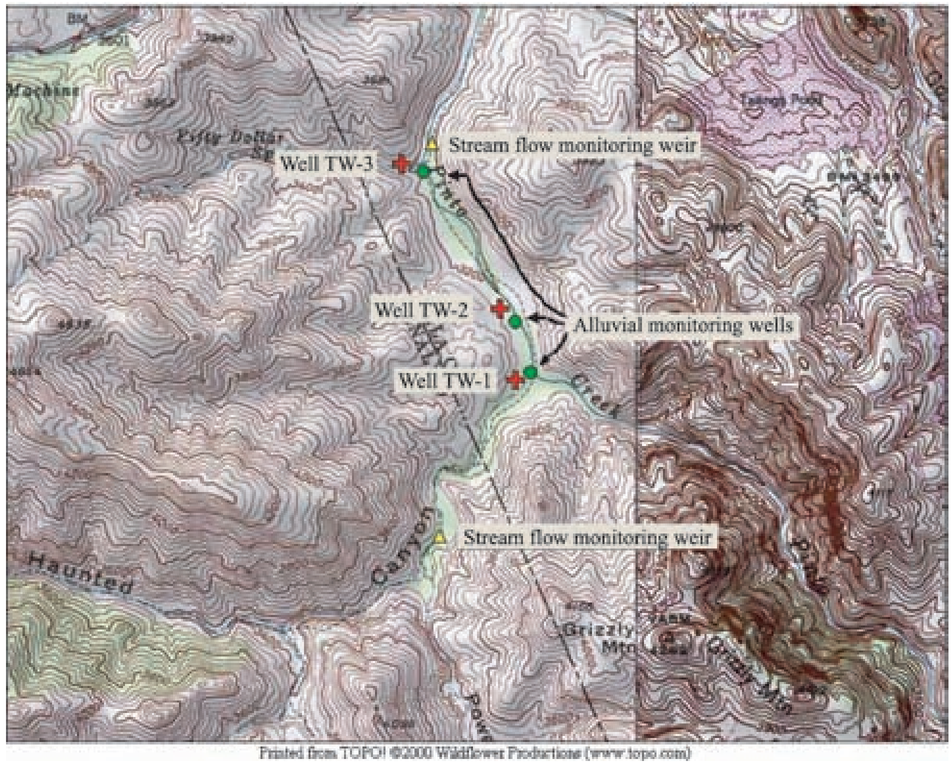



*Figure 3. Carlota Wellfield.*

water from Roosevelt Lake, five surface water reservoir sites on Pinto Creek and Powers Gulch, water purchased from nearby municipalities or other commercial sources, low quality water from adjacent mining operations, and groundwater from a variety of locations. For various reasons, many of these water supply sources could not meet mine requirements, and the source ultimately selected included groundwater from a wellfield located approximately two miles (3.2 km) downstream of the main project area near the confluence of Pinto Creek and Haunted Canyon (Figure 3).

Three test wells were drilled at this site from June to September 1993, ranging in depth from 755 feet to 1220 feet (230 m to 372 m) below ground surface. All three wells experienced artesian flows with artesian discharge from the middle well (TW-2) flowing at 250 gpm (946 Lpm). Test pumping of these wells was conducted to evaluate the long-term yield potential of the aquifer, and the impact of pumping on surface water resources and on alluvial groundwater elevations. Well TW-2 was pumped for 25 days at a rate of 600 gpm (2,271 Lpm). A monitoring network was installed to detect potential impacts. The network included three shallow alluvial monitoring wells, four bedrock complex monitoring wells, weirs at two springs, and a weir or Parshall flume at two locations in Haunted Canyon and Pinto Creek.

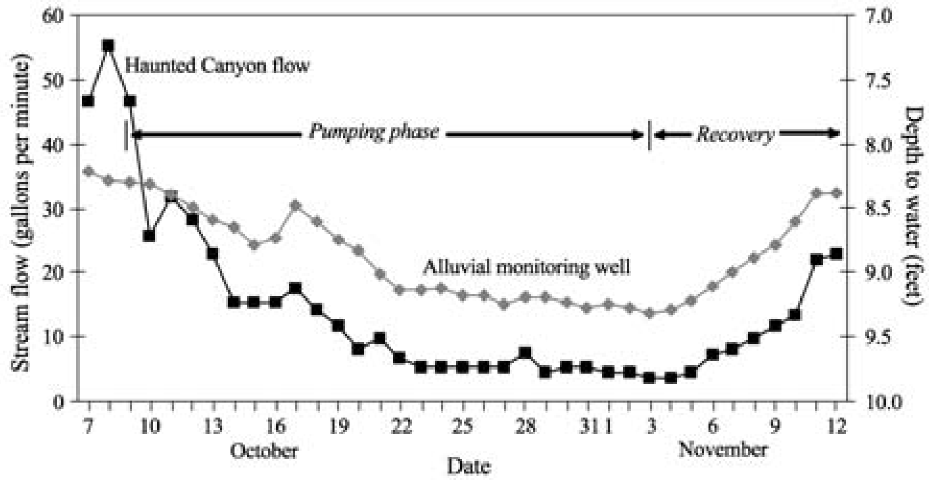
During the 25-day pump test of TW-2, stream flow at a weir in Haunted Canyon (located approximately 2,300 feet [701 m] south of the TW-2 well) declined from approximately 45 gpm at the start of the test to 5 gpm at the end of the test (170 to 19 Lpm). Flow increased progressively to approximately 27 gpm (102 Lpm) within a few days of shutting off the pump. The water level in an alluvial monitoring well in Haunted Canyon located approximately 1,550 feet (472 m) south of TW-2, declined approximately one foot during the 25-day test and recovered slowly following the test (Figure 4).

Based on these test results, the forest sent a letter to the Arizona Department of Water Resources (ADWR) requesting an appropriability determination. In Arizona, water pumped from a well is considered to be appropriable if withdrawing that water tends to directly and appreciably reduce flow in a surface water source. ADWR reviewed the aquifer test results and concluded that the well was withdrawing appropriable water and would need a water right if it was to be used. The Carlota Copper Company subsequently submitted a water right application. The forest protested the application based on its instream flow water right downstream on Pinto Creek. The forest negotiated a wellfield mitigation program with the mine that seeks to maintain median monthly flows in Haunted Canyon and Pinto Creek in exchange for the forest's withdrawal of its protest.

**Sunflower Well**

The second groundwater withdrawal project influencing the development of the forest's groundwater policy was

*Figure 4. Carlota Project pump test results.*




the Sunflower Well. This well was proposed as a water supply source for upgrading a portion of Arizona State Highway 87 that carries heavy traffic from the Phoenix metropolitan area to summer recreation areas in the high country along the Mogollon Rim in north-central Arizona. Water requirements for highway construction were estimated to be about 200 gpm (757 L per minute) for compaction of fills and for dust control.

The Sunflower Well is located on private land near Sycamore Creek, which has reaches of both intermittent and perennial flow near the well. Sycamore Creek, like Pinto Creek, is a stream with reaches of perennial flow in the Sonoran Desert. It supports valuable riparian vegetation, provides habitat for native fish, and is a popular recreation area.

The Record of Decision (ROD) for the Environmental Impact Statement (EIS) prepared for the highway upgrading project stated that construction water would not be withdrawn from Sycamore Creek. To evaluate the effects of the well on Sycamore Creek, an aquifer test with observation wells and a streamflow monitoring flume was conducted.

The proposed production well was completed to a depth of 240 feet (73 m) in fractured basalt. Water rose under artesian pressure to a depth of approximately 20 feet (6.1 m) below ground surface. The monitoring network consisted of four shallow observation wells in the alluvium bordering the creek, two deep observation wells in the bedrock basalt aquifer and a Parshall flume in a perennial reach of Sycamore Creek just downstream of the well (Figure 5). The aquifer test was originally scheduled for three days with the production well pumping at an average rate of 250 gpm (946 Lpm).

Water levels in the shallow monitoring wells declined before, during and after the test. Water levels declined at a slightly greater rate during the test. The majority of the decline was believed to be attributable to natural conditions. The impact of pumping on stream flow through the flume was dramatically different than the impact to the shallow observation wells. Prior to beginning the test the flow rate through the flume was about 90 gpm (90 Lpm). About six minutes after the pump in the production well was turned on, flow through the flume started to decline. Approximately six hours into the test, flow in Sycamore Creek declined to zero. One hour and 20 minutes after the pump was turned off, Sycamore Creek started flowing through the flume again. Two hours after the pump was turned off, flow through the flume was 37 gpm (140 Lpm), and 10 hours after turning the pump off, flow through the flume was 61 gpm (230 Lpm) (Figure 6).

Based on the results of this test the contractor was not allowed to use the well for the highway upgrade project.

### Mayfield Canyon Wellfield

The purpose of this project was to provide water for a subdivision and golf course near the community of Payson, Arizona. The wellfield was located on a parcel of private land, known as Calhoun Ranch, that is entirely surrounded by National Forest System lands. The proponents intended to construct a pipeline that would transport water from the wellfield across the forest and back onto private lands where the subdivision and golf course were located. Mayfield Canyon flows through the private lands where the wellfield is located, enters the forest for approximately one-half mile, then flows back onto private lands in the community of Star Valley (Figure 7). The stream becomes perennial on the Calhoun Ranch private lands due to groundwater discharge that seeps into the bed and banks of the channel and from a significant spring (estimated to discharge at approximately 30-40 gpm [113-151 Lpm]). Perennial flow continues downstream of the private land onto the forest for approximately 200 yards (183 m) until it seeps into

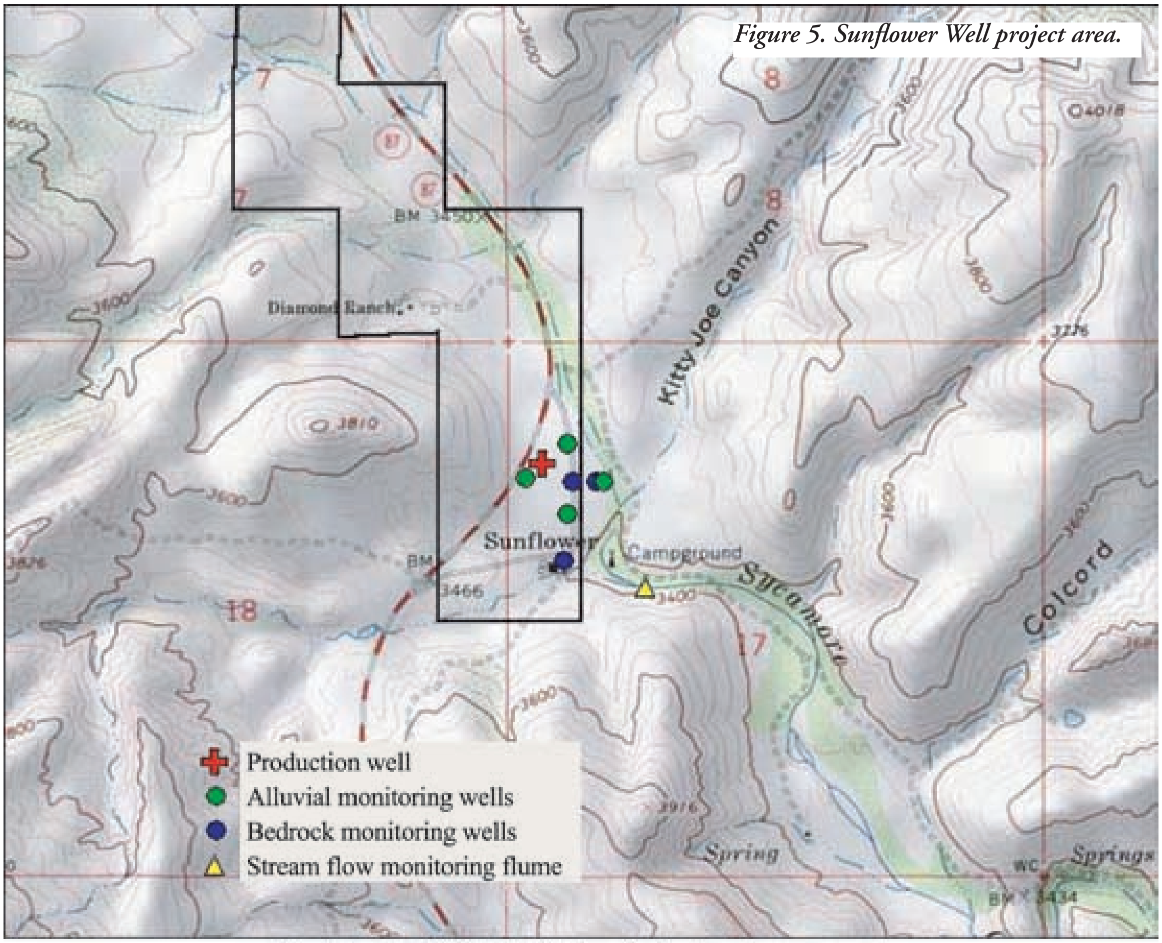


*Figure 5. Sunflower Well project area.*

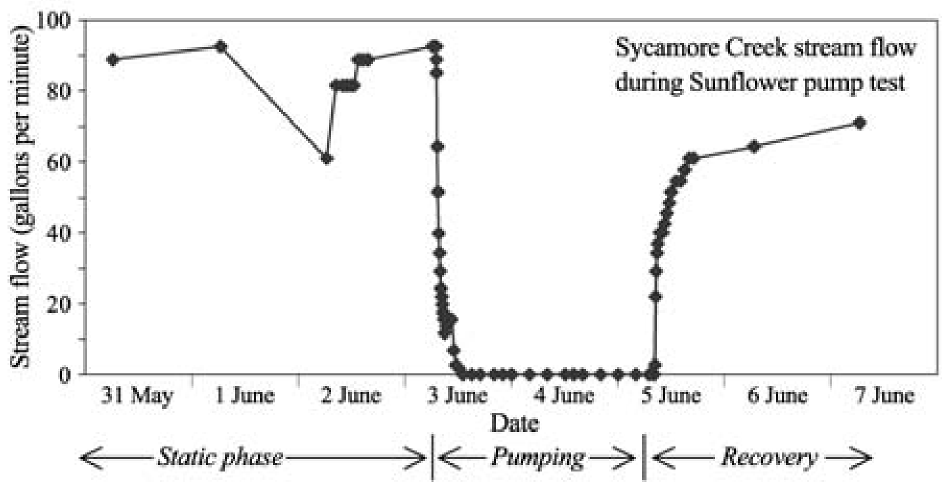


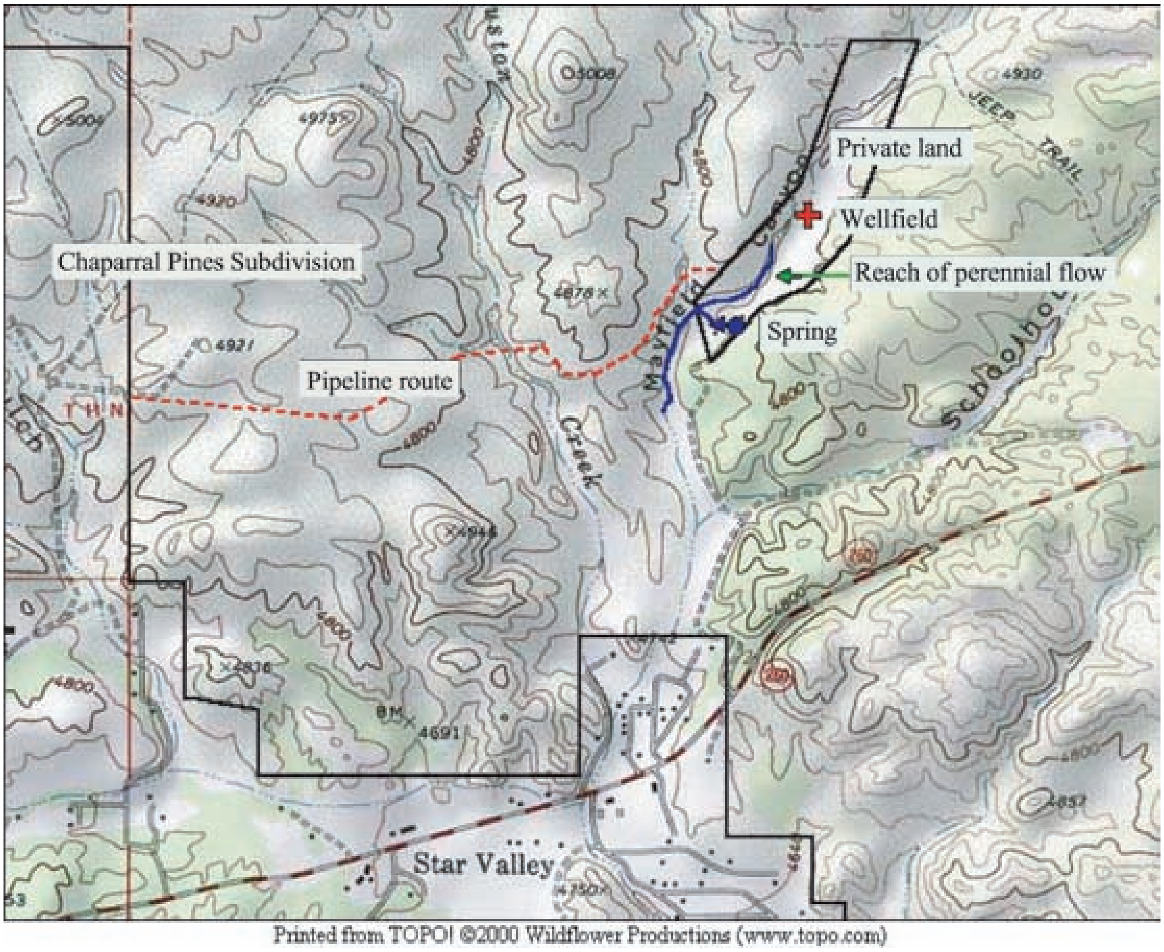
*Figure 6. Sunflower pump test, Sycamore Creek streamflow.*

the sands and gravels of the stream bottom alluvium. The reach of perennial flow on the forest supports a lush riparian zone of cottonwood and willow trees. Peak water requirements for the golf course and subdivision were estimated at approximately 360 gpm (1,362 Lpm). The residents of Star Valley who are dependent on wells for the majority of their water needs were concerned that development of the wellfield on Mayfield Canyon (which is up gradient of Star Valley) would reduce groundwater availability to their wells.

The subdivision developer needed a Special-Use Permit from the forest for the pipeline from Calhoun Ranch to the subdivision at Chaparral Pines. The forest, as part of its compliance with the National Environmental Policy Act (NEPA) evaluated the actions connected with the project proposal. In this instance, it meant looking at the impacts of pumping the groundwater as well as the impacts of the pipeline itself.

Eight wells were drilled at the Calhoun Ranch site ranging in depth from 200 to 500 feet (61 to 152 m)

*Figure 7. Chaparral Pines Wellfield and Pipeline.*




and completed in fractured granite. Prior to submitting an application for a Special-Use Permit, the developer completed a number of aquifer tests including a 33-day test on the most productive well, which was pumped at a constant rate of 300 gpm (1,135 Lpm) during the test. Drawdown in five observation wells ranged from 20 to 30 feet (6.1 to 9.2 m) during the test. Streamflow in Mayfield Canyon was not monitored during this test. The developer's consultant concluded that impacts on surface water flows from operation of the wellfield would be negligible because flow in Mayfield Canyon is intermittent and the result of precipitation events.

Once the developer submitted a Special-Use Permit application, the forest requested a second 30-day aquifer test with flow measurements in Mayfield Canyon to directly assess impacts to stream flows. The developer refused, stating that a long-term aquifer test had already been completed and that the consultants who conducted the test had reached their conclusions about groundwater-surface water impacts. As an alternative, the forest asked the developer to conduct a water budget analysis that would assess the impacts of groundwater withdrawals on inputs and outputs of water resources in the watershed. The developer agreed to this request and subsequently concluded that groundwater pumping would not reduce the surface runoff component of the water budget, but could affect baseflow in the reach of Mayfield Canyon above the cone of influence of the groundwater wells. A Special-Use Permit was subsequently issued and the photos in Figure 8 display the impacts of wellfield operation on the reach of Mayfield Canyon within the national forest.

## Groundwater Pumping Concerns

### Effect On National Forest Resources

Groundwater and surface water form an interconnected hydrologic system. Recharge to groundwater supplies originates from precipitation and surface waters. Conversely, groundwater discharge is the reason that perennial streams, springs and seeps flow throughout the year. Groundwater pumping from wells can result in lower water tables and reduced stream flows. Because surface water and shallow groundwater sustain riparian and aquatic ecosystems, groundwater removal can have negative impacts on these resources.

*Figure 8. Mayfield Canyon riparian vegetation, prior to (left) and following (above) startup of wellfield.*

**Effect on Adjacent Water Supplies**

Many public and private entities within and adjacent to the forest currently rely on groundwater for a variety of purposes. Authorization of additional wells and removal of groundwater from the forest can lower water levels and affect these existing groundwater users.

**Limited NEPA Analysis**

Historically, NEPA analyses of proposals to develop forest groundwater resources have focused on the impacts of drilling and the construction of infrastructure such as wells, pumping facilities, roads and power lines. Little attention has been paid to the potential impact on forest water resources, associated riparian areas, and adjacent water supplies. Continuation of our historic methods for evaluating impacts could result in the authorization of new water developments that adversely affect important forest resources and activities. The potentially serious degree of resource damage also implies that the forest should evaluate any new requests for groundwater carefully prior to authorization.

**Special-Use Permits Are Long-Term Commitments**

Special-Use Permits for the conveyance of water across the forest are issued for a specific number of years. Although the Forest Service has the legal right to deny reissuance of such permits, it is often difficult to do so. In essence, most Special-Use Permits for water are permanent commitments. This makes it very difficult to correct existing resource problems that can be attributed to such developments.

**Lack Of Consistency**

Historically, the forest responded with a variety of approaches to requests for the development and use of groundwater. In some instances we immediately denied such requests, while in others we encouraged such development and use. Such inconsistency without a sound rationale usually leads to problems.

## Groundwater Policy

**Policy: Groundwater shall be managed for the long-term protection and enhancement of the Forest's streams, springs and seeps, and associated riparian and aquatic ecosystems. Development and use of groundwater for consumptive purposes shall be permitted only if it can be demonstrated that such proposals will adequately protect Forest resources.**

**Criteria For Development And Use Of Groundwater**

Proposals to develop and use groundwater derived from National Forest System (NFS) lands must meet the following conditions:

A. The proposal to use water must be consistent with applicable laws, regulations, polices, rules, and forest land and resource management plans (Forest Service

Manual [FSM] 2702 & 2703).

B. The proposal to use water must adequately protect National Forest resources (FSM 2702.1 & 2541.34).

C. If the proposed place of use of water will be located on non-NFS lands, the proponent must demonstrate that alternative water sources do not exist off-forest (FSM 2703.2).

### Consistency With Existing Policies And Management Direction

The forest policy for the development and use of groundwater is consistent with National and Regional policy and direction. For instance, the Forest Service Manual (FSM) 2541.34 indicates that if projected water requirements of uses not directly related to Forest Service programs "will adversely affect national forest resources, the potential permittee must seek alternative water sources or develop mitigation plans acceptable to the Forest Service." Similarly, the manual indicates that Special-use authorizations should be denied if they are in conflict with other forest management objectives, or can reasonably be accommodated on non-NFS lands (FSM 2703.2).

## Procedures - Methods to Implement Policy

The evaluation of water development proposals has three phases.

### 1. Preliminary Analysis

This phase initiates the evaluation process. If water is to be used off-forest, the proponent must demonstrate that alternative water sources do not exist off-forest. For all proposals, the following information is assembled and evaluated.

*Description of Proposal*
Quantity of water needed
Infrastructure requirements

*Inventory of Key Resources*
The location of potentially affected surface water resources.
The location and description of riparian vegetation.
Any known Threatened and Endangered species.
Pertinent geologic information.
Pertinent hydrologic information.

*Inventory of Existing Water Developments*

### 2. Exploration And Testing

This phase involves drilling for a suitable water supply, and testing for impacts on forest resources and adjacent water supplies. The Exploration and Testing phase would be initiated only if the proposal satisfies the requirements of the screening process in the preliminary analysis phase.

***Temporary Permit Issued.*** If the Preliminary Analysis indicates a reasonable likelihood of developing water without adverse impacts on forest resources or adjacent water users, a Temporary Permit may be issued for the Exploration and Testing phase of the proposal. This Temporary Permit shall contain the conditions necessary to minimize impacts to forest resources.

If sufficient water is found in the exploration phase to meet the needs of the proponent, testing is then conducted.

***Testing Conducted.*** Prior to testing, a monitoring plan must be submitted to the Forest Service for approval. After approval of the monitoring plan, long-term pump testing, modeling, or both, are conducted, and effects of pumping are observed or predicted.

### 3. Construction And Production

This phase involves the permitting of all infrastructure, the conveyance of water, and long-term monitoring and mitigation. This phase occurs only if testing indicates that forest resources will not be adversely affected or can be mitigated, and nearby water developments can be adequately protected.

***Permit Issued.*** Infrastructure needed to produce and convey water is constructed.

***Monitoring And Mitigation.*** Any monitoring or mitigation measures necessary to ensure protection of forest resources during the construction of water storage and conveyance facilities, and during the long-term removal of groundwater will be included as a Plan of Operations attached to and made part of the Special-Use Permit. If long-term monitoring detects additional or unforeseen adverse impacts to forest resources that were not discovered during the exploration and testing phase, or if mitigation measures do not adequately protect forest resources, the Permit shall not be reissued.

## Other Considerations

### NEPA Analysis and Documentation

The scope of any analysis needed to comply with NEPA will depend largely on potential resource impacts, and on the level of public concern.

For NEPA purposes, groundwater exploration and development can often most logically be addressed in two distinct phases. The first NEPA analysis can address the impacts associated with the exploration and testing phase. This phase can be separated from the development and production phase because the availability of groundwater and the impacts from pumping are often unknown during the exploration phase. A second NEPA analysis can be conducted if a suitable supply of groundwater is found and if test pumping does not result in impacts that would constitute a reason for denial of a Special-Use Permit for the production phase. The second NEPA analysis would address impacts identified during the exploration and testing phase, from the construction of infrastructure, and from the operation of the proposed facilities.

### Water Rights

Applicable laws and regulations governing wells and water rights will be adhered to for all proposals.

## Conclusions

A rapidly growing population in the Southwest is causing increasing demands on scarce groundwater. Requests for Special Use Permits to withdraw groundwater on the national forests are now common and increasing as well. Case studies and hydrologic theory confirm that groundwater and surface water are usually strongly interconnected and form a single hydrologic system: groundwater withdrawals typically directly result in lower streamflows. Policies and procedures for considering groundwater development proposals are needed that work within the NEPA process to ensure that permits are granted only when consistent with our stewardship responsibilities to protect surface-water dependent values.

# USDA Forest Service Policy on Managing Groundwater Resources

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Until now, the USDA Forest Service lacked a national policy on managing groundwater resources of the national forests and grasslands. There are many problems and missed opportunities for resolving groundwater caused issues and concerns that the agency can best tackle with a nationally consistent and comprehensive groundwater policy. The policy proposed in this paper fulfills all of those needs: it covers water quantity and quality issues, clean-up of contaminated groundwater, commercial bottling operations, inventory and investigation procedures, and special use permitting of new wells.

Keywords: *groundwater resources, policies, permitting, aquifers*

## Background

In the past, the USDA Forest Service personnel responsible for managing the national forests and grasslands too often ignored the groundwater below their feet, tried hard to do so, or assumed that the same agency policies for managing surface water applied equally to groundwater. There were exceptions, of course, if some kind of sub-surface activity was proposed, such as mining, oil, gas or water well drilling, or clean-up at an abandoned mine site. The laissez-faire strategy worked pretty well in many cases, but over time there has been a steady increase in the number of cases where those strategies failed and caused adverse impacts to the lands or the natural resources located on those lands. By the late 1980s, hydrologists and geologists in the agency's national headquarters were working together to develop a national policy for groundwater management.

Bureaucratic turf wars between the two staff directors involved in this joint effort prevented the draft groundwater policy from being issued in 1989 as it could have been. When I arrived in the Washington Office late in 1989, I pursued tackling the bureaucratic issues for a year or so without success, then gave up on it. By the late 1990s with new directors in place, I again pursued bringing the draft policy to fruition by sending it out to the Regions for review and comment. I also formed an ad hoc team to revise the earlier draft based on the comments received and new information that had become available.

It occurred to me that field personnel would need two companion documents to this new policy to be able to use it successfully. One would be a user-friendly handbook or desk guide on techniques and methods proven useful for investigating, managing or mitigating groundwater underlying National Forest System (NFS) lands. The second document would be a compilation of federal and state laws, rules, regulations, and case law pertaining to groundwater in each of the 43 states that have NFS lands. Both of these documents have been completed.

## Current Groundwater Issues and Concerns

Freshwater aquifers currently supply 37 percent of the drinking water that Americans depend upon annually. A total of 83.3 billion gallons per day (bgd) (315 million cubic meters per day [$Mm^3d$])was withdrawn from the groundwater resource in 2000, up 14 percent from 1985, according to the U.S. Geological Survey (USGS 2003). Some 56.6 bgd (214 $Mm^3d$) was used for irrigation, 16 bgd (60.6 $Mm^3d$) for public water supply, 4.4 bgd (16.6 $Mm^3d$) for mining and 3.5 bgd (13.2 $Mm^3d$) for individual domestic water needs.

The U.S. Geological Survey identified 21 groundwater provinces in the United States (Meinzer 1923). Most aquifers within these provinces are found in valleys, on the Great Plains, and in relatively flat terrain along the East and Gulf coasts or the Great Lakes. Since NFS lands often are located in mountainous areas of the West and

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

along the Appalachian chain in the East, they are not usually overlying the major aquifers. There are some exceptions: some national forests and grasslands from Texas through Nebraska overlie the Ogallala and Edwards aquifers; portions of the Osceola and Ocala National Forests in Florida overlie the Floridian aquifer; several forests in North and South Carolina overlie coastal aquifers; some national forests in the Great Lakes basin overlie aquifers there; portions of the Custer National Forest in Montana, the Humboldt-Toiyabe National Forest in Nevada, and several national grasslands in Wyoming, North and South Dakota, Colorado, Kansas, Oklahoma, Oregon and New Mexico overlie important aquifers. Some of these aquifers are being heavily pumped with increasing risk of severe depletion that may cause many unintended consequences to both people and ecological values of those places.

Almost all national forest lands, wherever located, also serve as groundwater recharge areas because they typically receive more annual precipitation than nearby valley areas. This is a very important function they serve in the water cycle or water budget that hydrologists and water supply engineers plan on. It is very important to ensure that groundwater recharge areas do not serve as points of contamination of the aquifers. Yet, there is no national or even regional inventory of groundwater resources underneath NFS lands in this country. We must start to work on one soon; this paper supports that undertaking.

Based upon many experiences that the U.S. Environmental Protection Agency (EPA) has had since 1970 with clean-up of contaminated groundwater, it has become obvious that preventing contamination of groundwater is by far the least costly and most environmentally sound way to ensure the usability of that resource in the future. The Forest Service intends to follow such an approach, especially in the near future. This agency has only very limited hydro-geological expertise - only about six employees out of a professional workforce of about 8,000 currently have such a background.

The state laws that regulate groundwater resources too often ignore the real connections between groundwater and surface water that exist in nature. Many states completely separate the two kinds of water in their laws, or encourage maximum development of groundwater, sometimes with devastating consequences such as land subsidence, loss of wetlands, salt-water intrusion, loss of surface water flows, and other effects. California does not even have a state groundwater law. Some state laws were written in the 18th or 19th centuries and need to be modernized, in the opinion of many water experts and this author. The Forest Service respects the authority of states to allocate water and control water quality as delegated by the Congress through federal laws. The agency adheres to state water rights laws to the extent they are not incompatible with federal laws that govern the proper administration of NFS lands and resources. To ensure that Forest Service employees are familiar with state groundwater laws, a document that includes a short summary of the laws and includes Internet hot-links to the actual text of all of these state laws and regulations in the 43 states that contain NFS lands has been drafted (Glasser and Chapman 2006). That document will be posted on a Forest Service website in 2005.

## Groundwater Policy Components

There are a number of component parts to the proposed agency policy for groundwater (USDA Forest Service, In press) which will be briefly discussed in this paper. They include: objectives, responsibilities, definitions, assessments, uses, clean-up of contaminated groundwater, source water, permitting, monitoring, fees, legal aspects, and sustainability strategies.

### Objectives

The Forest Service will manage groundwater underlying NFS lands to ensure the long-term protection and enhancement of these aquifers and other groundwater systems, surface streams, springs, lakes, ponds and their associated riparian and aquatic ecosystems.

Further, authorization of consumptive water uses by other parties will occur only if such authorized uses can adequately conserve, restore, or protect dependent resources and values over the long run.

Both of these objectives are based upon a number of federal statutes and their implementing regulations governing the National Forest System from 1897 to the present.

### Responsibilities

The new policy includes a number of specific responsibilities of certain Staff Directors in the Washington Office, Regional Foresters, Station Directors and the Area Director; Forest Supervisors and Research Project leaders; and Project, Program or Team Leaders in the Research and Development Branch.

### Definitions

Some 17 technical terms used in the new policy are clearly defined to ensure understanding and common usage in the future.

**Assessments**

The use of appropriate methods, models, tools, techniques to investigate, inventory, assess or quantify the quality and the volume of groundwater resources underlying NFS lands is very important in achieving success in such endeavors. Temporal and three-dimensional spatial scales are also critical elements in these processes. The new policy and its related Technical Guide for Managing Ground Water are intended to be used in tandem by field practitioners. Some cautions on the use of these methods and tools are also noted in both documents.

**Groundwater Uses and Impacts**

The Forest Service has authorized many water wells that pump groundwater from underneath NFS lands, and it also has hundreds of its own water wells that serve administrative sites, recreational facilities and other uses. These uses will continue and new ones will undoubtedly be added in the future. The Forest Service needs to begin to quantify the amount of groundwater being withdrawn from beneath its lands by all water users if we are to work toward sustaining groundwater as a natural resource in perpetuity.

A provision of the new policy is a requirement to install water meters on all pipes four inches or larger in diameter used to withdraw groundwater for any purpose. This requirement will apply to both authorized pipelines and to agency owned pipelines. Annual withdrawals in cubic feet of water will be reported to the Director of Watershed, Fish and Wildlife in the Washington Office.

The new policy addresses impacts on groundwater related to mining, oil, gas and coal bed methane operations, geothermal facilities, tunneling projects, sand and gravel removal, and landfill operations that need to be recognized and appropriately addressed at the local, state or regional levels. Readers are referred to appropriate portions of Forest Service Manual (FSM) chapters 2810, 2820, and 2880.

**Clean-up of Contaminated Groundwater**

Direction is provided to prevent future contamination from agency authorized or conducted activities, and where contamination has already happened, to be pro-active in remediation. There is abundant existing direction and technical guidance on planning and implementing clean-up operations in FSM chapter 2160, the National Contingency Plan, USDA Manual DM 5600-1 Chapter V, and requirements of the Comprehensive Environmental Response Compensation and Liability Act of 1980 which need to be followed by anyone contemplating a groundwater clean-up operation.

**Conjunctive Use of Surface and Groundwaters**

The new policy states that one should always presume there are hydrologic connections between surface water and groundwater on NFS lands unless it can be clearly proven that there are none in the local setting. This is a reasonable, conservative assumption that we think is very important to achieving long-term sustainability of the groundwater resource at a minimum of cost. There are many real world cases where contamination of water occurred because it was wrongly believed there were no connections between ground and surface waters; in other cases, too much pumping of groundwater has dried up surface waters in streams, ponds, lakes, and wetlands. Also, removal of surface waters by diversion or pumping has caused declines in groundwater levels because the groundwater recharge mechanism has been shut off.

The Forest Service recognizes the growing trend toward conjunctive water management by many water utilities, districts, and planners. The agency needs to assure that its employees are also aware of this trend and are equipped to deal with it if such proposals to make use of surface water, groundwater or both, that originates under, on, or from NFS lands, arrive on their desks. Specific direction on evaluating these applications is given in the next section of FSM chapter 2543 - Permitting.

**Permitting**

A two-phase process for evaluating applications for new ground water resource developments of any kind on NFS lands is provided in this section of the policy. The reader should also see the paper by Martin and Loomis in this publication. In fact, much of the national policy on permitting water wells included in FSM 2543.5 originated from the process used by the Tonto National Forest (New Mexico) and was then codified by the Southwestern Region of the Forest Service.

Assuming there are no alternate water supplies outside the national forest, the first or exploratory phase of permitting is the information gathering and screening phase where, after National Environmental Policy Act (NEPA) analysis is completed, the project proponent may be authorized to drill one or more test wells and perform a 72-hour continuous pump test while measuring effects on the water table and surface waters nearby. Often computer modeling, additional drilling of wells, and surface water monitoring sites may be required. If it appears there is a large enough water supply of sufficient quality that can be developed in an environmentally safe and economically feasible manner, then plans for development are evaluated and documented in accordance with NEPA requirements.

The next phase is the issuance of permits for the construction of the water production facilities and associated infrastructure if located on NFS lands, once a NEPA decision and all applicable state authorizations are in place. FSM 2711 provides additional guidance about the permitting process. Monitoring and mitigation measures should be included in the permit and the annual plan of operations by the permittee.

### Laws, Rules and Regulations on Groundwater

There is no single federal law that addresses groundwater in a comprehensive manner. The Safe Drinking Water Act delegated primary responsibility for protecting drinking water to the states, whether from surface water or groundwater. The Clean Water Act implies that groundwater is to be managed like surface waters, but it does not set clear goals for managing groundwater.

State laws, rules and regulations for the allocation of groundwater among competing water users exist in almost all states. They are based upon one or more basic legal theories: absolute ownership, correlative rights, prior appropriation, and reasonable use. Many states artificially separated their surface water right laws from their groundwater laws, which has led to some damage to groundwater resources.

The Forest Service policy is to follow state water laws substantially and procedurally as long as they do not conflict with federal laws applicable to management of NFS lands and resources. In an effort to increase Forest Service personnel's awareness of state water laws and as an aid to water attorneys in the USDA Office of the General Counsel, an 86-page compendium of these laws, their regulations, and pertinent case law in the 43 states with NFS lands has been completed as a separate document. Contact the Forest Service Washington Office, Fish and Wildlife staff about how to access this document.

### Strategies for Sustaining Groundwater

The new policy contains five strategies designed by the U.S. Geological Survey (Alley et al. 1999) to sustain the availability and usability of groundwater resources in the United States. These strategies should work on NFS lands. There may be additional strategies that would work in local areas as well; the point is to try to use some strategy for many years or decades to ensure that the groundwater resource is not totally depleted, contaminated to a point where it becomes unusable by people or by dependent animal or plant life.

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# Section 2. Experimental and Research Watersheds

Overleaf:
Maybeso Creek, Maybeso Experimental Forest, Tongass National Forest, southeast Alaska. Photo by Michael J. Furniss.

# The Forest Service Barometer Watershed Management Program, a Historic Viewpoint

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During the 1960s, Byron Beattie, Director Division of Watershed Management and Edward Dortignac, Branch Chief of Water Resources of the USDA Forest Service National Office, Washington, DC, conceived a program to bridge the gap between watershed research results and management scale application of science-based principles. The proposal was to select, instrument and calibrate National Forest System watersheds in the range of 50,000 to 150,000 acres (20,200 to 60,700 ha) in each of several hydrologic provinces. Teams of watershed scientists including hydrologists, soil scientists, geologists, and natural resource managers would apply and evaluate science-based management prescriptions. This initiative was the impetus that brought an influx of scientifically trained hydrologists and soil scientists into the Forest Service. This effort included the establishment of a Watershed Systems Development Unit (WSDU) in Berkeley, CA, led by Clyde Shumway. WSDU provided technical support in acquiring state-of-the-art instrumentation and data management programs. An essential part of their effort was the development of computer programs to predict the effects of management activities on water yield and sediment. These were to be applied on the selected "barometer watersheds" as well as in support of the Pacific Southwest Water Plan initiative. Barometer watersheds varied in their success due, in part, to the difficulty of operating sophisticated technology in remote environments. Also, in many cases, coordinating the application of management prescriptions with calibration proved challenging. Regardless of the success of an individual barometer watershed, these efforts on the whole provided the platform for developing critical skills that formed the career foundation for many hydrologists and other earth scientists in the Forest Service.

Keywords: *representative watersheds, barometer watersheds, water yield, history, watershed management*

## Introduction

The U.S. Forest Service Barometer Watershed program was envisioned by Byron Beattie, Director, Division of Watershed Management and Edward J. Dortignac, Chief, Water Resources Branch, USDA Forest Service National Office, Washington, DC. Beattie and Dortignac described the broad goals and objectives of the program in their paper entitled "Using representative watersheds to manage forest and range lands for improved water yield" (Dortignac and Beattie 1965). The essence of the concept was to prototype science developed at plot and small watershed scale and pilot test these findings at a management scale and integrate them with ongoing multiple use practices. The outcomes of watershed prescriptions would be predicted in advance. The post-prescription outcomes would be evaluated and modified as necessary before being more broadly applied in the climatic-physiographic region, referred to as a hydrologic province, represented by the barometer watershed. Dortignac and Beattie (1965) describe the concept as follows:

> The knowledge gained from experimental watersheds of the Forest Service and the data accumulated on other representative watersheds establishes a broad base of knowledge for scientific management of forest and range lands. These findings make it possible to predict hydrologic behavior on a selected watershed for given climatic events, provided the watershed is intensively inventoried and appraised. A reasonably accurate prediction of results is essential

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

[1] Retired

to management decisions on whether or not to expend the energy and funds needed to implement a watershed prescription.

The Forest Service uses a system of "Representative Watersheds", 50,000 to 150,000 acres [20,200 - 60,700 ha] in size to bridge the gap between research findings and operational management of drainage basins for improving the timing, quantity and quality of water yield from the National Forests. These watersheds register the changes in water yield occasioned by a wide variety of activities in the watershed. From this, the term "Barometer Watersheds" was derived.

The timing for this program seemed opportune in its coincidence with the International Hydrologic Decade and the increased public interest in water yield opportunities (Barr 1956). Also, the Multiple Use Sustained Yield Act of 1960 created a new operating environment that required coordination among activities on the land. The Pacific Southwest Water Plan added additional impetus for water yield studies in watersheds tributary to the Colorado River and in California.

As envisioned by Beattie and Dortignac, a hydrologic province with broadly similar characteristics would be identified, and a representative watershed ranging from 50,000 to 150,000 acres (20,234 to 60,703 hectares) would be selected within this region. For example, the Wasatch Plateaus Province of central Utah was represented by the Straight Canyon Barometer Watershed. After careful survey and characterization of soils, geology, vegetation, climate and hydrology, these watersheds would have integrated multiple use prescriptions developed and applied. The Barometer Watersheds were to have state-of-the-art hydro-meteorological instrumentation installed to evaluate the effects of these integrated prescriptions on water yield characteristics. In addition to the stream gaging stations and recording precipitation gages, a central weather station was included that logged net radiation, dew point, wind at two levels, and temperature. These measurements were supplemented with storage precipitation gages, snow pillows and snow courses.

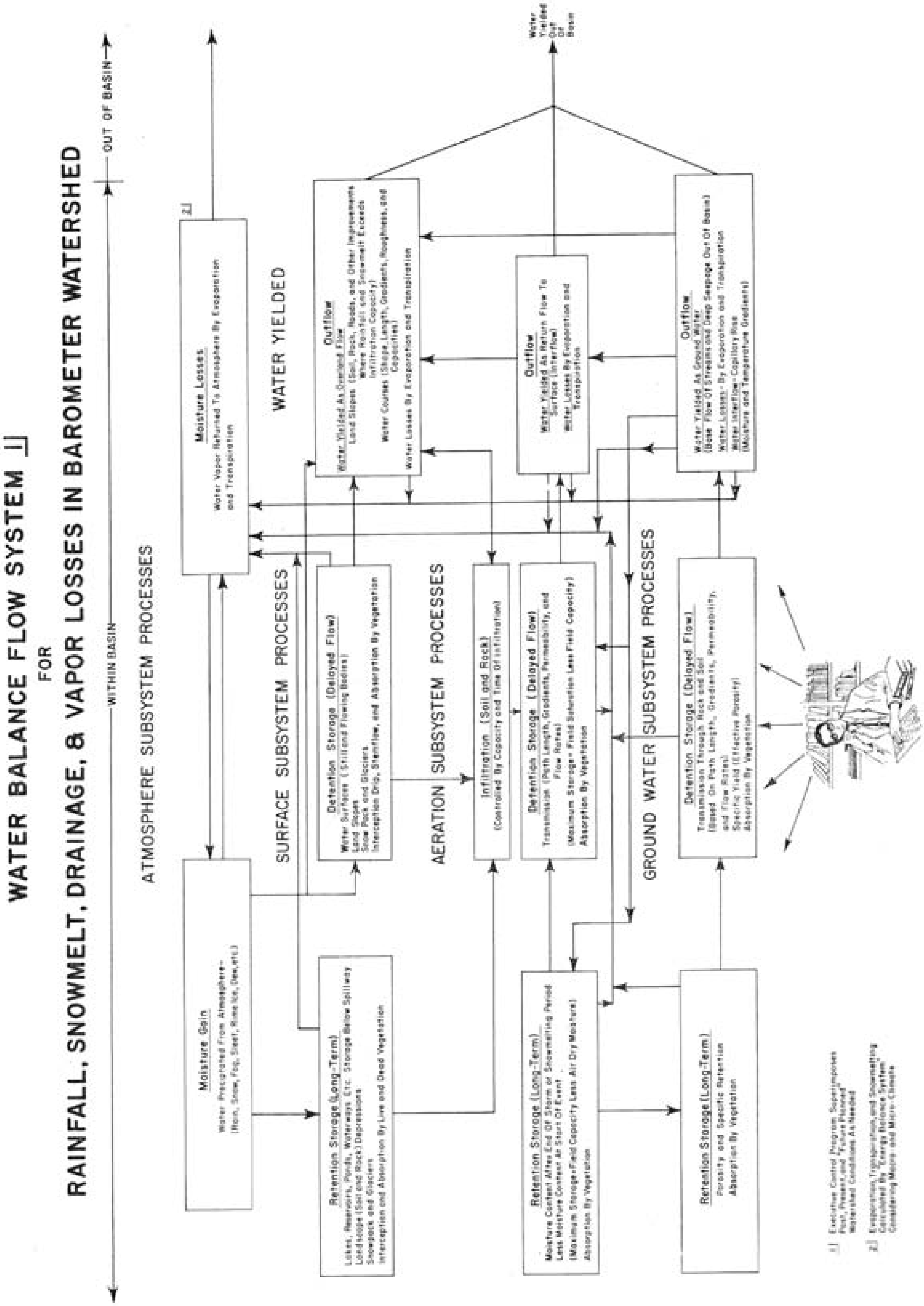
Beattie and Dortignac prepared a number of additional papers that described the program, as well as describing watershed management concepts that could be applied (Beattie 1962, 1967a, 1967b; Dortignac 1966, 1967). The Glazebrook (1969) paper described progress to that point and indicated that the number of watersheds would not be increased beyond those already established. Glazebrook also stressed that barometer watershed prescriptions would be evaluated in the context of ongoing forest planning efforts. Prescriptions would be considered as alternatives in the plans and implemented if selected in the planning process.

## Operations

Essential to this effort was the prediction in advance of the expected outcomes and effects of proposed watershed and other resource prescriptions. Some of the conceptual considerations the watershed scientist needed to evaluate are described in the water balance flow chart in Figure 1. The Watershed Systems Development Unit (WSDU) was established in 1966 to provide support to the field units in installing and maintaining the equipment and to provide the necessary computer programs to translate and manage the data. Of equal importance was the development of computer models to predict the water yield outcomes associated with various prescriptions. A program called "BURP" predicted the water yield outcomes from application of vegetation management prescriptions. The WSDU unit was led by Clyde Shumway and housed at the Pacific Southwest Research Station in Berkeley, CA. Cliff Mansfield provided instrumentation support. By the time the unit was established and operating, a backlog of untranslated data tapes had accumulated at many of the barometer watersheds. A key part of the data management process was a machine to read the punch paper tapes and convert them into computer cards for processing by the computer. This machine was acquired in the late 1960s and experienced considerable down time due to mechanical problems. The machine was housed in Ogden, UT, and all the data from the various watersheds was processed through this machine. Getting the data in proper format and correcting for time errors and missing data required a considerable amount of the barometer hydrologist's time. The computer program development took place on the highly capable computers at the University of California at Berkeley. After development and testing these programs had to be adapted to the less capable computer systems available at the regional office level. Barometer hydrologists pioneered in the use of some of the earliest remote terminal systems available for accessing the central computer systems over phone lines from ranger stations.

The predicted outcomes of the applied prescriptions were to be compared to the measured outcomes. The intent was to refine and adjust the data acquisition and the model until it produced predictions with a reasonable accuracy. Once validated, the model and prescriptions could be applied throughout the hydrologic province, providing managers with predictable outcomes of their planned activities.

These barometer watersheds and the data management and predictions were to be managed on the ground by a




After Dortignac and Beattie 1965

**Figure 1. System for Evaluating Water Yield**

corps of watershed scientists that included hydrologists, soil scientists and geologists. Large numbers of these specialists were hired beginning in the mid 1960s and extending into the early 1970s. Glazebrook (1969) indicates, for example, that the number of watershed scientists employed by the Forest Service went from 4 in 1961 to 112 in 1969. These people were well trained academically but faced a steep learning curve on the job to cope with myriad daily challenges.

At the outset, 50 provinces were identified that involved National Forest System lands and 50 barometer watersheds were planned. (Delk 1979). By 1969, 23 of the anticipated 50 had been established (Glazebrook 1969). The established barometer watersheds, as of March 1970, are listed in Table 1.

There was wide variation in the level of investment and activity involved in establishing hydro-meteorological instrumentation. This was also true of efforts to characterize the vegetation, soil, climate and geology. For example some watersheds like Lake Fork, East Fork Smiths Fork, Straight Canyon, Encampment River, Black River, Entiat River and Umatilla River were projects where most of the anticipated instrumentation was installed and operating. Other watersheds achieved varying levels of characterization and instrumentation. By 1979, the Delk report identified only 12 watersheds as still operating at some level (Delk 1979). The operating barometer watersheds are identified in bold in Table 1.

## Assessment

Based on the analysis and findings of the Delk (1979) report, the National Program emphasis was discontinued. Regions and forests were left to determine what level of emphasis and priority should be given to continuing the Barometer Watershed Program on a local basis. The challenges imposed by the National Environmental Policy Act (NEPA), National Forest Management Act (NFMA), and other acts usually resulted in a choice to shift personnel and funding to these more urgent demands. By the mid

*Table 1. Established Barometer Watersheds. These are the 24 barometer watersheds that were established by 1970.* **The watersheds identified in bold type are the ones that remained active at the time of the Delk Report in 1979.** *R-1 is the USDA Forest Service Northern Region, R-2 is Rocky Mountain Region, R-3 is Southwestern Region, R-4 is Intermountain Region, R-5 is Pacific Southwest Region, R-6 is Pacific Northwest Region, (R-7 was merged with R-9), R-8 is Southern Region, R-9 is Eastern Region, R-10 is Alaska Region.*

| | Barometer Name | State | Region | Hydrologic Province |
|---|---|---|---|---|
| **1.** | **Meadow Creek (Horse Cr)** | **ID** | **R-1** | **Northern Rocky Mountains (Selway R.)** |
| 2. | West Fork Madison River | MT | R-1 | Western Rocky Mountains (Madison R.) |
| **3.** | **Lake Creek** | **CO** | **R-2** | **Central Rocky Mountains (Arkansas R.)** |
| **4.** | **Encampment River** | **WY** | **R-2** | **Sierra Madre (North Platte R.)** |
| 5. | Salome | AZ | R-3 | Central Arizona (Salt R.) |
| **6.** | **Black River** | **AZ** | **R-3** | **Mogollon Rim (Salt R.)** |
| **7.** | **Straight Canyon** | **UT** | **R-4** | **Central Utah Plateau (San Rafael R.)** |
| **8.** | **Antimony Creek** | **UT** | **R-4** | **Southern Utah Plateau (Colorado R.)** |
| **9.** | **East Fork Smiths Fork** | **UT** | **R-4** | **Uinta Mountains (Green R.)** |
| 10. | Big Creek | CA | R-5 | Southern Sierra Mountains (Kings R.) |
| 11. | Upper Santa Ynez River | CA | R-5 | South Coastal (Santa Ynez R.) |
| **12.** | **Green River** | **WA** | **R-6** | **Northwest Middle Cascades (Puyallup R.)** |
| **13.** | **Entiat River** | **WA** | **R-6** | **North East Cascades (Columbia R.)** |
| **14.** | **Umatilla River** | **OR** | **R-6** | **Northern Blue Mountains (Columbia R.)** |
| 15. | Upper Clackamas River | OR | R-6 | West Slope Middle Cascades (Willamette R.) |
| 16. | Upper Sauk River | WA | R-6 | North West Cascades (Skagit R.) |
| **17.** | **Davidson River** | **NC** | **R-8** | **S. Appalachian Mtns. (French Broad R.)** |
| 18. | Upper North River | VA | R-8 | Valley & Ridge (Potomac R.) |
| 19. | Cranberry River | WV | R-9 | Appalachian Plateau (Kanawha R.) |
| 20. | Hurricane Creek | AR | R-9 | Ozark Plateau (White R.) |
| 21. | Kawishiwi River | MN | R-9 | Laurentian Upland (St. Louis R.) |
| 22. | Wild River | NH | R-9 | New England (Androscoggin R.) |
| 23. | Pine River | MI | R-9 | Lower Michigan (Manistee R.) |
| **24.** | **Kadaskan River** | **AK** | **R-10** | **Island Southeast (Coastal SE Alaska)** |

1980s only a few barometer watersheds struggled on. Most of these had a research study underway making the continued investment more attractive. The program is described in the Forest Service Manual (USDA Forest Service 1965) and the progression in direction can be seen in the revision (USDA Forest Service 1979). The 1965 direction focuses heavily on the technical application of scientific principles and watershed management concepts. By contrast the 1979 direction focuses more on coordination with research efforts and forest planning processes.

The Delk (1979) report provided an insightful assessment of the status of the program. It also described what had been achieved as compared with the original concepts described by Dortignac and Beattie (1965). Delk also provided some views regarding how the program might be adapted to be more relevant and useful in light of current programs and emphasis in the Forest Service. He noted that the barometer program was very successful as a training ground for many of the cadre of hydrologists who currently served the national forests. However, this program was less successful in accomplishing the representative watershed role for a variety of reasons. Drawing on Delk and personal experience the following points may provide useful insights to those charged with developing similar efforts in the future.

***Technology.*** The desired outcomes of the barometer watershed effort relied on cutting edge and yet-to-be-perfected technology. Watershed characterization included stream gaging, precipitation, and climatic measurements. The belief was that current chart recorder technology would produce a backlog of undigested data. To overcome this, punched paper tape technology was selected. This equipment offered the possibility of rapid reduction and compilation of data. The actual situation proved more problematic and the equipment was subject to more mechanical wear and tear, required electrical energy, and thus had a higher maintenance requirement in remote locations. The equipment frequently failed and data was lost until parts could be obtained and installed.

The data tapes required specialized technology to translate the punch paper tapes to computer cards and then to process them through computer programs to produce data records. A considerable quantity of data tapes had been produced before the tape translator reader was acquired. The tape translator was also subject to frequent breakdowns and delays in receiving replacement parts. This added to a further backlog of unresolved data and an accumulation of undetected instrument calibration problems.

The computer programs to compile the data were under development concurrently with the initial data acquisition. These factors all combined to produce a data analysis backlog that was difficult to overcome. Hindsight suggests that using existing proven data recording technology might have produced better results. At least providing the proven technology as a redundant backup to the punched paper tape systems, as was done by the US Geological Survey, would have provided more reliable and continuous data sets. As reliable improved technology becomes available it can be brought on-line.

***Coordination.*** The outcomes of the barometer watershed effort depended on predicting the results of an integrated prescription, then implementing the prescription and testing the actual outcome with the predicted outcome. The time horizon to accomplish this would likely require at least ten years using the paired watershed approach. This would involve five years of calibration followed by five years of post-activity evaluation. The reality was that coordinating timber harvest and other activities with barometer watershed objectives was not achieved for a variety of reasons. These included inability to delay ongoing timber harvest activities, failure of timber markets to develop as planned, fires, and changing environmental requirements.

***Scale Issues.*** Study strategies for dealing with watersheds of 50,000 to 150,000 acres (20,200 to 60,700 ha) were inadequate. While perhaps a realistic management scale, they represent a huge departure from small research watersheds and plot studies. The relative amount of change possible from an activity is limited by scheduling, timing, duration and extent of the treatment relative to the size of the watershed as a whole. In addition, a range of environmental constraints and limitations required by consideration for other resource values effectively reduced the magnitude of the prescribed treatment on runoff. A further consideration is the inherent limitation on the accuracy of stream gages on larger flowing rivers. Taken together, these factors made it unlikely that any anticipated resource use or activity would progress at a rate and magnitude to produce a detectable change over the larger watershed area. The lack of detectable change would make it difficult to validate predictions. Hindsight suggests more focused evaluation of smaller management scale watersheds might have been more effective. Perhaps scaling up from one square mile (2.6 $km^2$) research watershed results to a ten square mile (26 $km^2$) watershed application with replication within the larger 50,000 to 150,000-acre (20,200 to 60,700-ha) watershed might have produced measurable changes to evaluate. Another possibility would be the use of nested watersheds. For example, some successful studies at Horse Creek, a tributary of the Meadow Creek Barometer on the Clearwater National Forest, Idaho, and Coon Creek, a tributary of the

Encampment River Barometer on the Medicine Bow National Forest, Wyoming (sub-watersheds within larger barometer watersheds), could provide useful information regarding the type of results that could be achieved when applied in a larger watershed. A study at Battle Flat on the Prescott National Forest, Arizona, did rely on the development of extensive networks of nested stream gages. Unfortunately the studies did not get beyond the calibration stage before being discontinued.

***Scientific Skills and Experience.*** Those few barometers that had higher degrees of success benefited from involvement of experienced forest service research scientists. These, for example, included studies at Horse Creek, Coon Creek, and Entiat, and other locations. Other joint efforts involving pilot demonstration watersheds between National Forest Systems and Research at Beaver Creek on the Coconino National Forest in Arizona are good models of the cooperation needed to have a greater likelihood of successful outcomes.

***Adaptability.*** As Delk (1979) points out, the legal, institutional and external requirements imposed on land managers had changed considerably in the years since the program started. Priorities had shifted. The funding process had changed as well, and the amount of funding available was diminished. The barometer program required a sustained effort over a period exceeding a decade to be successful. Even if the technology and trained personnel had been available at the outset, it is unlikely that the effort could have responded to the changes in funding and priority at the scale that was undertaken. Perhaps a greater emphasis on a few prototypes to demonstrate the concept might have proven more effective. A tangible proof of concept is a powerful advocate for the value of a program. Prototyping also allows discovery of flaws and the opportunity for adjustments to be made before broader applications are implemented. Future programs of this nature must consider how they will adapt to rapidly changing priorities, requirements and funding.

## Accomplishments

As Glazebrook (1979) pointed out, even though the original planned effort was blunted, there were a number of successes. For example, the barometer watershed program has provided insight into the hydrologic functioning of large watersheds under different conditions of geology, soils, climate, landforms and vegetation. These areas provided excellent training grounds for forest land managers, soil scientists and hydrologists. They have also provided valuable insights to the public regarding watershed management through show-me trips, media articles and interpretative signs. These areas, in some cases, provided venues for scientific study both by internal research scientists and by external cooperators. Meeting the challenges of managing data and developing predictive programs were the forerunners of current planning and assessment tools used in watershed management and land management planning. The barometer watershed effort also produced new analytical methods for dealing with wildland hydrology issues and improved the ability of the Forest Service to deal with watershed issues. A significant part of this improvement is due to the increase in the number of trained scientific professionals in soils and hydrology fostered by the barometer watershed program.

## Summary

As we look to the future, it is clear that land management planning and decision making are advantaged by having facts about the climatic and hydrologic situation. Knowledge of the vegetation, soils and geology, coupled with these data, provides an opportunity to improve our ability to evaluate proposed actions in advance of implementation. This predictive ability offers the opportunity to modify actions or incorporate mitigation as was attempted in "An approach to water resources evaluation of non-point silvicultural sources" (WRENSS) (USDA FS 1980). These water facts are vital to the effectiveness of scientifically trained hydrologists and soil scientists in providing advice to managers. Programs such as the barometer watershed management effort have provided additional insights into how wildlands operate. Continuing to emphasize gathering data at strategic sites and pilot testing research findings on a management scale remain valuable tools in closing the gaps between scientific knowledge and management applications. Closing this gap remains one of the key challenges facing land management agencies in the future. Efforts are continuing to improve the speed with which we bring science to bear on management problems. Care needs to be taken, however, in how we deal with new abilities to acquire data. Technology is improving in its ability to gather data effectively at less cost in remote areas. This improved ability to acquire data places a greater burden on the analyst to wisely choose how to strategically set up the data acquisition network to meet objectives. The data acquisition effort must be operated effectively so that data becomes useful information to help guide management. We must avoid the temptation to acquire data merely because it is easy to do so. Data is of little value if it is just collecting dust in an archive.

Overall, while the barometer watershed program failed to achieve all that it set out to accomplish, the program did provide some valuable insights into the operation of wildland watersheds. Approaches similar to the barometer program can lead to improved modeling of watershed processes, predicting effects of management prescriptions, and identifying critical variables to be measured. Cooperative efforts between the National Forest System and Research and Development are a key factor in attaining successful outcomes in future efforts of this nature.

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# Development of Watershed Hydrologic Research at Santee Experimental Forest, Coastal South Carolina

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Managing forested wetland landscapes for water quality improvement and productivity requires a detailed understanding of functional linkages between ecohydrological processes and management practices. Watershed studies are being conducted at USDA Forest Service Santee Experimental Forest, South Carolina, to understand the fundamental hydrologic and biogeochemical processes and their linkages with soils, vegetation, topography, climate, and management practices in the low gradient forested landscapes of the South Carolina Coastal Plain. This study presents an overview of and builds on the long-term watershed hydrologic research begun in 1964 by our predecessors at this experimental forest. Monitoring and modeling studies using a paired watershed approach are being conducted to describe the effects of management practices on two first-order, forested watersheds. Long-term flow data from two 160-ha first-order, one 500-ha second-order, and one 4,500-ha third-order watersheds, provide an opportunity to evaluate the flow dynamics and hydrologic effects of scale, land use distribution, and climate on these coastal watersheds. DRAINMOD-based models are being tested with these data for their applicability as a water management tool on these poorly drained natural forested watersheds. The long-term information on hydro-meteorology, water quality and water table levels from these watersheds has also provided baseline data on the eco-hydrologic processes that are useful to researchers, planners, land owners and industries for the assessment of land management and climatic impacts. Such information for poorly drained low gradient coastal watersheds is becoming increasingly important for sustainable development as population pressure and timber demand continue to rise in the southeastern United States.

Keywords: *poorly drained soils, forested wetlands, forest management, outflow (runoff), water budget, water quality, hydrologic modeling, DRAINMOD*

## Introduction

### Historical Development Before Hurricane Hugo (1989)

In the early 1960s, limited information on hydrologic processes, flooding patterns, and water balance components was available for the low gradient, forested wetlands of the humid coastal plain of South Carolina, though similar information and data were continuously becoming available for upland forests through the US Forest Service Coweeta Experimental Forest in North Carolina. With continuing growth in the timber industry, the public and landowners started to become concerned about impacts of forest management (harvesting, thinning, etc.) on runoff, soil moisture, and flooding on these low gradient poorly drained coastal plains in the southeastern United States. In order to address these issues, a first-order experimental watershed (WS 77) with a drainage area of 160 ha (~400 acres) was created in 1963 within the US Forest Service's 2468-ha Santee Experimental Forest (SEF), under the leadership of Dr. Cortland E. Young, Jr., and Dr. Ralph A. Klaiwitter at the US Forest Service Southeastern Forest Experiment Station in Charleston, South Carolina. The SEF was established in 1938, some 55 km northwest of Charleston (Figure 1; Appendix A) for scientific studies (Table 1). The main objectives of the first study were to quantify the evapotranspiration (ET) of a typical coastal plain pine forest, and evaluate the excess soil moisture status using detailed measurements of water budget components. In 1964 another, much larger, watershed (WS 78, 5000 ha [~ 12000 acres]) was added to study the precipitation-runoff relationships of two different-sized watersheds in coastal forest systems (Figure 1). Forest Service scientists, assisted by hydrologists at the U.S. Geological Survey in

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

*Figure 1. Location of experimental watersheds 77, 78, 79, and 80 within Francis-Marion National Forest, South Carolina (from 1964 map). Note that watersheds 77, 79, and 80 are within the 2468-ha Santee Experimental Forest, established in 1938.*

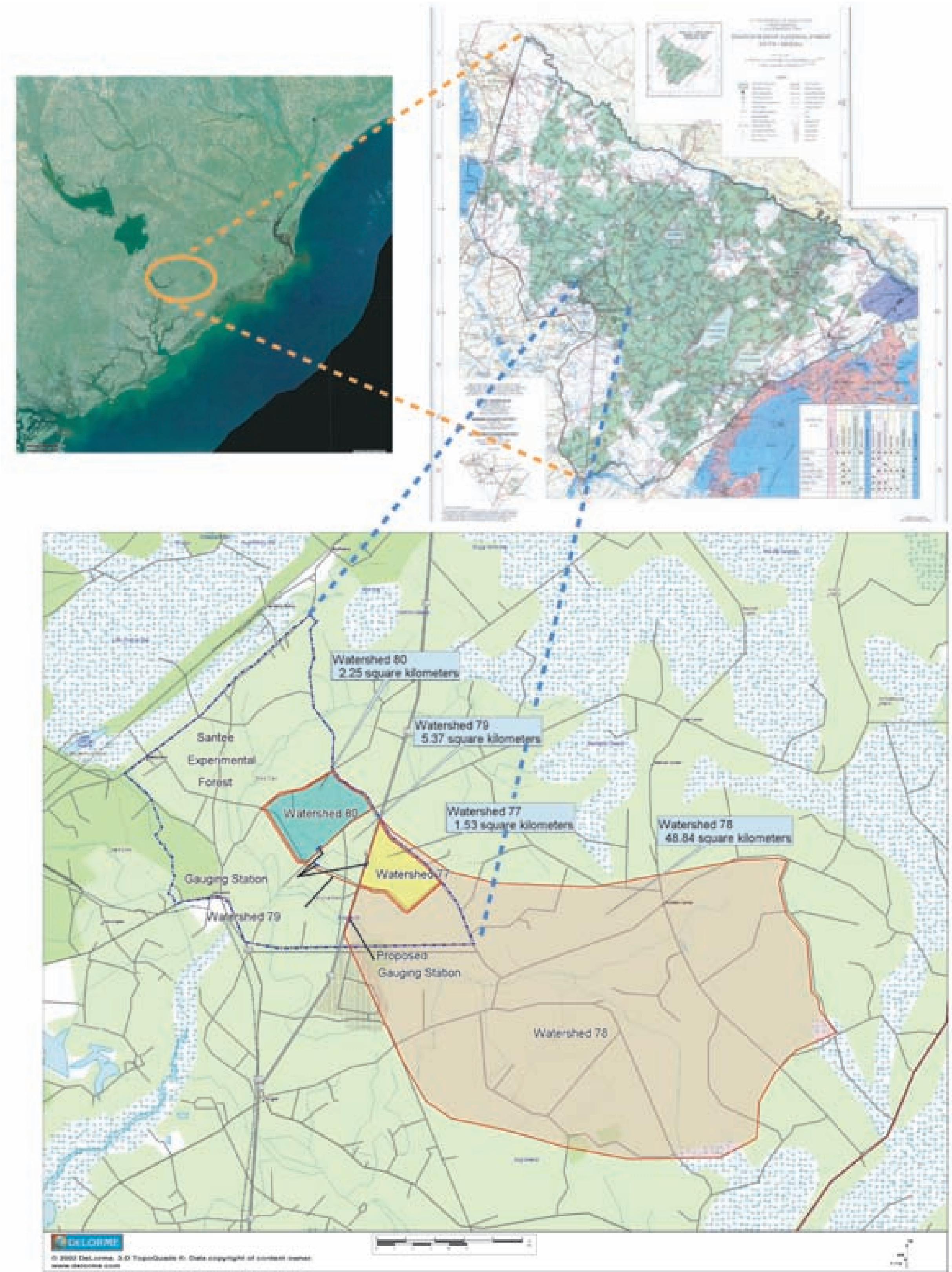

*Table 1. Types and descriptions of infrastructure for each of the four watersheds at the Santee Experimental Forest, South Carolina.*

| Watershed No. | Drainage Area | Period of Record | Design of the Outlet | Associated Data | Condition | Needs |
|---|---|---|---|---|---|---|
| 77 (Treatment) (First order, Fox Gully) | 160 ha | 1963-81; 1989 - present | Compound V-weir | Stage, Soil moisture, Water quality, GW levels, Met station | Good, monitoring continuing (No data 1981- 1989) | Analysis and publications of old data. Some ongoing. |
| 78 (Turkey Creek) | 5000 ha | 1964-84; 2005 - present | Outlet in a dam | Stage, Velocity, Flow rates | Discontinued in 1984 | Analysis and publications; Monitoring water quantity and quality is starting soon. |
| 79 (Second order, Fox Gully) | 500 ha | 1966-73; 1989-90; 2003 - present | V-weir and 3-box culvert | Stage, Water quality | Good, monitoring continuing | Processing data analysis, Publications |
| 80 (Control) | 206 ha 155 ha since November 2001 | 1968-81; 1989- present | Compound weir | Stage, Water quality, GW levels, Met station, Throughfall | Good, monitoring continuing (No data 1981-1989) | Analysis of old data and publications ongoing. |

Columbia, SC, installed a stream gaging station on WS 78 and collected data from 1964 to 1984 (Table 1).

Building upon the excellent cooperation between National Forest and Experimental Station, in 1965 Young and Klaiwitter added an additional gaging station on a 500-ha (~1200-acre) second-order watershed (WS 79) (Table 1, Figure 1, Appendix A). This provided an opportunity for Forest Service scientists and researchers to compare the effect of watershed size on precipitation-runoff relationships for these coastal forested wetlands, which would have been very difficult with only the original two watersheds (WS 77 and WS 78). While these studies were still ongoing, Young and Klaiwitter capitalized on the opportunity provided by the construction of Yellow Jacket Road by the Francis-Marion National Forest in 1968, by adding another 200-ha (~500-acre) experimental watershed (WS 80) draining to Fox Gully Branch (Figure 1; Appendix A). With the establishment of a flow gaging station in 1968 (Table 1), these four watersheds of varying sizes could be used to study not only the soil moisture and runoff processes, but also the effects of different types of treatments such as eradication of understory, clearcut, thinnings, drainage, and impoundments. A paired watershed approach was suggested with the fourth watershed (WS 80) as a control and the first watershed (WS 77) as a treatment for studying the effects of various silvicultural management treatments. The outlet systems on these watersheds were designed with compound v-notch weirs to accommodate high floods, as well as to hold sufficient water to support other management objectives such as timber, wildlife, forage and aquatic biota (Klaiwitter 1970). Some of the main objectives of these proposed studies on forested wetlands and their water resource and water management issues were outlined in the Southern Research Station (SRS) report (USDA FS 1963). All of these experimental watersheds were included in the inventory prepared by the American Geophysical Union (AGU 1965).

Monitoring was discontinued on the first-order, paired watersheds WS 77 and WS 80 in November 1982, and on the large watershed, WS 78, in November 1984. Data recording on the second-order watershed (WS 79) was not available after 1978. No further monitoring except for the weather station at the Santee Headquarters was conducted until October 1989, when Hurricane Hugo struck these experimental watersheds and forests. The chronology of activities on these watersheds is given in Table 2.

## Developments after Hurricane Hugo (1989)

After Hurricane Hugo hit the experimental watersheds in late September 1989, the treatment watershed (WS 77) was salvage harvested. The control (WS 80) was not salvaged, with most of the trees, stumps, and branches left undisturbed in the forest. At the same time, recognizing a need to understand the hydrologic and water quality

*Table 2. Chronology of watershed activities at Santee Experimental Forest.*

| Year | Description |
|---|---|
| 1937 | Santee Experimental Forest established |
| 1946 | Weather station for rain and temperature measurements established at Santee Headquarters |
| 1963 | Watershed WS 77 established as a treatment watershed |
| 1964 | Watershed WS 78 established as a large fourth-order watershed |
| 1966 | Watershed WS 79 established as a second-order watershed |
| 1968 | Watershed WS 80 established as a control watershed |
| 1968 | Flow monitoring initiated in November |
| 1963 - 1968 | Young and Klaiwitter studies |
| 1974 - 1977 | Binstock (1978) Study on WS 77 and WS 80 |
| 1976 | Water quality monitoring initiated |
| 1980 | Richter (1980) and Richter et al. studies on WS 77 and WS 80 |
| 1981 | Flow and water quality monitoring discontinued on all but WS 78 |
| 1984 | Flow monitoring discontinued on watershed WS 78 |
| 1989 | Hurricane Hugo damages the forest in September |
| 1989 | Both flow and water quality monitoring reactivated in November on watersheds WS 77, 79 and WS 80 |
| 1990 | WS80 is non-salvage harvested (all roots, stumps, branches left intact on the watershed) |
| 1990 | Rain and temperature measurements established at Met25 |
| 1992 | Manual wells established on WS 80 and WS 77 |
| 1994 | Plots established for growth study (Hook et al. 1991) |
| 1996 | Automatic recording WL40 wells established on WS 80 and WS 77 |
| 1996 | Electronic data loggers installed at Met25 (rain and temperature), CR10 Campbell Scientific data logger installed at Santee Headquarters weather station |
| 1999 | Long-term study of vegetation dynamics initiated (Burke 1998) |
| 2000 | Sun et al. study on WS 77 and WS 80 |
| 2001 | Binkley (2001) study; Secondary outlet unplugged, reducing WS80 drainage area to 160 ha |
| 2003 | Miwa et al. study; Amatya et al. studies; WS 77 undergoes prescribed burning on 10 May; Throughfall monitoring on WS 80 begins; Backup flow meter installed on WS 79 and 80; Harder study begins on WS 80. |
| 2004 | A collaborative project to reinitiate monitoring of WS 78 on Turkey Creek and its hydrological study begins; Harder study completed with 2003-04 data. |
| 2005 | Streamflow monitoring on Turkey Creek begins in January; A collaborative study with Florida A&M University begins on this watershed; A new study on biomass removal by prescribed fire begins on WS 77, 79, and WS 80. |

impacts of hurricanes and other natural disturbances, monitoring of both the water quantity (outflow) and quality were resumed.

Streamflow gaging stations on both the first-order (WS 77 and WS 80) and second-order (WS 79) watersheds were upgraded with automatic GL3150 (Global Water)[1] sensors with pressure transducers for recording stage height to estimate flow rates. Flow monitoring at the large fourth-order watershed (WS 78) was not resumed. A fully automatic CR10 (Campbell Scientific) weather station was installed in 1996 at the Santee Headquarters to monitor air temperature, humidity, wind speed and solar radiation needed for the estimates of evapotranspiration (ET). An additional sensor to measure net radiation was added in 2003. Watersheds WS 77 and WS 80 were also equipped with automatic stations – precipitation recorders in 1990, additional sensors to measure air and soil temperature in 1995. Several manual monitoring wells were installed on both of the first-order watersheds in 1990. Two shallow automatic recording wells were installed on WS 77 and one on WS 80 in 1992 (Appendix A). One additional deep automatic well was installed on WS 80 in 2003. Throughfall gages were also installed across watershed WS 80 in July-August 2003. A chronology of various activities that took place on these watersheds is shown in Table 2.

## Other Planned Monitoring

- To re-install the evaporation pan and monitoring device to measure pan evaporation at the weather station at Santee Headquarters.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

- To install backup data loggers at WS 77 and WS 79 to insure against loss of flow data.
- To install piezometers on the control watershed (WS 80) to examine the deep groundwater fluxes in this system.
- To measure leaf area index (LAI) and stomatal conductance of the pine-hardwood stand on the control watershed (WS 80).
- To install the Eddy Flux tower to quantify the carbon and water fluxes on WS 80 with mixed pine-hardwood stands.

## Data Analysis and Management

Most of the strip chart and magnetic tape data from the rain gages and flow recorders used on the watersheds before the Hurricane Hugo were sent to Coweeta Hydrologic Laboratory in North Carolina for digitizing into electronic formats. Precipitation, weather, flow (for WS 77, WS 79, and WS 80) and water table data were converted to digital formats. Accordingly, all data from 1964 through July 1999 have been checked for appropriate QA/QC (Gartner and Burke 2001) and then archived in a single Microsoft Access database. Efforts are underway to append the database with data from August 1999 to date. These data are currently being stored at the Center for Forested Wetlands Research in Charleston, South Carolina. Also based on a recent Memorandum of Understanding with Atlanta-based Tetra-Tech, Inc., flow data from watershed WS 78 for the period of 1964 to 1973 has been converted into digital formats. Data from 1974 to 1976, processed at Coweeta Hydrologic Laboratory, were already in digital formats, and no data have yet been found for 1977 to 1984. Only the field service records on paper formats are available through May 1984. The recorded stage heights taken every two to four weeks of the service period may be used to derive the discharges using the stage discharge relationship created in 1964.

The Center for Forested Wetlands Research (CFWR) at Southern Research Station Unit 4103 has recently participated in an Internet-based hydrologic data sharing program (HYDRODB 2004) developed by Oregon State University under the sponsorship of the US Forest Service and the National Science Foundation's Long Term Ecological Research (LTER) program (*http://www.fsl.orst.edu/climhy/hydrodb/harvest.htm*). CFWR has also posted hydrologic and metadata from Santee Experimental Forest watersheds WS 77 and WS 80 on HYDRODB for internet based data sharing where researchers and users can download data for inter-site comparisons and various other research and study purposes.

## Results To Date

Only a limited amount of information was published from data measured between 1964 to 1982 on these experimental watersheds. Young and Henderson (1965, 1966) published the procedures for measurement of soil moisture and pan evaporation, respectively, at the study site. Young (1966) reported a two-year water budget for the treatment watershed (WS 77), concluding that excess water in the form of runoff could be problematic in downstream flooding, and that there was no dependable base flow generated from this natural watershed. Young (1967) also described the flooding pattern, flashiness, and effects of storage on these forested lands in controlling the outflow processes. The limited records then showed that the Santee watershed (WS 77) tended to release rainfall more quickly than do other forested areas in the Southeast. Young and Klaiwitter (1968) found the total runoff varying between 427 to 869 mm for three above-average rainfall years, yielding 38% on average of the total rainfall lost to runoff from WS 77. Young et al. (1972) also presented an analog version of a hydrologic model for a wetland forest at this site. Significant works evaluating the hydrologic and water quality effects of prescribed burning using the paired watershed approach on WS 77 and WS 80 were published by Binstock (1978), Richter (1980) and Richter et al. (1983a, 1983b). Binstock (1978) found no significant effects on the water quality or the soil chemistry of the experimental watershed following a prescribed winter burn. Richter (1980) found an average annual outflow to precipitation ratio of 27% (with a range of 15% to 43%) for 1965 to 1978 for WS 77, while an average ratio of 20% (with a range of 12% to 30%) was found on the control, WS 80, from 1970 to 1978. No published information has yet been found on the fourth-order Turkey Creek watershed (WS 78) and the second-order Fox Gully Creek watershed (WS 79) (Figure 1).

Hook et al. (1991) published some information on the impacts of Hurricane Hugo. Sun et al. (2000) evaluated the water budgets and water table pattern of the two experimental watersheds, finding average annual outflow to precipitation ratios of 30% for WS 80 and 23% for WS 77. Later, Binkley et al. (NCASI 2001) published water chemistry data from these two watersheds in their study of the nutrient concentrations of over 300 streams in small, forested watersheds across the continental United States. Miwa et al. (2003) studied the stream flow dynamics and hydrograph characterization of these watersheds. They demonstrated that headwater stream flow was highly responsive to rain events and that the stream processes are regulated by rainfall intervals, antecedent soil moisture, vegetation, soil types, and physical characteristics of the watershed including topography and surface water storage.

More recently, Amatya et al. (2003a) compared the six-year hydrology of the control watershed (WS 80) with that of an artificially drained watershed in eastern North Carolina. Results showed that WS 80 had much shallower water table depths with higher frequency outflows as compared to the North Carolina watershed, even though WS 80 had lower average annual rainfall. Amatya et al. (2003b) also tested a DRAINMOD hydrology model developed for poorly drained soils to evaluate the hydrology and water budget of WS 80, and demonstrated the potential of the model to accurately describe the hydrology of natural forested wetland given reliable inputs of soils and weather data. Most recently, Harder (2004) completed a study characterizing the detailed water budget of the control watershed (WS 80).

Because of the extended period of near-surface water table elevations caused by large storm events in 2003, with the highest annual rainfall (1671 mm) in 14 years (1990-2003), the stream runoff for the control watershed accounted for as much as 48% of the total rainfall. The results of the study served both to characterize hydrologic processes (runoff, water table response to rainfall, ET and soil moisture dynamics), and to quantify the water budget for a wet year (2003) and dry winter/spring season (2004) of the first-order forested watershed. Harder also provided a most comprehensive review of the studies conducted so far on this watershed. Some of the information on the Santee experimental watersheds is also reported in a recent publication by Amatya et al. (2004a).

## Recent Ongoing Studies

Recent studies on the Santee Experimental Forest watersheds aim to:

- Use the historical flow and water quality data from the first-order control watershed (WS 80) and sample storm events from the second-order watershed (WS 79), for estimating reference loads for comparison with developed watersheds in the region, and also for developing a Total Maximum Daily Load (TMDL) for Charleston Harbor, in collaboration with Atlanta-based Tetra-Tech, Inc. and Charleston-based JJ&G Engineering Consultants (Miller and Amatya 2004).
- Use the historical data from three experimental watersheds (WS 79, WS 80, and WS 78) for the comparison of rainfall-runoff relationships, flow duration curves and flood frequency analyses (Amatya and Radecki-Pawlik 2005).
- Test the hydrology of the control watershed (WS 80) using a physically-based distributed model (MIKE-SHE) and apply the model for evaluation of management impacts in collaboration with the US Forest Service, Southern Global Change Program.
- Use field-measured data and water budget from the control watershed (WS 80) to refine the testing of DRAINMOD model and compare results with the Thornthwaite water balance model (Thornethwaite and Matther 1955).

## Rationale for Continuing Future Studies

The hydrologic and water quality effects of silvicultural management practices including prescribed burning, harvesting and thinning have been a major area of research in the southeastern United States. The Southern Forest Resource Assessment (SOFRA 2002) emphasized a need for research to assess the long-term cumulative non-point source impacts of silvicultural activities on water quality and overall watershed health. The dominant water quality issues are sediment, roads (as sources of sediment), nutrients, fires, (as sources of sediment and nutrients), pesticides and water temperature (Jackson et al. 2004). Although studies to address some of these issues have been done in the past (Riekerk 1989; Ursic 1991; Shepard 1994; Amatya et al. 1997; Sun et al. 2000, 2001; Xu et al. 2002; Amatya et al. 2004b), these studies were either mostly limited to hydrology or covered only a shorter period.

Prescribed burning as a forest management tool, as developed in the Atlantic Coastal Plain (Richter et al. 1982), specifically at the Santee experimental watersheds, was shown to have insignificant effects on the quality of ground and surface water. It reduces fuel loads, controls certain tree pathogens, improves wildlife habitat, and restores desired ecosystems. Few data are available, however, on the effects of this management tool on the hydrology and water quality of wetlands (Jackson et al. 2004). Similarly, solid data on forest fertilization effects and the effects of various best management practices (BMPs) on water quality are lacking for poorly drained coastal forests.

In order to understand and assess these impacts on forested wetlands as affected by year-to-year variation in climate, it is necessary to develop water and nutrient budgets using long-term data. Long-term hydrologic data are essential for understanding hydrologic processes, as baseline data for assessment of impacts and conservation of regional ecosystems. At the same time, they are also very crucial for developing and testing hydrologic and water quality models for answering questions that are difficult to investigate by monitoring, either due to spatial and temporal scale issues, or to complex interactions of parameters on these poorly drained low-gradient systems.

A large quantity of data for wet pine flats (managed plantations) and their impacts on hydrology and water quality in the coastal North Carolina exists in the literature (Amatya et al. 2004b). These systems are established on artificially drained lands, and also intensively managed for timber production. However, little information is available on naturally drained forests of pine mixed with hardwood stands. The forests at the Santee experimental watersheds are managed and operated by the Francis-Marion National Forest for forest and wildlife conservation practices, reducing risks of wild fire, and also for timber management.

A recent study comparing an artificially drained managed pine forest with conventional ditches (25 ha) in coastal North Carolina with a naturally drained less managed mixed (pine-hardwood) forest (200 ha) in coastal South Carolina showed that the latter had much shallower water table depths with higher frequent outflows as compared to the artificially drained one, even though the latter had lower average annual rainfall (Amatya et al. 2003b). This suggests that drainage alone does not necessarily determine total outflow, which may also depend upon the soil type and the argillic horizon. Therefore, data from these headwater coastal forested watersheds, which are distinct from the drained, managed pine forests, are extremely valuable and need analysis and interpretation for scientific studies and assessment of impacts.

As envisioned by earlier Forest Service researchers in the 1960s, the information on water budgets and effects of watershed sizes on precipitation-runoff relationships, hydrograph shapes, flow patterns (magnitudes and distributions) can be very useful for planners and designers in forest management, water and nutrient management, flood control structures, wetland restoration and conservation in the naturally drained low gradient forested lands of the coastal plain. Such data are becoming even more vital as the population pressure and development near the coastal waters continues to increase in the southeastern U.S. The long-term data available for these experimental watersheds for 20 years or more can serve as a reference for evaluating impacts of developing these coastal forests and also as a basis for developing predictive equations in similar ungaged basins in the region (Wagener et al. 2004). Furthermore, these data can be used to analyze the trend of outflows as affected by changes in land use and climatic variation. As an example, flow and water chemistry data from the experimental control watershed (WS 80) for the period 1976-81 and 1989-92 and the recent (2004) storm event sampling data on the second-order watershed (WS 79) are being used as a baseline for reference, undeveloped watershed loads for comparing loads from developed lands in the Charleston Harbor watershed, for which a water quality model is being developed (Lu et al. 2005). These experimental watersheds are also continuously being used as a field laboratory for learning forest hydrogeologic research by students at the College of Charleston, South Carolina.

With the support from the US Forest Service, Southern Research Station, the Center is doing its best to keep up these experimental watersheds as the only long-term coastal forest experimental station in the Southeast for continuing eco-hydrologic studies, along with other scientific studies including prescribed burning, regeneration and management of bottomland hardwoods, restoring wetland hydrologic functions, and carbon sequestration on the coastal forest ecosystems to provide the knowledge needed for their sustainable management. These objectives are consistent with the recommendations of a recent workshop to discuss the role of coastal zone in global biogeochemical cycles (Siefert 2004), and may also help advance hydrologic science in the 21st century (CUAHSI 2003). Most importantly, continuing research at Santee Experimental Forest will help realize the visions of our Forest Service predecessors who installed the experimental watersheds in 1963 as a pilot laboratory for South Carolina and adjacent states (Young 1967).

## Future Planned Studies

Future research efforts at the Santee experimental watersheds will:

- Compare the hydrology and water quality of two first-order watersheds (WS 77, treatment) and (WS 80, control) using data before and after Hurricane Hugo.
- Use both the first-order paired (WS 77, WS 80) and part of the second-order (WS 79) watersheds for studying both the plot- and watershed-scale effects of biomass removal by thinning and prescribed burning on nutrient cycling and transport.
- Study the water quality effects of partial prescribed burning on the treatment watershed (WS 77) using the paired watershed approach with WS 80 as a control.
- Revitalize the watershed-scale study on the third-order Turkey Creek Watershed (WS 78). This is consistent with one of the Forest Service goals (2004-08) to monitor water quality impacts of activities on National Forest lands.

### Revitalization of the Watershed-Scale Study on Turkey Creek Watershed (WS 78)

As a result of continued collaborative efforts to develop and expand the studies on existing experimental watersheds at Santee Experimental Forest, a recent study proposal to revitalize the abandoned watershed-scale study at Turkey Creek watershed (WS 78) (Figure 1) was funded by the Forest Service Southern Research Station Challenge Cost Share Program matching the funds provided by National Council of Air and Stream Improvement (NCASI), Inc. The 5,000-ha watershed has 52% forest cover (mostly within the Francis-Marion National Forest), 28% wet shrubs and scrub, 14% wetlands and water, with the remaining 6% developed for agricultural lands, roads and open areas (Figure 2).

The main objectives of the study are to resume the hydrologic monitoring of the watershed, followed by water quality sampling. The data from past and current monitoring will be used: (a) to compare the flow dynamics among three experimental watersheds of various sizes; (b) to examine the pre- and post-hurricane flow dynamics; (c) to study the effects of land use change and, possibly, the climatic variation on the water yield and flow dynamics (Figure 2); (d) as baseline data for evaluating impacts; and (e) to develop and test DRAINMOD-based and other watershed scale hydrologic models for these poorly drained sites to predict the flow dynamics, water budget and impacts on hydrology and water quality. These modeling studies will also be able to specifically address questions about the cumulative effects of harvesting, thinning, prescribed burning, and biomass removal on hydrology and water quality. Other benefits may include predicting the spatial and temporal distribution of surface and groundwater tables, wetland hydrologic functions, and nutrient and sediment exports. The results will help the national forest manage its lands, roads and trails for operational purposes such as reducing fire hazards, restoration, water management, and transportation needs. The watershed may also be a potential site for studying effects of various forest BMPs, land management practices, and ecological and biogeochemical processes including carbon sequestration and methane ($CH_4$) gas flux dynamics. Furthermore, the site may be a candidate for testing new monitoring technologies such as ADV (Acoustic Doppler Velocity) measurement on slow-moving streams, remote sensing for deriving LAI for over- and under-story vegetation, temperature, soil moisture, and albedo, and Doppler-based precipitation, as needed for large scale hydrology modeling.

The current supporters and collaborators in this study include: the US Forest Service, Southern Research Station, for funding support; National Council of Air and Stream Improvement (NCASI), Inc., for partial funding support; Center for Forested Wetlands Research, SC, as principal investigator (PI); College of Charleston, South Carolina, as Co-PI, research collaborator; University of Krakow, Poland, as a research collaborator; Francis-Marion National Forest, SC, for watershed GIS database and other information support; the US Geological Survey, SC, for installation, servicing and data collection at stream gaging station; Tetra-Tech, Inc., Atlanta, Georgia, as a cooperator in data digitizing and sharing, and South Carolina Department of Transportation for giving access for installation of the gaging station.

## Preliminary Work on Turkey Creek Watershed

So far, work on the Turkey Creek experimental watershed (WS 78) has encompassed the following activities:

1. Processing and analysis of daily flow data from the watershed for 1964 to 1976.

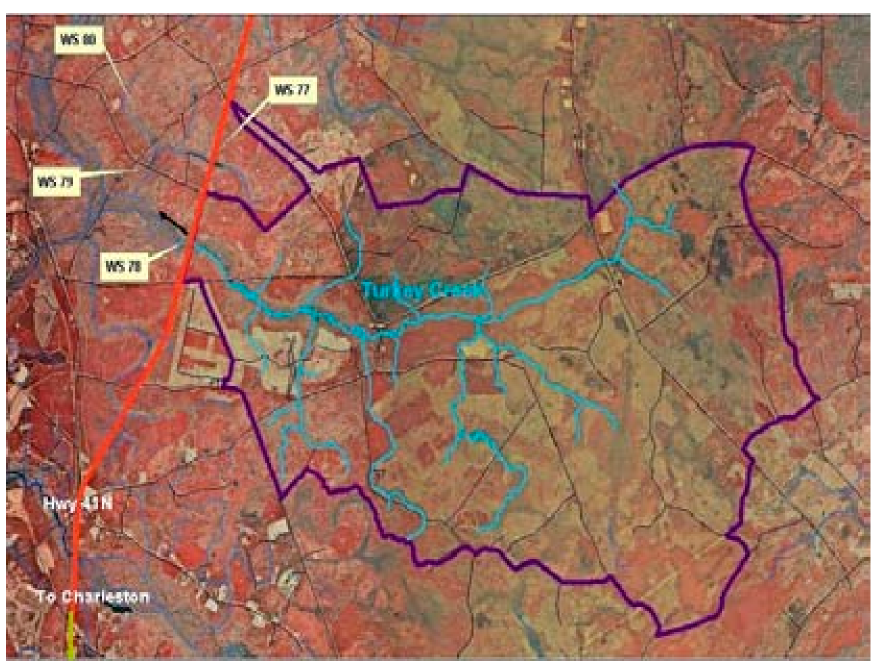


*Figure 2. Land use distribution map of 5,000-ha Turkey Creek watershed (WS 78).*

2. Flow frequency duration analysis.

3. Development of flood frequency curves and comparison with smaller watersheds (WS 80 and WS 79) in the vicinity.

4. Determination of rainfall-runoff relationships and comparison with WS 80 and WS 79 (Figure 3).

5. A collaborative agreement with the Agricultural University of Krakow, Poland for conducting the hydrologic study on Turkey Creek watershed.

6. A paper documenting the preliminary results of comparison of stream flow dynamics of watersheds (WS 77, WS 80, and WS 79) for the 2005 ASAE Annual conference (Amatya and Radecki-Pawlik 2004).

7. Acquisition of satellite imagery, aerial photographs, and GIS data layers on topography, hydrography, soils, and land use (US Forest Service, Francis-Marion and Sumter National Forest Office, SC).

8. Acquisition of similar GIS data layers from Berkeley County Office, SC.

9. Acquisition of historic aerial photographs, GIS layers and data base on forest management practices within Turkey Creek watershed (Francis-Marion National Forest).

10. A cooperative agreement between the Center and College of Charleston for the installation of a stream gaging station at the outlet of Turkey Creek watershed and for a student assistant for data processing and field work.

11. A cooperative agreement between the College of Charleston and USGS District Office in Columbia for the complete installation, servicing and real-time data retrieval, QA/QC and data sharing through the Internet.

12. An agreement between USGS and the South Carolina Department of Transportation (DOT) for the installation of and access to the monitoring gage within the right-of-way of the new bridge being built at Turkey Creek on Highway 41N.

13. A first cooperators' project meeting took place on 9 December 2004. The USGS collaborator reported that the gaging station on Turkey Creek will be installed by January 2005. Questions and discussions on multiple hydrology related research issues such as spatial moisture predictions, flooding, ET estimates, sampling for mercury, assessment of geomorphological characteristics, etc., were raised by the cooperators.

14. A temporary stream gaging station and a rain gage were installed on 16 December 2004. They will collect data until the permanent gages are installed after the construction of the new bridge on Highway 41 (Turkey Creek).

15. A PhD candidate from the Civil and Environmental Engineering Department at Florida A&M University has planned to conduct his field research related to wetland hydrologic functions on this watershed.

16. A fourth project cooperators' meeting is planned for 27 July 2006.

17. Turkey Creek Watershed initiatives were recently featured in Forest Service Southern Research Station's Compass Magazine (From Mountain Headwaters to the Sea), Issue 5, Spring 2006.

The re-initiation of the large, forested watershed study (5,000 ha) on the South Carolina coastal plain, with support from the USFS Southern Research Station and the NCASI, Inc., completes the development of a multi-scale hydrology and ecosystem monitoring framework. The current milestone, re-initiating the gaging of the Turkey Creek Watershed, represents the fulfillment of a gaging network encompassing 1st-, 2nd- and 3rd-order streams; thereby facilitating the examination of the interactions of land use or disturbance regime with streamflow and nutrient export dynamics at multiple scales. For example, historic stream flow data prior to Hurricane Hugo (1989) may be examined with post-disturbance data. The Turkey Creek Watershed Study is a multi-collaborator effort, with precipitation and stream flow data being collected continuously as a part of the US Geological Survey's real-time stream monitoring network. The College of Charleston has installed deep groundwater table wells, and the Francis Marion National Forest is helping to install multiple shallow wells to enable the assessment of surface-subsurface flow interactions, and stream water quality sampling stations will be installed by the Forest Service in cooperation with the USGS during summer 2006.

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***Appendix A. Santee Experimental Paired Watersheds Characteristics***

a. Established in 1965 within the US Forest Service's Francis-Marion National Forest, South Carolina
b. A paired watershed approach on flat, poorly drained soils of lower Atlantic coastal plain
c. WS 80: 200 ha – Control; WS 77: 160 ha – Treatment, WS 79: 500 ha – 2nd-order watershed
d. On 1st-order headwater streams - Tributary of Turkey Creek within the Cooper River Basin
e. Surface elevations from 4.0 to 10.0 m above mean sea level
f. Soils: Primarily loams strongly acidic characterized by seasonally high water tables and argillic horizons at 1.5 m depth
g. Vegetation: Loblolly pine (*Pinus taeda*), longleaf pine (*Pinus palustris*), baldcypress (*Taxodium distichum*) and sweet gum (*Liquidambar styraciflua*)
h. Mean annual rainfall: 1220 mm; Mean annual temperature: 18°C


Satellite image of three experimental watersheds (77, 79, and 80) draining to Turkey Creek (a new watershed scale study) within Santee Experimental Forest with gaging stations (triangular symbols) and Santee Headquarters Weather Station.

Watershed related Web sites:
**http://www.srs.fs.usda.gov/charleston/santee.html**
(For general information)
**http://www.fsl.orst.edu/climhy/hydrodb/harvest.htm**
(For metadata and data harvesting)
The monitoring and watershed studies are maintained by US Forest Service, Southern Research Station, Center for Forested Wetlands Research (SRS-4103), 2730 Savannah Highway, Charleston, SC 29414. For further information about the study sites contact: Dr. Devendra M Amatya, Ph.D., P.E., Research Hydrologist, Tel: 843-769-7012; damatya@fs.fed.us

# Understanding the Hydrologic Consequences of Timber Harvest and Roading: Four Decades of Streamflow and Sediment Results From the Caspar Creek Experimental Watersheds

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The Caspar Creek Experimental Watersheds were established in 1962 to study the effects of forest management on streamflow, sedimentation, and erosion in the rainfall-dominated, forested watersheds of north coastal California. Currently, 21 stream sites are gaged in the North Fork (473 ha) and South Fork (424 ha) of Caspar Creek. From 1971 to 1973, 65% of the timber volume in the South Fork was selectively cut and tractor yarded, and from 1985 to 1991, 50% of the North Fork basin was harvested, mostly as cable-yarded clearcut. The South Fork logging resulted in annual suspended sediment load increases exceeding 300%. Mass-wasting has been predominantly associated with roads, landings, and tractor skid trails in the South Fork. Accelerated mass-wasting and renewed sediment mobilization in the South Fork have occurred since 1998. Peak flow increases detected following North Fork logging are attributable to reduced canopy interception and transpiration. These recovered to pretreatment levels about 10 years after logging, followed by renewed increases from pre-commercial thinning. Annual sediment loads increased 89% in the partially clearcut North Fork and 123% to 238% in 4 of 5 clearcut sub-basins. Twelve years after logging, elevated storm-event sediment yields persist in some clearcut tributaries.

Keywords: *experimental watershed studies, road effects, sediment yield, peak flows, erosion, timber harvesting*

## Introduction

For more than four decades, researchers have investigated the effects of forest management on streamflow, sedimentation, and erosion in the Caspar Creek Experimental Watersheds. The California Department of Forestry and Fire Protection and the USDA Forest Service, Pacific Southwest Research Station, began a simple paired watershed study in 1962 with the construction of weirs on the two major Caspar Creek tributaries, the North Fork (NFC) and the South Fork (SFC). Today, researchers operate 21 gaging stations within the experimental watersheds and use data loggers programmed with sophisticated sampling algorithms, instream turbidimeters, and automated pumping samplers to measure water and sediment discharge. Although much of this research is devoted to quantifying the impacts of modern forest management, it also provides valuable data on hydrologic recovery and the lingering effects of more than a century of timber harvest and roading in the Caspar Creek basin.

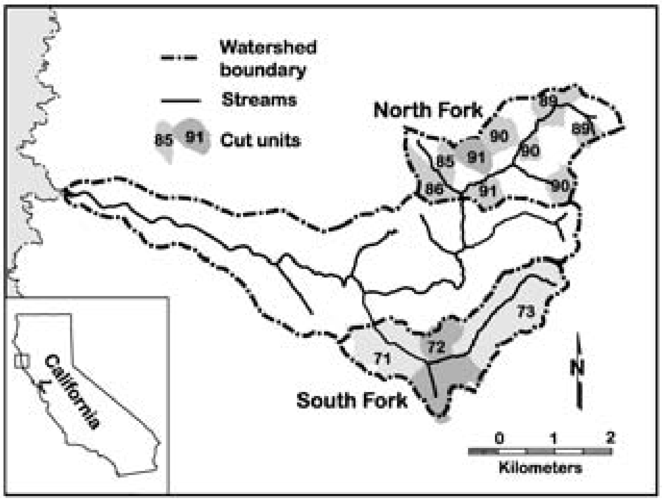
## Methods

### Site

The Caspar Creek Experimental Watersheds are located about 7 km from the Pacific Ocean and about 10 km south of Fort Bragg in northwestern California at lat 39°21´N, long 123°44´W (Figure 1). Uplifted marine terraces incised by antecedent drainages define the youthful and highly erodible topography with elevations ranging from 37 to 320 m. Hillslopes are steepest near the stream channel and become gentler near the broad, rounded ridgetops. About 35% of the basins' slopes are less than 17 degrees, and 7% are steeper than 35 degrees. Soils are well-drained clay-loams, 1 to 2 meters in depth, derived from Cretaceous Franciscan Formation greywacke sandstone and weathered, coarse-grained shale.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

*Figure 1. Caspar Creek Experimental Watersheds.*




The climate is typical of low-elevation coastal watersheds of the Pacific Northwest. Winters are mild and wet, characterized by periods of low-intensity rainfall delivered by the westerly flow of the Pacific jet stream. Snow is rare. Average annual precipitation is 1,170 mm. Typically, 95% of precipitation falls during the months of October through April. Summers are moderately warm and dry with maximum temperatures moderated by frequent coastal fog. Mean annual runoff is 650 mm.

Like most of California's north coast, the watersheds were clearcut and broadcast burned largely prior to 1900. By 1960, the watersheds supported an 80-year-old second-growth forest composed of coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and grand fir (*Abies grandis*). Forest basal area was about 700 $m^3$/ha.

## Measurements

The 473-ha North Fork of Caspar Creek and the 424-ha South Fork of Caspar Creek have been gaged continuously since 1962 using 120° v-notch weirs widening to concrete rectangular sections for high discharges. During the early 1980s, three rated sections were constructed upstream of the North Fork weir and 10 Parshall flumes were installed on North Fork subwatersheds with drainage areas of 10 to 77 ha.

Stream discharge was initially recorded using mechanical chart recorders. These were replaced in the 1980s with electronic data loggers equipped with pressure transducers. Early suspended sediment estimates were derived from sediment rating curves, manual depth-integrated sampling, and fixed stage samplers (Rice et al. 1979). Statistically based sampling algorithms that trigger automated samplers were used beginning in the 1980s (Lewis et al. 2001). In addition, the sediment accumulation in the settling basin upstream of each weir has been surveyed annually.

Periodic field surveys have documented the location, size, and disposition of landslides and fluvial erosion. Erosion features greater than 7.6 $m^3$ (10 $yd^3$) have been inventoried annually since 1986 in the North Fork, and since 1994 in the South Fork.

## Treatments

After establishing a calibration relationship between the North Fork and the South Fork (1963 to 1967), a main-haul logging road and main spurs were built in the South Fork. The road right-of-way occupied 19 ha, from which 993 $m^3$/ha of timber was harvested. The entire South Fork watershed was logged and tractor yarded between 1971 and 1973 using single-tree and small group selection to harvest 65% of the stand volume. Roads, landings, and skid trails covered approximately 15% of the South Fork watershed area (Ziemer 1981). Almost 5 km of the main-haul and spur roads (out of approximately 10 total km) were decommissioned in 1998.

A study of cumulative effects began in 1985 in the North Fork watershed. Three gaged tributary watersheds within the North Fork were designated as controls while seven were designated for harvest in compliance with the California Forest Practice Rules in effect in the late 1980s. Two units (13% of the North Fork watershed) were clearcut in 1985-86. After calibration, clearcut logging began elsewhere in the North Fork in May 1989 and was completed in January 1992. Clearcuts occupied 30-99% of treated watersheds and totaled 162 ha. Between 1985 and 1992, 46% of the North Fork watershed was clearcut, 1.5% was thinned, and 2% was cleared for road right-of-way (Henry 1998).

In contrast to the harvest treatment of the South Fork in the 1970s, state rules mandated equipment exclusion and 50% canopy retention within 15 to 46 m of watercourses providing aquatic habitat or having fish present. Most of the yarding (81% of the clearcut area) was accomplished using skyline-cable systems. Yarders were situated on upslope landings constructed well away from the stream network. New road construction and tractor skidding was restricted to ridgetop locations with slopes generally less than 20% and affected only 3% of the watershed area. Four harvest blocks, 92 ha total, were broadcast burned and later treated with herbicide to control competition (Lewis et al. 2001). Pre-commercial thinning in 1995, 1998 and 2001 reduced basal area in treated units by about 75%.

## Results

### Streamflow

Previous publications detail the magnitude and duration of streamflow enhancements following timber harvest in the Caspar Creek basins (Ziemer 1981, 1998; Lewis et al. 2001; Keppeler and Lewis, in press). In the North Fork, the average storm peak flow with a two-year return period increased 27% in the clearcut watersheds (Ziemer 1998) and 15% in the partially clearcut watersheds. Ongoing measurements show a return to pre-treatment flow conditions on NFC approximately 10 to 11 years post-harvest except for a renewed response to the pre-commercial thinning. Of particular interest is that even under the wettest antecedent moisture conditions of the NFC study, increases averaged 23% in clearcut watersheds and 3% in partially clearcut watersheds. These results are explained by wetter soils in logged units resulting from reduced transpiration and increases in net precipitation due to reduced canopy interception after clearcutting (Reid and Lewis, in press).

### Sediment Loads

Sediment load estimates for the North Fork and South Fork are the sum of the sediment deposited in the weir pond and the suspended load measured at the weir. Comparison of sediment loads produced following the 1971-73 harvest of South Fork and the 1989-92 harvest of North Fork must be made cautiously. Improved and more intensive sampling methods greatly enhance the accuracy of load estimates for the latter study. Large landslides in the North Fork in 1974 and 1995, and the 1985 harvest in the North Fork complicate the analysis.

South Fork suspended sediment loads increased 335% (1,475 kg $ha^{-1}$ $yr^{-1}$) after road building and averaged 331% (2,877 kg $ha^{-1}$ $yr^{-1}$) greater during the 6-year period after tractor logging. Annual sediment load (including suspended and pond accumulations) increased 184% for the 6-year post-harvest period 1972-1978 returning to pretreatment levels in 1979 (Lewis 1998).

North Fork annual sediment loads increased 89% (188 kg $ha^{-1}yr^{-1}$) in the partially clearcut watershed and between 123% and 238% (57 to 500 kg $ha^{-1}$ $yr^{-1}$) in 4 of 5 clearcut basins during the 1990-96 post-harvest period (Lewis 1998). The load decreased by 40% (551 kg $ha^{-1}$ $yr^{-1}$) in one clearcut basin. Sediment loads in some North Fork tributaries remained elevated through hydrologic year 2003, twelve years after harvest (Keppeler and Lewis, in press).

Although Thomas (1990) reported that SFC sediment concentrations appeared to be returning to pre-treatment levels in the early 1980s, analysis of more recent data suggests renewed sediment mobilization. The 1998 and 1999 pond depositions were the largest on record at SFC, but not exceptional at NFC. A double mass plot of pond accumulations indicates an increase in deposited sediments at SFC relative to NFC starting in 1998. The same is true to a lesser extent in suspended sediments (Figure 2). Regression analysis of SFC versus NFC pond accumulations indicates a significantly higher slope for the period 1998-2004 compared to 1974 -1997.

Since the suspended sediment data have better temporal and spatial resolution, Lewis' 1998 analysis of NFC was extended using storm load data from control tributary gages H and I to investigate whether the relative change in suspended sediment was due to changes in the North Fork, changes in the South Fork, or both. A plot of the percentage departures from the prelogging (1986-1989) regression of NFC versus HI, shows elevated sediment levels for 1993-1998 only (Figure 3). An analogous plot for SFC versus HI shows elevated sediment levels for some small events in 1993-1997, but most consistently for all

*Figure 2. Double mass curve of South Fork pond accumulations and suspended sediment relative to North Fork 1986 through 2004.*

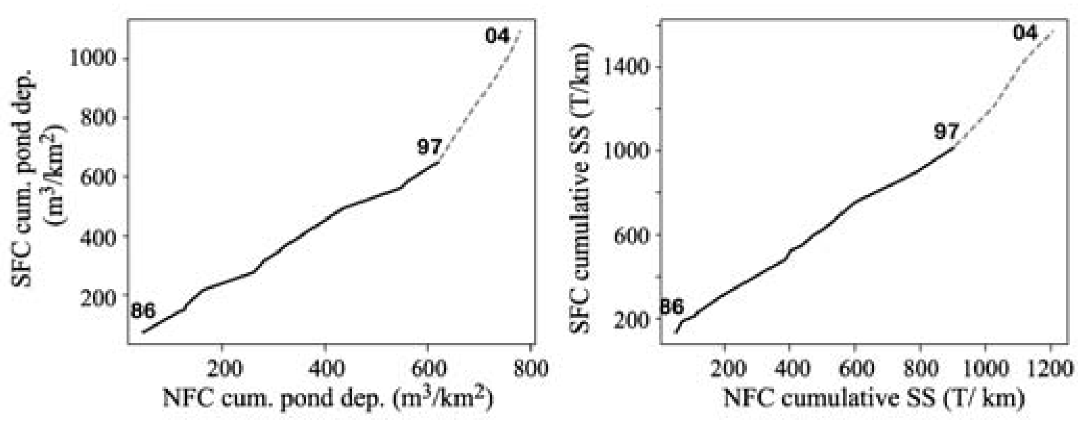
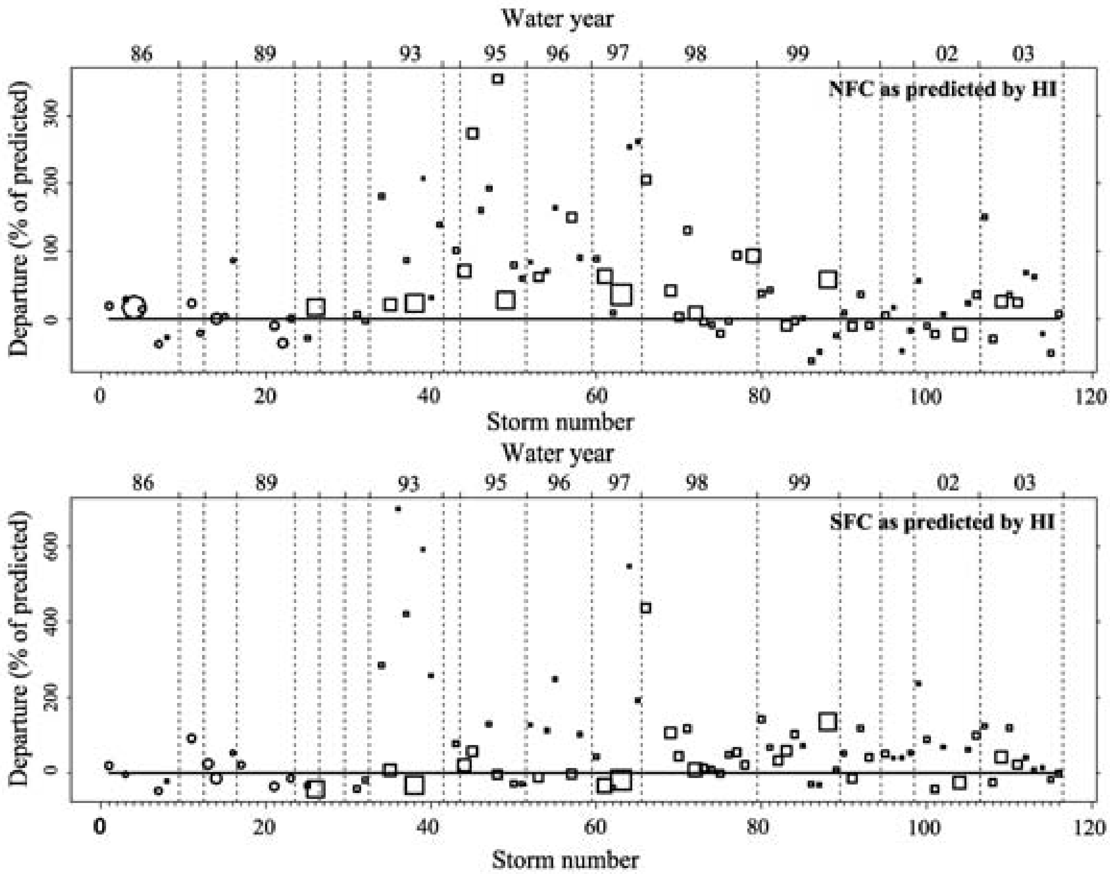


*Figure 3. Suspended sediment percentage departures from the 1986-1989 regressions of NFC and SFC versus two untreated North Fork Controls (HI). Marker size is relative to HI storm load.*




size events in 1998-2003. Thus the change in relation between NFC and SFC starting in 1998 appears to be a combination of declining loads at NFC and increasing loads at SFC.

To be more rigorous and quantitative about the suspended sediment changes, the gaging records were broken into three periods: NFC prelogging (1986-1989), NFC postlogging (1990-1997), SFC "episode" (1998-2003). These periods included 23, 41, and 52 storm events, respectively. Log-log regression models were fit relating NFC and SFC to HI for the three periods and tested to determine if a unique slope or intercept was appropriate for each period (Figure 4). For the NFC model, a parallel regression model with three intercepts and one slope was adequate. For the SFC model three intercepts and three slopes needed to be retained. Nine post-hoc comparisons of intercept and slope for each period were made. The NFC parallel regression for the 1990-1997 period was significantly different (higher) than either of the other periods, and the SFC 1990-1997 regression had significantly different (lower) slope than the 1998-2003 period. The SFC 1986-1989 slope was similar to the SFC 1998-2003 slope, but did not differ significantly from the 1990-1997 period, possibly due to the smaller number of storms in 1986-1989 compared to 1998-2003 (Table 1).

*Table 1. Comparison of regression and intercepts (NFC and SFC) and slopes (SFC only) for three different time periods. Bonferonni's procedure was used to limit the experimentwise error rate to 0.05 which requires setting the pairwise comparison error rates to 0.05/9 = 0.0056. By this criterion, the only significant differences were (1), (3), and (9).*

| | Comparison | Significance ($p$) |
|---|---|---|
| 1 | NFC 90-97 intercept to NFC 86-89 intercept | 0.000014 |
| 2 | NFC 98-03 intercept to NFC 86-89 intercept | 0.50 |
| 3 | NFC 98-03 intercept to NFC 90-97 intercept | 0.00000032 |
| 4 | SFC 90-97 intercept to SFC 86-89 intercept | 0.039 |
| 5 | SFC 98-03 intercept to SFC 86-89 intercept | 0.096 |
| 6 | SFC 98-03 intercept to SFC 90-97 intercept | 0.40 |
| 7 | SFC 90-97 slope to SFC 86-89 slope | 0.096 |
| 8 | SFC 98-03 slope to SFC 86-89 slope | 0.983 |
| 9 | SFC 98-03 slope to SFC 90-97 slope | 0.00037 |

*Table 2. Summary of post-disturbance Erosion Features greater than 7.6m³.*

| | South Fork Caspar | | | | North Fork Caspar | | | |
|---|---|---|---|---|---|---|---|---|
| | # | Volume (m³) | m³/ha | Delivery | # | Volume (m³) | m³/ha | Delivery |
| Post-disturbance[1] | 130 | 65312 | 154 | na | 116 | 6496 | 14 | 40% |
| road-related | 115 | 41706 | 98 | 68% | 7 | 424 | 1 | 8% |
| wind-related | 5 | 13985 | 33 | na | 74 | 1466 | 3 | 29% |
| > 1000 m³ | 18 | 52120 | 123 | na | 1 | 3605 | 8 | 46% |
| 100-1000 m³ | 38 | 10507 | 25 | na | 5 | 944 | 2 | 26% |
| HY1990-2004 | 38 | 5804 | 14 | 61% | 147 | 9121 | 19 | 45% |
| road-related | 34 | 5557 | 13 | 63% | 10 | 2495 | 5 | 52% |
| wind-related | 4 | 264 | 1 | 21% | 86 | 1732 | 4 | 27% |
| > 1000 m³ | 0 | 0 | 0 | na | 2 | 5618 | 12 | 52% |
| 100-1000 m³ | 12 | 4961 | 12 | 62% | 5 | 944 | 2 | 26% |

*[1] Includes hydrologic years 1968-1976 on South Fork, 1990-1998 on North Fork.*

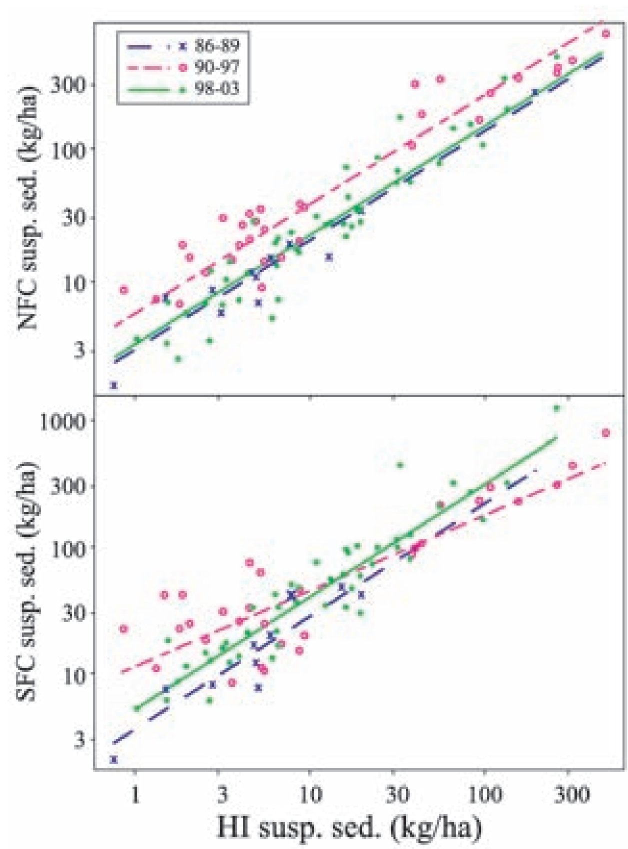
Based on the 1986-1989 relations, the observed sediment from NFC exceeded the predicted sediment by 49% in 1990-1997 and by 12% in 1998-2003. The corresponding numbers for SFC were -20% and +45%, but the only significant difference for SFC was the slope between the last two periods. Based on the 1990-1997 period, the observed sediment from SFC 1998-2003 exceeded the predicted sediment by 36%. If the 1986-1989 and 1990-1997 periods are combined to predict suspended sediment for 1998-2003, the observed sediment from SFC exceeded the predicted sediment by 47% (185 kg ha$^{-1}$ yr$^{-1}$). (Compared to the 1986-1989 regression, the combined regression predicts lower loads in large storms above ~50 kg/ha at HI.) Thus, it is only during relatively large storm events (> 20 kg/ha at HI) that SFC suspended sediment systematically exceeds the pre-1998 relationship (Figure 4).

## Erosion

Erosion inventory data helps to explain sediment load changes. As with sediment loads, improved protocols provide more detailed information on mass-wasting processes than is available for the earlier SFC inventories. Inventories have been more frequent and more intensive on the North Fork since 1986 and the South Fork since 1994. Nonetheless, the contrasts are quite apparent. During the 1970s, the South Fork landscape experienced mass-wasting an order of magnitude greater than that which followed NFC harvesting of the 1990s. SFC erosion has been predominantly related to the roads, landings, and skid trails. In contrast, most North Fork erosion features have been associated with windthrow disturbances and typically displaced and delivered smaller volumes of material. Two large landslides, one related to a preexisting mid-slope road, account for more than half of NFC mass-wasting (Table 2).

Another episode of road-related landsliding commenced in the South Fork in the mid 1990s. Of the 31 SFC landslides documented between 1995 and 2004, 94% are road, landing, or skid trail related. These more recent landslides displaced 4,123 m³ and had an average delivery ratio of 85%. A deteriorating network of logging roads and skid trails continues to deliver sediment to the stream channel and explains much of the recently enhanced SFC sediment production previously discussed. This

*Figure 4. Suspended sediment regression results by period for North Fork (NFC) and South Fork (SFC) versus control (HI).*



renewed sedimentation may also be a manifestation of the extreme stormflows of 1998 and 1999 and the erosional costs of recent road decommissioning. The 1998 road decommissioning effort removed almost 18,000 $m^3$ of fill from aging stream crossings, but treatment-related erosion contributed 750 $m^3$ of sediment.

## Conclusions

Timber harvest and road building affect runoff processes, sediment yields, and erosion, but the response is highly variable. Caspar Creek studies document increases in peak flows, suspended sediment loads, and erosion after two very different harvest treatments. California's modern forest practices rules appear to mitigate, but do not eliminate, these impacts.

Erosion and sedimentation from ground extensively disturbed by road building and tractor yarding remain elevated decades after harvest. The present condition of the South Fork watershed is typical of many of the tractor-yarded lands in the redwood region that are entering yet another harvest cycle. Greater understanding of the interactions between proposed activities and prior disturbances is crucial for improved forest management. Thus, a third phase of research is underway to examine the effects of re-entry on the previously tractor-logged South Fork watershed. Much remains to be learned regarding restoring forest ecosystems and mitigating harvest impacts. The Caspar Creek Experimental Watersheds will continue to serve as a resource for furthering this research endeavor.

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# Forest Road Erosion Research at the Coweeta Hydrologic Laboratory

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The Coweeta Hydrologic Laboratory, Southern Research Station, USDA Forest Service, has been conducting basic and applied research addressing erosion and sedimentation from forest roads for over seventy years. This research has resulted in development of local, state and federal forest road construction standards, development and application of forest road bioengineering and National Forest System road best management practices (BMPs). Our most recent research has documented the effects of large-scale forest road reconstruction and BMP implementation on erosion rates, stream sedimentation and water quality in the southern Appalachian Mountains. Currently, we are developing and validating three methods to differentiate between natural and anthropogenic sediments in streams. These methods allow us to accurately quantify the direct impacts of forest roads on stream sediment budgets, sediment residence time and sediment transport rates.

Keywords: *Roads, road management, sedimentation, erosion control, best management practices, forest practices, watershed management, water pollution*

## Introduction

The Coweeta Hydrologic Laboratory in Otto, North Carolina, is a research work unit of the USDA Forest Service, Southern Research Station (Figure 1). Coweeta was established in 1934 as an experimental forested watershed. The research mission focused on investigating the impacts of watershed management activities on water yield and water quality and expanding our knowledge and basic understanding of forest watershed hydrology.

The scientists and engineers who worked at Coweeta in the early years recognized that erosion and sedimentation from gravel roads was a major threat to forestry operations, water quality and water supply, aquatic ecosystems, hydrologic and hydraulic infrastructure. Consequently, scientists at the Coweeta Hydrologic Laboratory have conducted a wealth of research addressing the impacts of forest road construction, forest best management practices, road use, and road maintenance practices on hydrology, water quality and road longevity since 1934. Sun et al. (2004), Jackson et al. (2004) and Swift (1988) have previously summarized much of the history of forest road research conducted at Coweeta. In this paper, we provide an overview of these earlier works to set the historical context for a subsequent review of our contemporary forest road research.

## Historical Forest Road Research of the Coweeta Hydrologic Laboratory

When the Coweeta Hydrologic Laboratory was established in 1934, engineers at the time recognized that erosion of forest roads was a serious problem (Figure 2). Road erosion reduced road life, increased maintenance expenses, damaged vehicles and harmed the aquatic environments. Some of the earliest research studies were conducted by C. R. Hursh, who recognized the inherent erodibility of cut and fill slopes and employed what we now call bioengineering to stabilize roadways (Figure 3). Significant reductions in soil loss from forest roads were accomplished by mulching or vegetating the adjacent cut and fill slopes (Hursh 1935, 1939, 1942). Project specifics including an evaluation of different plant types and bioengineering methods are summarized by Swift (1988). While improving and facilitating the construction

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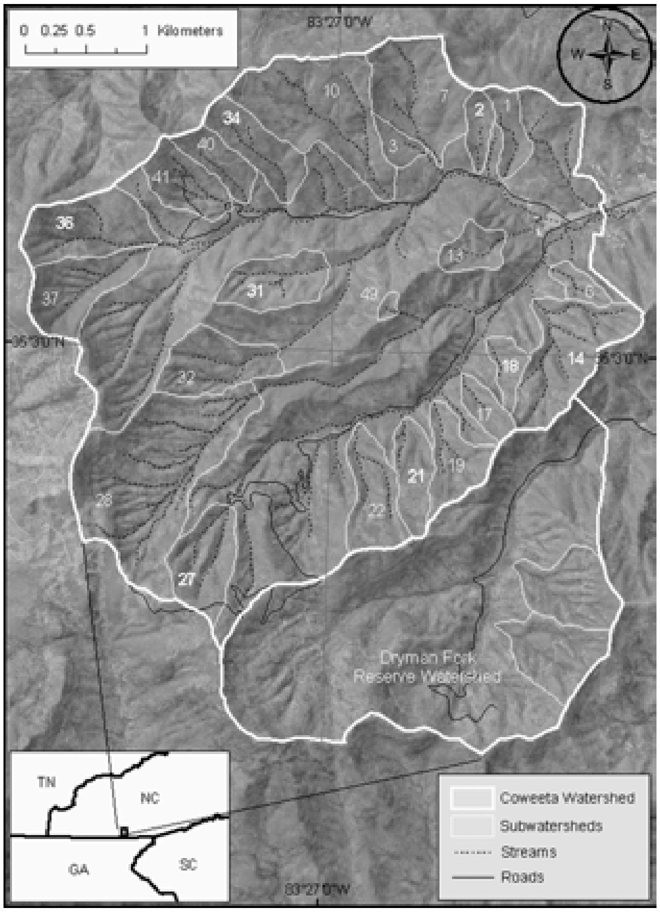
*Figure 1: Coweeta Hydrologic Laboratory and its Experimental Watersheds.*




of roads was a major motivation for this research, Hursh laid the foundation for subsequent research that specifically addressed the impacts of roads on stream water quality.

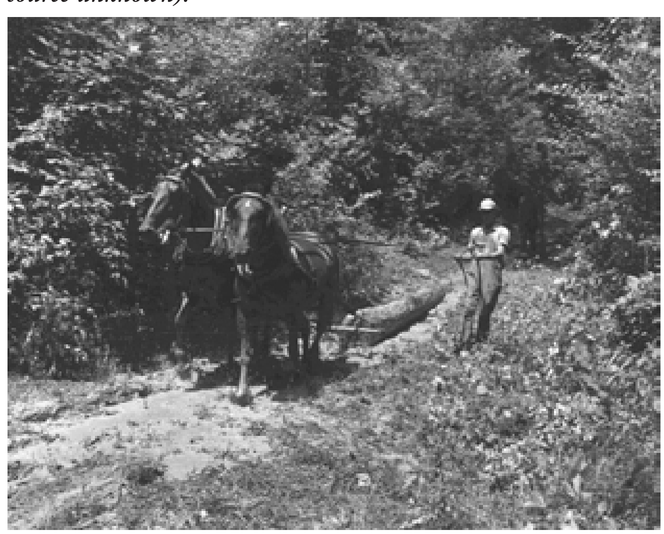
In 1942, a research demonstration project was initiated on Watershed 10 (Figure 1) to scientifically document the impacts of mountain logging practices on water quality. Typical logging practices, such as using ephemeral channels and riparian areas for skid trails (Figure 4), generated 408 $m^3$ of soil loss per km of road constructed (Lieberman and Hoover 1948a). Sediment delivery to streams was high and total suspended solids peaked at 5700 ppm (Lieberman and Hoover 1948b). Road erosion was so severe that downstream fish populations were significantly reduced (Tebo 1955), the roads became unusable and were decommissioned (Swift 1988).

Progressing from lessons learned in the exploitive logging experiment, Coweeta scientists conducted forest harvesting experiments to demonstrate how sound road building and watershed management practices accommodate water quality preservation and timber harvesting. Two watersheds were contracted for harvesting in 1955: Watershed 40 was to be harvested while managing for preservation of water quality and the adjacent Watershed 41 was harvested to

*Figure 2: Erosion of an old logging road (photo by C.R. Hursh).*

*Figure 3: Example of early bioengineering to stabilize a cut slope road embankment (photo by C.R. Hursh).*

*Figure 4: Skidding logs in the riparian area during an early logging experiment at the Coweeta Hydrologic Laboratory (photo source unknown).*

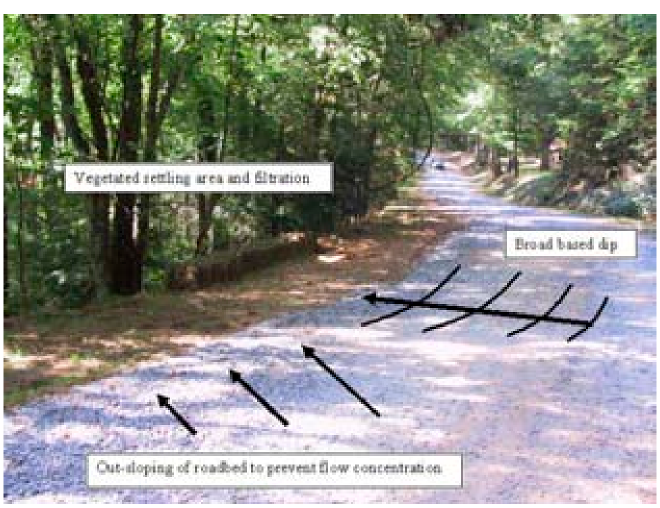


facilitate timber extraction. Road construction practices on Watershed 40 were tightly controlled. Swift (1988) provides a discussion of specifics including road placement, width, engineering and vegetative methods. The implemented construction practices included contour roads, skidding logs away from streams and preventing stream disturbance. While these techniques protected water quality, they were deemed impractical by potential users because of perceived implementation and management costs (Swift 1988).

The Stamp Creek Demonstration Project in northeastern Georgia addressed the perceived cost limitations of adopting improved road designs and best management practices (Black and Clark 1958). From 1956 to 1960, forest harvesting was conducted on the Stamp Creek watershed with consultation on road design from Coweeta Hydrologic Laboratory scientists. Road maintenance and construction techniques employed were economically feasible because the roads were specifically designed to require minimal maintenance. Road quality and timber access improved, facilitating forest harvesting operations while minimizing impacts on water quality (Swift 1988).

These, along with other sustainable forest road construction practices, were employed in the multiple resource watershed management experiment in 1962. This experiment on Watershed 28 applied the multiple-use management concept that provides simultaneous benefits of forest products, fisheries and wildlife, and recreation needs while enhancing water yield and preserving water quality for municipal needs. New road building techniques such as out-sloping and broad based dips (Figure 5) were used to replace center crowned roadbeds, water bars, ditches and culverts to drain runoff. Hewlett and Douglass (1968) described these road engineering methods that further reduced road runoff and erosion. The experiment was so successful that the road building methods were adopted as standards for forest road construction by the national forests in Region 8 (the Southern Region) of the USDA Forest Service (Swift 1988).

***Figure 5: Example of a properly constructed broad based dip from the Conasauga River Large-Scale Watershed Restoration Project, Cohutta Ranger District, Chattahoochee National Forest, USDA Forest Service (photo by M.S. Riedel).***



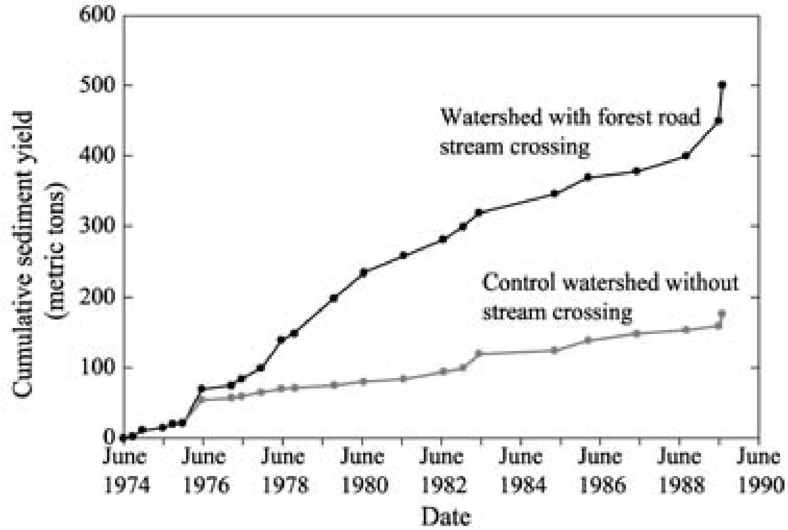

Forest road research continued at Coweeta, striving for the goal of the "self maintaining road". Swift (1984a, 1984b) began a series of experiments to directly quantify where, when and how sediments were eroded from forest roads and to develop specific road engineering practices that would eliminate sediment sources. Swift and Burns (1999) and Swift (1988) have synthesized much of the knowledge about techniques learned from these comprehensive studies. Some of the most important findings include;

- Soil losses are greatest immediately after construction (Swift 1984a).
- Coarse gravel and grassing of roadbeds reduces erosion (Swift 1984a).
- Bare cut and fill slopes accounted for 70 to 80 percent of the total soil losses.
- Vegetating cut and fill slopes and graveling roadbeds reduced erosion to less than 10% of pre-treatment (Swift 1984b).
- The use of vegetated filter strips and brush barriers on fill slopes retains the majority of eroded sediments within the roadway (Swift 1985, 1986).
- Nearly 100% of the sediment yield increase to streams following total forest harvest originated from stream crossings representing only 1% of the total watershed area and 17% of total road length (Douglass and Swift 1977).
- Erosion and sedimentation from forest road stream crossings may affect the sediment budgets of streams for decades (Figure 6).
- Proper design of stream crossings, isolating roads from adjacent streams, and diverting road runoff onto the forest floor greatly reduce and may even prevent stream sedimentation (Douglass 1974; Swift 1985; Swift and Burns 1999).

## Current Forest Road Research of the at Coweeta Hydrologic Laboratory

Current research of the Coweeta Hydrologic Laboratory represents a logical progression from the foundation of knowledge developed from the historical research. We have further advanced our ability to: (1) predict forest road erosion and sediment yield; (2) implement and evaluate effectiveness of forest road best management practices; and (3) quantify and understand stream channel sedimentation

*Figure 6: Cumulative sediment yield from a stream with road crossings as compared to a control watershed with no road crossings (adapted from Swank et al. 2000).*




and sediment transport, sediment budgets and sediment cycling, and fluvial sediment dynamics.

**Prediction of Erosion and Sediment Yield From Roads**

The ability to accurately predict forest road erosion and sediment yield is crucial to preventing and mitigating stream sedimentation impacts. This is especially true with cumulative effects analysis when the long-term operation of hundreds of miles of forest roads across all landscape scales represents a large and chronic sediment source.

L.W. Swift developed a spatially explicit sediment transport model for the southern Appalachians (EPA 2000) that was incorporated into a spatially explicit GIS based soil erosion model (McNulty et al. 1995; McNulty and Sun 1998). Greenfield et al. (2001) further developed the model, incorporated empirically based sediment routing functions and the ability to estimate average annual stream sediment yields. This model, the "Sediment Tool", was incorporated into the U.S. Environmental Protection Agency's Watershed Characterization System (WCS) (EPA 2000). The Sediment Tool is a spatially explicit, GIS based, finite element, lumped parameter model which generates estimates of soil erosion, sediment routing and sediment yield. While this model is used for TMDL analysis and development, it had never been validated for such an application.

Riedel and Vose (2002a) customized data and data structure for WCS and the "Sediment Tool" to incorporate National Forest System roads, forest road management practices, and the highest quality terrain data in the remote mountains of the Chattahoochee National Forest in northern Georgia. They monitored road erosion and sediment yield from a wide variety of unpaved roads in the region. While they were able to qualitatively calibrate the model to observed data, they found model sensitivity to road characteristics was limited by the governing equations within the model and the resolution of the input digital elevation models. Simulated roadbed erosion and sediment yields were biased and did not agree with observed data.

Riedel and Vose (2003) subsequently monitored road erosion and sediment yield on a subset of the road sites after reconstruction and implementation of forest road best management practices (BMPs). The Sediment Tool did not accurately predict road erosion, sediment yield and BMP performance. Riedel and Vose concluded such application was beyond the capabilities of the model and that it should be better suited to larger scale applications such as land cover change analyses. Bolstad et al. (2006) have further validated the model on a larger scale across five watersheds in the southern Appalachian Mountains. These watersheds include two forested controls, a watershed with mountain home development impacts, another affected by valley agricultural practices, and one with mixed land use.

**Implementation and Effectiveness of Forest Road Best Management Practices**

Forest road research at Coweeta has long addressed the reduction of road erodibility, road sediment yield and stream sedimentation through the development of forest road BMPs. Clinton and Vose (2002) conducted one of the first comprehensive studies investigating forest road erosion that included paving as a BMP. While paving logically reduces the erodibility of forest roads, threats from potential impacts on stream sedimentation and the delivery of total petroleum hydrocarbons (TPH) were documented for the first time. As expected, the paved road system generated the least sediment, aggregate base gravel roads generated more and the unimproved road

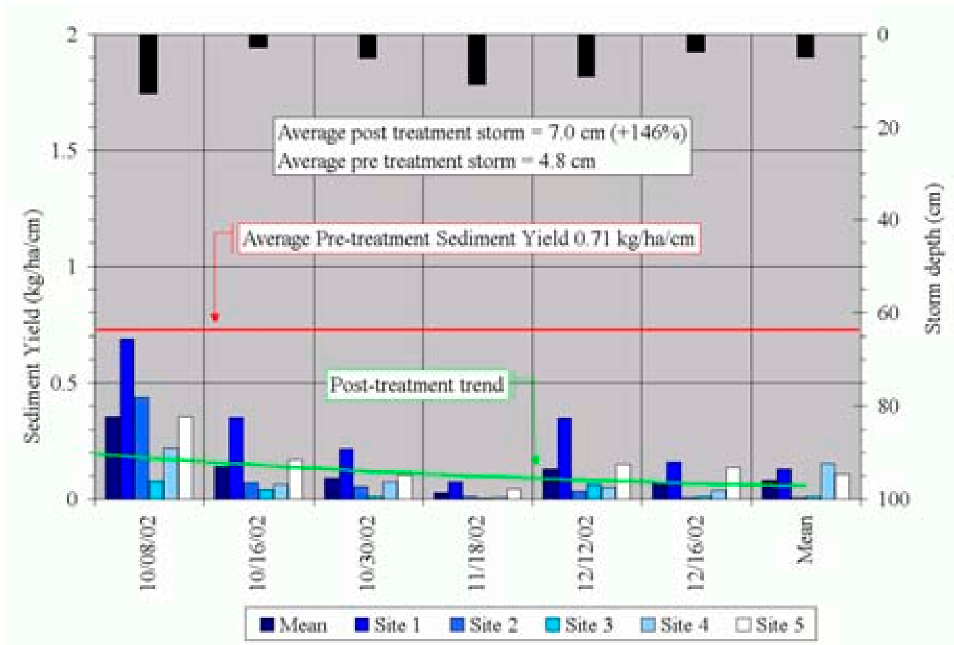



*Figure 7: Comparison of pre and post-treatment sediment yield following reconstruction of a forest road with best management practices in the Conasauga River Large-Scale Watershed Restoration Project, Cohutta Ranger District, Chattahoochee National Forest, USDA Forest Service (Riedel and Vose 2003).*

generated the greatest amount of sediment. The distances of sediment transport away from the road bed were, in order of decreasing distance, paved, improved gravel, improved gravel with sediment control and unimproved gravel. While TPH were found in runoff water at the edge of newly paved roads, the concentrations were extremely low. No TPH were found in collected runoff below the road, nor in stream water or stream bottom sediments, suggesting that TPH sorbed to sediments before reaching the streams. Clinton and Vose found gravel roads with failed BMPs (due to improper installation, lack of maintenance, or both) provided little, if any reduction in sediment yield as compared to gravel roads with without BMPs.

Riedel and Vose (2003) monitored sediment yield and transport in the Chattahoochee National Forest beginning in autumn 2001. During the summer of 2002, road reconstruction and installation of BMPs were completed along more than 20 miles (32 km) of forest roads (Figure 5). Sediment yield from these roads was monitored through autumn 2002. Despite a 46% increase in rainfall from the pre- to post-treatment period, road reconstruction reduced average sediment yield by 70% (Figure 7) (Riedel and Vose 2003). Specific examples of the road reconstruction and BMP implementation are reported by Riedel and Vose (2003).

**Stream Channel Sedimentation and Sediment Transport**

The transport of sediments sourced from gravel roads as bedload, despite the potential implications for aquatic ecosystems, has historically received very little research attention. Riedel et al. (2003), having previously identified road sediments deposited in the streambed and noticing ecological impacts (Riedel and Leigh 2004), initiated a pilot streambed mobility study. Several transects of scour and deposition pins were installed along a study reach, immediately adjacent to an unpaved gravel road (Figure 8). The stream scoured up to 10 cm of sand from its bed, exposing buried riffles and partially clearing pools of sediment (Figure 9). The sand and fine gravel in this stream were very dynamic. In-stream scour and deposition occurred frequently. No in-stream deposition occurred during small events, when road runoff was negligible. During larger events, road runoff and in-stream sediment deposition occurred. These results indicate that the implementation of forest road BMPs facilitates stream restoration, because mountain streams are capable of clearing the road sediments from their substrate if external sediment sources are eliminated.

**Sediment Budgets and Sediment Cycling**

Riedel and Leigh (2004) and Riedel et al. (2003) investigated methods of differentiating between natural and road derived sediments in stream channels. Van Lear et al. (1995) reported roads account for 85% of the potential sediment supply for streams in this region; however, no studies have attempted to directly validate this. Sediment samples from roads, native geology, soils and streambeds were gathered from a watershed in northern Georgia and numerous experimental watersheds at the Coweeta Hydrologic Laboratory. The samples were analyzed for total elemental composition using a triple acid digest. This allowed for the differentiation between geologically old,

*Figure 8: Conceptual diagram of scour and deposition pins installed in a stream channel. A loose washer is placed on each pin before installation. The elevations of the washers resting on the sediment surface are measured. Following a storm event, the depths of sediment on the washers and the distances the washers have fallen are measured to reveal streambed scour (ds), streambed deposition (df) and net streambed change (df-ds) during the storm event.*

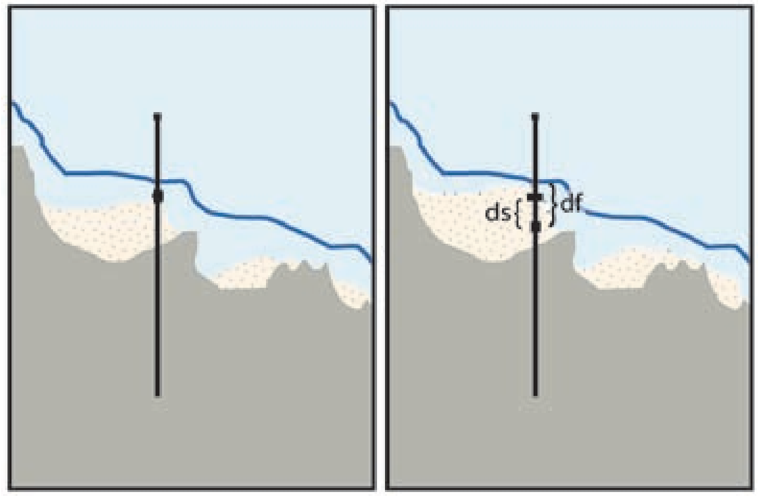
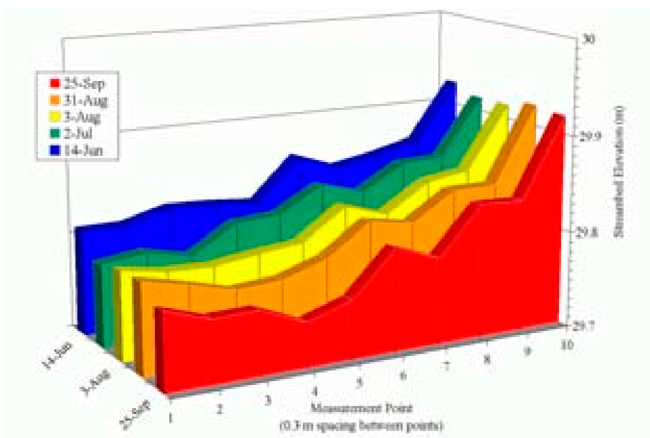



*Figure 9: Net scour of a streambed cross-section over a 3½-month period (Riedel and Leigh 2004).*




native sources of coarse streambed sediments (sand-size and finer) and fresh quarry-sources of streambed sediment such as road aggregate. Elevated sodium and strontium were clear indicators of road sediments and in-channel sedimentation from excessive road sediments. At these study sites, 50 to 75% of stream sediments finer than 2 mm were sourced from roads (Riedel and Leigh 2004).

**Fluvial Sediment Dynamics**

Riedel and Vose (2002b) monitored streamflow and water quality in mountain streams of northeastern Georgia to determine the impacts of gravel roads on suspended sediment budgets. An EPA benchmark stream with minimal sediment impacts served as a reference with which to compare results from three other mountain streams. Total suspended solids (TSS) concentrations were not representative of suspended sediment because the organic and mineral components of TSS were highly variable between streams. Excessive loading of suspended mineral sediment was linked to gravel roads adjacent to the affected streams. Mineral sediment loading was highest in autumn during peak road use for recreational and hunting activities. They concluded TSS could not be reliably used for the establishment of Total Maximum Daily Loads (TMDLs) for forested streams, because it did not differentiate between the suspended organic matter derived from naturally occurring allochthonous inputs versus mineral sediments from development and roads.

With additional monitoring, Riedel et al. (2003) determined that during larger storm events, road runoff and in-stream sediment deposition occurred. The two undisturbed forest streams showed no sedimentation impact because they were sediment supply limited, whereas the two streams with road impacts experienced sedimentation because sediment supply exceeded transport capacity. The authors hypothesized that the most significant impact of roads on aquatic ecosystems in this region was from streambed sedimentation. Consequently, TSS based TMDLs may not address the causes of sediment impairment of aquatic ecosystems.

In subsequent work, Riedel et al. (2004) determined that water quality parameters on these streams varied significantly on a seasonal and storm event basis. TSS data on the benchmark stream and a forested stream exhibited strong hysteresis (lag between effect and cause), were elevated on the rising limbs of hydrographs, and declined rapidly on the recession limbs—further evidence of sediment supply limitations. While there was weak hysteresis apparent in the constituent concentrations and loadings of the impaired streams, it was not statistically significant. They developed a "hydrograph threshold" approach to constructing sediment rating curves that facilitated the development of sediment based TMDLs that directly linked loading rates to discharge frequency and duration relationships.

## Summary

The impacts of forest harvesting on sediment yield are directly related to skid trail layout and road building and maintenance activities associated with gaining forest access and removing timber from the woods. When roads and skid trails associated with forest harvesting are properly constructed and maintained, forest harvesting generally has a minimal impact on stream sedimentation. Conversely, poor logging practices and the incorrect design and maintenance of forest roads cause significant stream sedimentation. Many of the historical and often ill-conceived methods of forest road construction and maintenance caused large increases in forest soil erosion and stream sedimentation. Based on decades of research to improve road construction and maintenance, numerous practices that minimize erosion and sedimentation have been identified. Examples of these practices are coarser paving gravels, grassed roadbeds, the construction of broad based dips, brush sediment barriers along road margins and road buffer strips.

Sedimentation of streambeds may also be prevented by the proper use and maintenance of forest road best management practices. Indeed, in steep mountain streams, forest road reconstruction and adoption of BMPs may facilitate stream restoration because the reduction of road sediment yield allows streams to flush themselves of previously deposited road sand and fine gravel. Historical and current research suggests the long held ideal of a "self-maintaining" forest road may nearly be attainable.

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# The Entiat Experimental Forest: A Unique Opportunity to Examine Hydrologic Response to Wildfire

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Water is generally regarded as the most important natural resource in the interior Columbia River basin (ICRB). Public agencies managing forested headwater source areas are under increasing pressure to document water quantity and quality, and the effects of background and anthropogenic disturbances that influence them. Fire is widely recognized as the primary disturbance process affecting ecological systems in the ICRB. For these reasons land management agencies seek a more complete understanding of processes that generate and maintain streamflow as well as effects of fire and post-fire treatments on water quantity and quality. Although effects of wildfire are issues of major concern, they remain poorly understood at the catchment scale, largely because site specific data from both before and after wildfire are rare. The Entiat Experimental Forest (EEF) in central Washington State provides this type of hydrologic record of fire effects, owing to a severe wildfire during the summer of 1970, following ten years of stream gaging as part of a controlled land use experiment. Data collection continued after the fire through 1977. The entire dataset provides an archive for assessment of hydrologic response and model formulation, calibration, and testing. Research at the EEF is being revived to model effects of fire on water quantity and quality, including effects on water source, flowpath, timing, and post-fire recovery of hydrologic processes. We are taking a diagnostic approach to gaging to understand internal catchment behavior and develop a functional characterization of the EEF catchments. Change detection modeling employing the Hydrologiska Byråns Vattenbalansavdelning [HBV] rainfall-runoff model is being applied by: (1) comparing observed runoff to runoff simulated from pre-fire parameters, (2) comparing simulations based on pre-fire parameters to simulations based on post-fire parameters, and (3) directly contrasting pre-fire with post-fire parameter values. Preliminary modeling results suggest that effects of the 1970 fire included greater snow accumulation, earlier initiation of snowmelt runoff at lower mean air temperatures, more rapid melt, increased soil moisture, and sharply increased runoff. Gaging at other catchments in the larger Entiat River subbasin creates a foundation for nested watershed monitoring and modeling to address spatially distributed hydrologic processes in this portion of the ICRB.

Keywords: *hillslope hydrology, conceptual catchment modeling, rainfall-runoff modeling, HBV runoff simulation model, fire effects*

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## Introduction

Water is generally regarded as the most important natural resource in the interior Columbia River basin (ICRB). It is essential for human consumption, ecosystem function, and habitat for aquatic organisms, including sensitive species. Water supports a multi-billion dollar economy in agriculture, power generation, recreation, mining, and manufacturing. Public agencies managing forested headwater source areas are under increasing pressure to document effects of background and anthropogenic disturbances on water quantity and quality.

Fire is widely recognized as the primary disturbance process affecting ecological systems in the ICRB. Fire can affect snow accumulation, snowmelt, surface runoff, subsurface water routing and storage, timing and quantity of streamflow, chemical and thermal water quality, aquatic habitat of sensitive species, and human water use. For these reasons land management agencies seek a more complete understanding of processes that generate and maintain streamflow, and of the effects of disturbance, such as fire and post-fire treatments, on water quantity and quality.

Major wildfires are bringing increasing attention to potential effects of fire and associated land management activity, such as fire suppression and salvage logging, on water quantity and quality. This is particularly true in the western U.S. and some European countries where large, severe wildfires are perceived to be occurring with greater frequency (Conedera et al. 2003; Pierson et al. 2001; Rieman et al. 2003; Robichaud and Elsenbeer 2001). Similarly, effects of post-fire rehabilitation on runoff, peak flows, erosion, sedimentation, and other fire-affected processes is receiving increasing attention (Robichaud et al. 2000).

Fire has been an important disturbance process in the ICRB for millennia (Hessburg and Agee 2003; Wright and Agee 2004). Damage to forest vegetation and the litter layer by fire can expose soil to rainsplash and hasten delivery of precipitation to the soil surface, thereby increasing runoff and surface erosion (Johansen et al. 2001; Robichaud and Brown 1999). Soil infiltration capacity can be reduced when surface pores are sealed by ash or fine sediment made available by destruction of soil structure and mobilized by rainsplash, and by fire-induced formation of hydrophobic (water repellant) compounds on the soil surface (DeBano et al. 1977; DeBano et al. 1998; Giovannini et al. 1988; Martin and Moody 2001; Robichaud and Hungerford 2000; Wells 1981; Wright and Bailey 1982). Reduced infiltration through these mechanisms and reduced evapotranspiration caused by damage to vegetation can result in increased runoff, flooding, sediment mobilization and delivery to channels, and debris flows (Beschta 1990; Cannon et al. 2001; Conedera et al. 2003; Elliott and Parker 2001; Krammes and Rice 1963; Meyer and Wells 1997; Tiedemann et al. 1979; Wells1987). Increased peak flows can increase channel bed and bank erosion, further increasing sediment concentration in streamflow (Beschta 1990; Swanson 1981; Wondzell and King 2003). Large volumes of soil and nutrients can be transported to channels by fire-related debris flows (Helvey et al. 1985; Meyer et al. 2001).

Fire can also affect water quality by increasing nutrient losses to erosion, reducing nutrient uptake, and increasing leaching (Beschta 1990; Richter et al. 1982). Fire can volatilize nitrogen in vegetation and litter, increase nitrification, and mineralize cations, which may be redistributed and converted to more soluble salts. Increased runoff can result in increased total cation and bicarbonate losses (Grier 1975; Tiedemann et al. 1979; Wells et al. 1979). Fire can also increase stream water temperature, primarily by increasing exposure to solar radiation (Anderson et al. 1976, Beschta 1990; Tiedemann et al. 1979). Recovery of pre-fire watershed conditions depends largely on recovery of terrestrial plant communities, with associated increases in infiltration and evapotranspiration (Pierson et al. 2001; Swanson 1981; Wright and Bailey 1982).

Despite the importance of wildfire as an ecological and social issue, relatively few hydrologic data exist beyond the plot and hillslope scales. Fire data at the catchment scale are mostly associated with paired watershed studies of prescribed fire effects on water quantity and quality. Catchment scale hydrologic effects of wildfire are less well known, because pre-fire data are rarely available (Moody and Martin 2001). Previously published work having site-specific, pre-wildfire data includes a study from the San Dimas Experimental Forest in southern California (Hoyt and Troxell 1934) and one from a eucalyptus forest in Australia (Langford 1976).

Another of these rare "natural fire experiments" comes from the Entiat Experimental Forest (EEF), located in central Washington State (Helvey 1980). Data from the EEF provide a resource for model formulation, calibration, and testing of wildfire effects on catchment scale runoff. These data also provide an opportunity to contrast long-term hydrologic recovery between catchments that were or were not subject to post-fire rehabilitation treatments (Woodsmith et al. 2004). In this paper we focus on effects of fire on runoff. We present background information on the EEF and historical data collection. We then discuss our objectives and approach to current and future investigations, and the preliminary results of hydrologic change detection modeling.

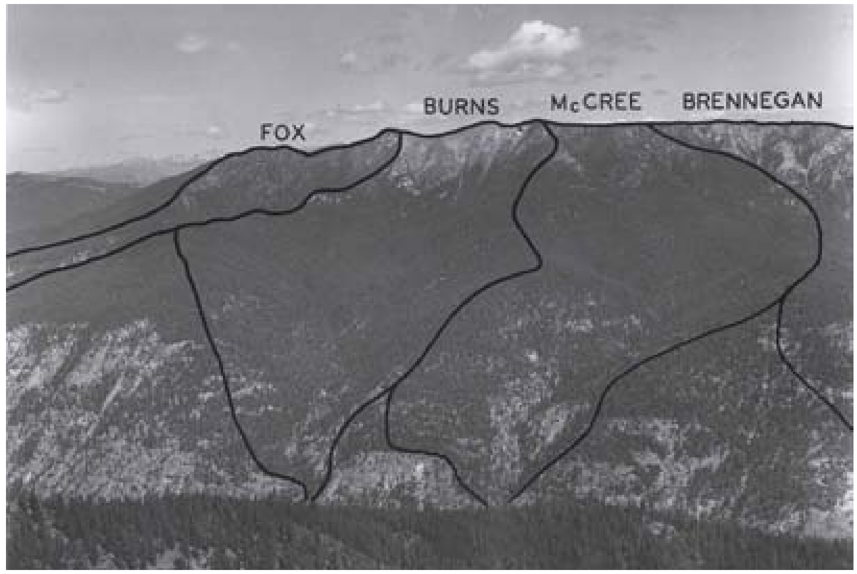



*Figure 1. The Entiat Experimental Forest, looking toward the northeast.*

## The Entiat Experimental Forest

The EEF consists of three adjacent catchments, McCree Creek, Burns Creek, and Fox Creek, each approximately 500 ha in size (Figure 1). They are subwatersheds in the Entiat River subbasin in central Washington State on the east slope of the Cascade Range about 55 km north of Wenatchee at latitude 47°57'N, longitude 120°28'W. Catchment elevations range from 549 to 2134 m, mean aspects from 205 to 237 degrees, mean channel gradients from 27 to 29 percent, and mean hillslope gradient is about 50 percent. Mean annual temperature at 920 m elevation is 6.7°C. Mean annual precipitation is 58 cm; most falls from November to May, and only 10% falls from June to September. Seventy percent of precipitation is snow, and hydrographs are dominated by snowmelt. Annual peak flows occur in May or June. During the period 1962-1970, fifty percent of the time discharge was greater than 12.7, 20.7, and 19.2 liters per second (L/s) and mean maximum daily flow was 164.4, 243.7, and 167.2 L/s in McCree, Burns, and Fox Creeks respectively (Helvey 1974; Helvey et al. 1976a; Tiedemann et al. 1978).

Bedrock is primarily granodiorite and quartz diorite. Glaciofluvial sediment is abundant on the lower slopes. Glacier Peak is 56 km to the northwest, and pumice deposits from multiple eruptions vary from a few centimeters to more than six meters in thickness. Soils are well-drained Entisols. Prior to a severe fire in 1970 the forest overstory consisted predominantly of ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) at higher elevations. Stand-replacing wildfire had apparently not occurred in the 200 years prior to 1960, although fire scars on large trees indicated a history of periodic fire (Helvey et al. 1976a).

Studies on the EEF were originally established to examine effects of timber harvesting and road building on quantity, quality, and timing of streamflow. Site selection criteria included: (1) three or more 2.5-15.5 km2 catchments; (2) similarity among catchments in climate, physical characteristics, and vegetation, all of which should represent much of the forested land east of the Cascade Range crest in Washington State; (3) absence of disturbance by recent fire, heavy grazing, logging, or road building; and (4) reasonable year-round access (Helvey et al. 1976a).

## Historical Data

Data collection in the EEF began in 1960 and continued through 1977. During the period 1960-1970 discharge data were collected using sharp-crested, 120-degree, V-notch weirs near the mouth of each of the three experimental catchments. Weir ponds had capacities of 20-50 $m^3$. Stage height was measured using a stilling well float and punch tape recorder.

Following 10 years of calibration, the EEF catchments burned unexpectedly on 24 August 1970 as part of a 486 $km^2$, lightning-caused wildfire complex (Helvey 1980; Martin et al. 1976). Tiedemann et al. (1978) describe fire effects in the EEF as severe and uniform. However a few small patches, generally less than 10 ha, of mature ponderosa pine survived. By the end of the 1971 growing season, land surface cover by native and seeded plants averaged only 8.6 percent (Tiedemann and Klock 1973). During the fire, discharge in McCree Creek declined from 6.25 to 1.71 L/s, and immediately after the fire, strong diurnal discharge patterns were nearly eliminated owing to reduced transpiration (Berndt 1971).

After the fire two contour roads were constructed in McCree and Burns catchments, dead trees were logged, and grass and clover seed and nitrogen fertilizer were applied by helicopter (Helvey 1980). Fox Creek was designated an experimental control and not seeded, fertilized, roaded, or logged (Tiedemann and Klock 1976). Effects of wildfire on streamflow quantity, quality, and timing became primary research objectives, and were examined until the cessation of data recording in 1977 (Helvey 1980).

In mid-March 1972 record high air temperatures and an exceptionally deep snowpack produced flows greater than three times the maximum measured during calibration in McCree Creek. On 18 March a debris flow, apparently initiated by failure of weathered granitic material on steep slopes, destroyed the McCree Creek weir. Intense rainstorms on 9 and 10 June initiated a similar failure and debris flow in Fox Creek, destroying that weir (Helvey 1974). These weirs were replaced during the summer and autumn of 1972 with Parshall flumes at the gauging sites. Post-fire gaging records for McCree and Fox Creeks were incomplete owing to persistent sedimentation in the flumes. During 1973-1975 those missing data were estimated from discharge at the Burns weir (Helvey 1980; Helvey and Fowler 1999). Record quality, based on U.S. Geological Survey standards (Corbett 1943), was excellent for all stations until 1972. Records for Burns were good for 1972-1977 and fair to poor for Fox and McCree (Helvey and Fowler 1999). During the first post-fire year total water yield from the EEF was 50% greater than predicted using the Entiat River and nearby Chelan River as controls (Helvey 1974). The most complete post-fire discharge data were from Burns Creek. During water years 1972-1977 measured runoff in Burns Creek exceeded predictions by 10.7 to 47.2 cm, using the Chelan River as a control (Helvey 1974).

Precipitation was measured in shielded weighing-bucket gages with a 203-mm orifice. Only one gage in the study area, approximately 200 m from the Burns Creek weir, covered the entire period of record. After 1972 storage gages were installed at nine locations distributed throughout the McCree and Burns catchments. High elevation gages were serviced only once each year due to difficult access, but a more frequent schedule was kept where feasible. These other gages provided data for periods of approximately one year each. An additional six gages within 48 km of the EEF have records covering the study period (Bowles et al. 1975).

Water temperature sensors and punch tape recorders were installed in 1968 at the three gaging stations and temperature was recorded hourly. Three additional recorders were installed in Fox Creek in the fall of 1972 (Helvey and Fowler 1999). Mean daily maximum water temperatures during December 1969 to February 1970 were approximately 3°C, and 10 to 11°C in July and August before the 1970 fire (Helvey 1974; Helvey et al. 1976b). During the first two post-fire years mean daily maximum water temperatures increased in Burns Creek by 5-6°C based on control data from the Entiat River (Helvey 1974; Helvey et al. 1976b). In general stream temperatures peaked in the summer 1973 and declined until the end of data collection in 1977 (Helvey and Fowler 1999).

Beginning in 1966 air temperature and humidity measurements were made using a hygrothermograph and chart recorder at the Burns weir weather station. Daily maximum and minimum values were recorded (Helvey and Fowler 1999). Mean daily maximum air temperatures during December 1969 to February 1970 were -1.1°C, and 32.2°C in July and August before the 1970 fire (Helvey 1974; Helvey et al. 1976b). Tests for post-fire changes in mean monthly air temperature were inconclusive (Helvey et al. 1976b). Aerial measurements of midslope soil and plant surface temperatures were made on 29 August, 1969, near the time of maximum daily air temperature. Mean values ranged from 19.8 to 22.9°C (Tiedemann et al. 1978). Post-fire vegetation development for the years 1971-1974 is summarized in Tiedemann and Klock (1976).

## Current and Future Investigations

The EEF provides a rare opportunity to investigate hydrologic recovery from severe wildfire, post-fire salvage logging, and rehabilitation treatments by drawing from its rich data record and initiating new studies of fire effects on water quantity, quality, and temperature (Woodsmith et al. 2004). In 2003 we began reanalyzing the EEF historical records and reinstrumenting the three gaging stations with redundant stage height recorders (pressure transducers and capacitance rods) and water temperature sensors. We reinstrumented the former Burns weir (920 m) and Fox Creek (650 m) weather stations with rain, air temperature, humidity, barometric pressure, and wind speed sensors, all recording to data loggers. During spring 2004 two similar weather stations were added, one on the eastern McCree catchment divide (1300 m) and one on the Burns-Fox divide (2000 m) (Figure 1). In addition, Parshall flumes with recording pressure transducers were installed on Burns Creek and on one of its tributaries at about 1200 m elevation, and 30 self-contained, logging water temperature sensors were installed along the entire length of Burns Creek.

Objectives of current and future research include: (1) reanalysis of historical data to assess fire effects on runoff; our results will be compared to those previously published for the EEF using traditional paired watershed approaches; (2) contrasting hydrologic recovery between catchments where post-fire rehabilitation measures were applied (McCree and Burns) vs. no treatment (Fox); (3) assessment of post-fire hydrologic recovery, including analysis of the new hydrologic record for signatures of the 1970 fire and post-fire treatments; (4) analysis of water sources, flow paths, and timing of water delivery, with emphasis on the Burns Creek subwatershed where the most complete historical record exists; and (5) with improved understanding of catchment hydrology, evaluating hydrologic change associated with current land management practices, including fuels treatments, and transportation network management. Results will serve as a platform for virtual experiments simulating fire under current conditions. In future work we will use eleven other gaged catchments in the Entiat River subbasin to form the basis for nested hydrologic monitoring in this portion of the ICRB.

## Approach

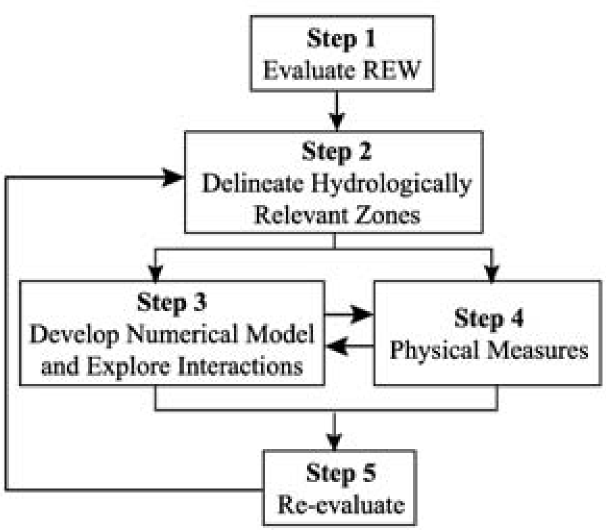
Following methods in McDonnell and Vache (in press), we are taking a diagnostic gaging approach to understand internal catchment behavior and develop a functional characterization of the EEF catchments. We are identifying first-order controls on hydrologic processes and investigating how these are linked to produce runoff at the subwatershed scale. This leads to a simple model structure that corresponds directly to the basic conceptual understanding of the catchment hydrology to test thinking about hydrologic processes and process linkages. Model structure and instrumentation are being developed concurrently to determine what to measure, where, and in what order. This approach to functional characterization of a catchment can be described in five steps (McDonnell and Vache in press) (Figure 2):

1. ***Field reconnaissance to investigate process scales*** – the representative elementary watershed (REW) is identified. This is the minimum catchment area at which hydrologic processes are representative of a larger scale. Determination of this area is commonly done through dilution gaging at a large number of tributary junctions to look for a relatively constant relationship between runoff rate and catchment size. At this threshold scale larger basins can be thought of as superpositions of smaller units.

2. ***Delineation of the dominant runoff producing zones and processes*** – these are represented as reservoirs in conceptual box models. These zones can be identified through longitudinal stream surveys using water temperature, conductivity, or pH as initial tracers. Anomalies at tributary junctions indicate reservoirs with different residence times, subsurface storage volumes, or exposure to disturbance.

3. ***Development of a simple, lumped, conceptual model to test thinking about catchment processes and characterize first-order process controls (Figure 3).*** This approach can incorporate "soft data" or qualitative knowledge of catchment behavior, such as the proportion of the catchment subject to saturation. Commonly this is knowledge that cannot be used as direct numbers,

*Figure 2. A diagnostic approach to understanding internal catchment behavior and developing a functional characterization of catchment hydrology (McDonnell and Vache, in press).*



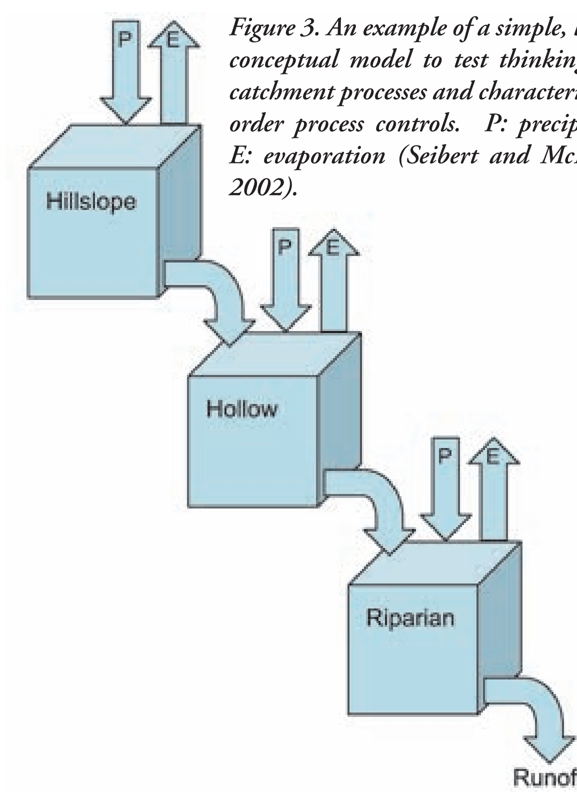




*Figure 3. An example of a simple, lumped, conceptual model to test thinking about catchment processes and characterize first-order process controls. P: precipitation, E: evaporation (Seibert and McDonnell 2002).*

but can be used as fuzzy measures of model simulation and parameter value acceptability. This injects some experimentalist common sense into the calibration process, providing a more “real” model of the catchment that better captures the key processes controlling catchment response (Seibert and McDonnell 2002).

4. ***Physical measures and characterization of dominant runoff producing processes*** – reservoirs, pathways and constants are added to the simple box model. The developing model focuses further instrumentation, gaging, and watershed characterization. Results are used to explore and represent the dynamic nature of the system and provide a useful framework for gauging. Only fundamental controls on hydrologic processes are included. The emphasis is on realistic internal dynamics, rather than forcing model efficiency. This step can include feedback to step 3, and acts as a springboard to more complex approaches. Visual modeling software is useful for this step. Figure 4 provides an example from McDonnell and Vache (in press) of an application from another study area.

5. ***Develop more complete measurements and understanding of runoff processes including more detailed characterization of flow sources, pathways, and ages.*** This can include: more rigorous gaging including at tributary junctions, quantification of details of runoff response to rainfall, identification of thresholds in reservoir connections, and analysis of stream and groundwater chemistry to characterize water source areas and residence times. Improved understanding may force re-evaluation of earlier models.

To further understanding of internal catchment behavior we will install a series of nested discharge measurement stations to assess longitudinal contributions of groundwater to stream discharge, thereby delineating dominant runoff producing zones and processes. We will further analyze water sources and pathways using tracers, including water temperature, conductivity, and others (McDonnell and Tanaka 2001). Analyses of stable isotopes, in particular $^{18}O$, in stream water can be extremely valuable in defining water age. This allows determination of the proportion of “old” vs. “new” water in runoff and leads to definition of runoff sources and flowpaths. The role of physiographic and landscape characteristics in the composition of water will be assessed following the approach of McGlynn et

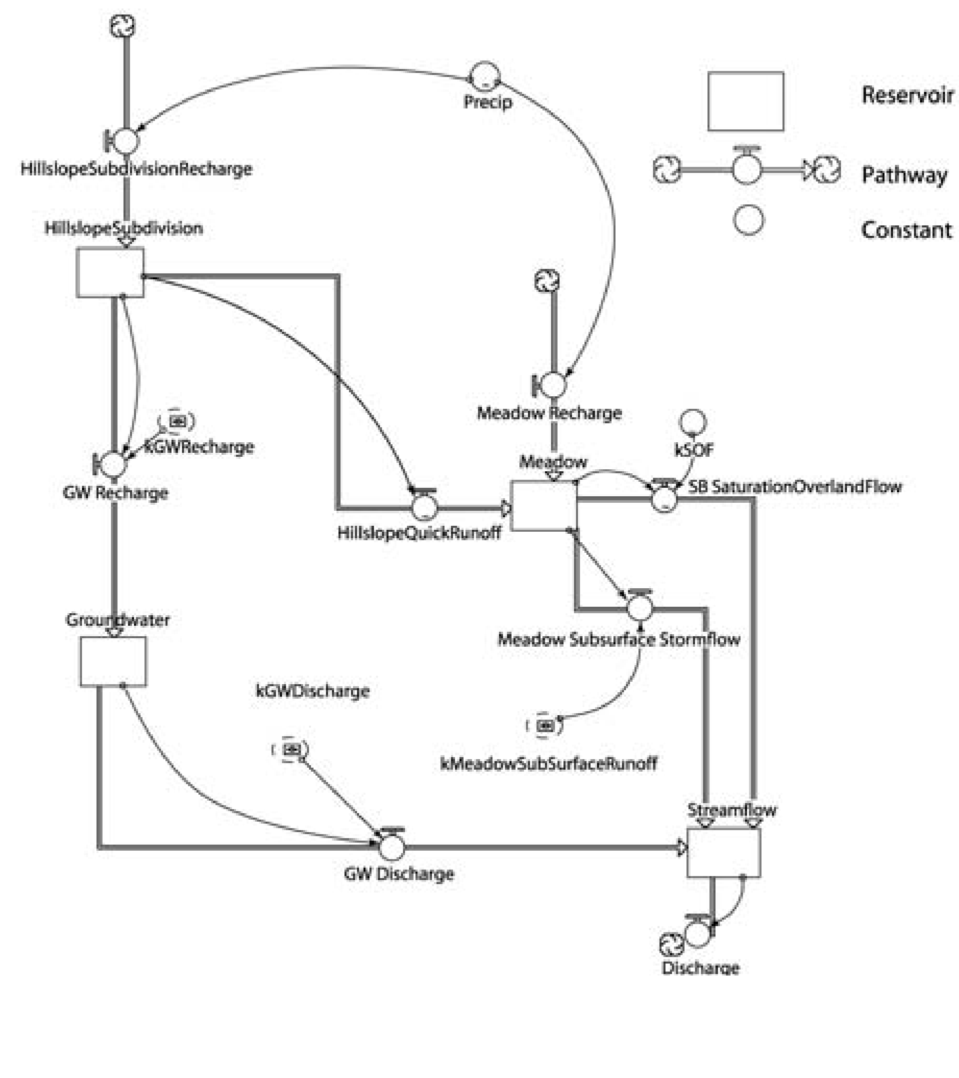



*Figure 4. An example of a refined conceptual model of runoff processes using “STELLA” (High Performance Systems Inc.)[1] visual modeling software (McDonnell and Vache 2004). Details in this example are not relevant to the Entiat study area.*

1 The use of trade names is for the information and convenience of the reader. Such use does not constitute an official endorsement by the U.S. Department of Agriculture of any product to the exclusion of others that may be suitable.

al. (2003), who found that streamwater composition was controlled by the distribution of tributaries, related sub-catchment area, and the associated mean water residence time of each. Distinctions among water sources, flowpaths, and ages have important implications in assessment of the effects of disturbance including fire. For example, studies in other areas have indicated that the majority of runoff can be "old" groundwater, rather than storm event water, implying that immediate effects of disturbance may be strongly damped by the influx of pre-disturbance water, possibly from other parts of the catchment.

## The HBV Model

We are employing the Hydrologiska Byråns Vattenbalansavdelning [HBV] rainfall-runoff model (Bergstrom 1995) as a tool for change detection, whereby the effects of the 1970 fire will be assessed through the gaging record. We use EEF field data to make the HBV model more distributed and more tailored to the specifics of the EEF catchments, following methods of Seibert and McDonnell (2002). Early post-fire and current gage data will be analyzed to see if change can be detected relative to the 1960s pre-fire condition. HBV is a simple, conceptual model for runoff simulation, which is widely used in Nordic countries. It is semi-distributed in that it accommodates division into sub-catchments and elevation and vegetation zones. HBV lends itself to conceptualization of a catchment as a series of linked reservoirs that can be represented as boxes in simple flow diagrams (Figure 5) (Seibert 1996).

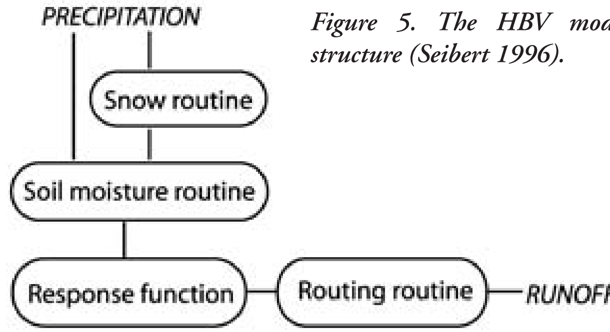



*Figure 5. The HBV model structure (Seibert 1996).*

| Submodel | Input data | Output data |
|---|---|---|
| Snow routine | Precipitation, temperature | Snow pack, snowmelt |
| Soil routine | Pot.Evap., precipitation, snowmelt | Act.Evap., 'soil moisture', groundwater recharge |
| Response function | Groundwater recharge, (pot. ET) | Runoff, 'Groundwater level' |
| Routing routine | Runoff | Simulated runoff |

The HBV model simulates daily discharge using daily rainfall, temperature, and potential evaporation as input. Rainfall and temperature values are the weighted means among stations and are corrected for elevation by zone. Potential evaporation estimates are normally monthly mean values based on the Penman formula or evaporimeters. The long-term mean of the potential evaporation for a certain day can be corrected to its value at day t by using deviations in temperature from its long-term mean and a correction factor (Seibert 1996).

Precipitation is simulated to be either snow or rain depending on whether the temperature is above or below a threshold temperature (TT). All precipitation simulated to be snow (that falling when the temperature is below TT) is multiplied by a snowfall correction factor to account for losses to evaporation and sublimation and measurement error, which tends to be greater than for rainfall measurement. Typical correction factor values for forested areas are about 0.8. Snowmelt is calculated using a simple degree-day method. Meltwater and rainfall are retained within the snowpack until they exceed a certain fraction of the snow water equivalent. Liquid water within the snowpack refreezes according to a refreezing coefficient applied to TT (Seibert 1996). The refreezing coefficient, snowfall correction factor, and TT are adjustable model parameters, rather than empirically derived quantities.

Rainfall and snowmelt (P) are divided into water filling a conceptual soil box and groundwater recharge depending on the relation between water content of the soil (SM), its largest value, field capacity (FC), and the parameter 'Beta'. At low soil moisture all rain and snowmelt goes to soil moisture storage. At field capacity (maximum soil moisture storage), all rain or snowmelt goes to groundwater recharge (Figure 6). Actual evaporation from the soil box equals potential evaporation if SM/FC is above LP, while a linear reduction is used when SM/FC is below LP (Figure 7) (Seibert 1996).

Groundwater recharge is added to an upper groundwater box or reservoir. From there water percolates to a lower groundwater box at a maximum rate. Runoff from the groundwater boxes is computed as the sum of two or three linear outflow equations depending on whether or not recharge in the upper groundwater box is above a threshold value. Outflow at time t is proportional to water storage (S) as determined by the coefficient "k" (Figure 8). The first estimate of the groundwater response parameter (k) is taken from the slope of hydrograph recession curves. Finally, simulated groundwater outflow is transformed

*Figure 6. The HBV soil moisture routine – contributions from rainfall or snowmelt to soil moisture storage and to the upper groundwater zone. FC is the maximum soil moisture storage, BETA is a parameter that determines the relative contribution to runoff from rain or snowmelt (Seibert 1996).*

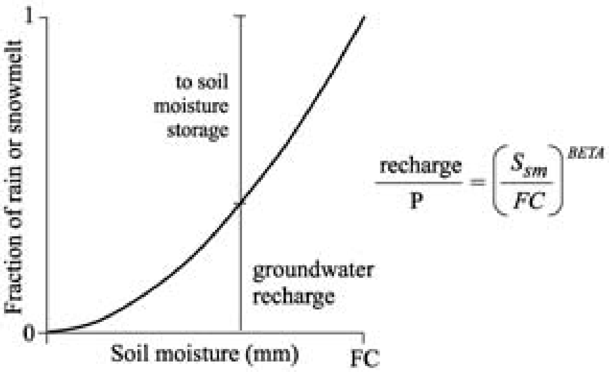
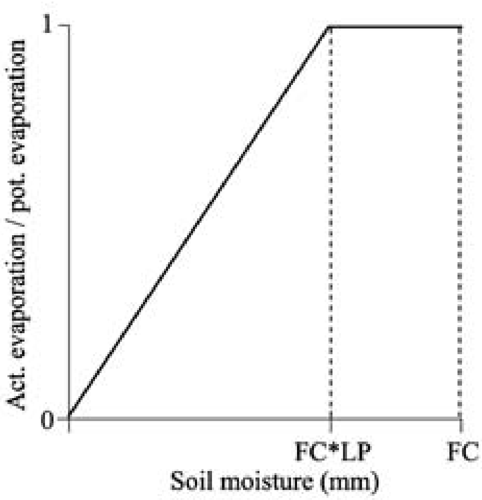


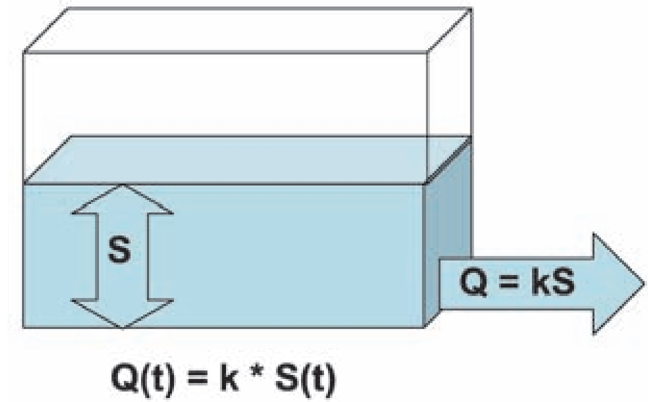

*Figure 7. The HBV model – change in actual evaporation depending on soil moisture storage. FC is a model parameter and not necessarily equal to measured values of 'field capacity'. LP is the soil moisture value above which actual ET reaches potential ET (Seibert 1996).*




to simulated catchment runoff by a weighting function, which distributes runoff from one time step onto the following days (Seibert 1996).

Distributions of reasonable parameter values are developed using a Monte Carlo approach. Parameter values are chosen randomly within a specified range for each run, and a large number of model runs, each generated by a distinct parameter set, are performed. Working with a set of parameters, rather than a single value, allows computation of parameter confidence intervals and reduction in parameter uncertainty (Seibert 1997). Best fit parameter sets are selected through an assessment of the fit of simulated to observed runoff data based on visual inspection of fit, accumulated difference between

*Figure 8. The HBV model – simple linear reservoir response function. The model of a single linear reservoir is a simple description of a catchment where the runoff Q(t) at time t is proportional (k) to the water storage S(t) (Seibert 1996)*




simulated and observed values, and statistical criteria. Commonly, the coefficient of efficiency is used to evaluate model fit. This coefficient compares the prediction by the model with the simplest possible prediction, a constant observed mean value over the period. Alternatively multiple objective functions can be used, with measures combined through fuzzy logic algorithms (Seibert 1996; Seibert 1997).

## Application of the HBV Model

We employ the HBV model to evaluate hydrologic change in the EEF data (Seibert et al. 2004), and report preliminary results here to illustrate the approach. Publication of final results is forthcoming. Change was evaluated by: (1) comparing runoff simulated from pre-fire parameter sets to observed runoff (simulation vs. observation); (2) comparing simulations based on pre-fire parameter sets to simulations based on post-fire parameter sets (simulation vs. simulation); and (3) directly contrasting pre-fire with post-fire parameter values. The simulation vs. observation approach involves calibrating parameter sets using pre-fire data, simulating pre- and post-fire runoff from these parameter sets and driving variables, then contrasting simulated to measured runoff. This is done by contrasting the statistical central tendency and dispersion of residual (observed minus simulated) distributions for the larger peak flows. Dispersion of this distribution provides a measure of parameter uncertainty. The simulation vs. simulation comparison is done by calibrating separate parameter sets for pre- and post-fire runoff data. Separate simulations of the larger post-fire runoff events are run for these parameter sets using post-fire driving variables. Simulated values are then compared to a hypothetical

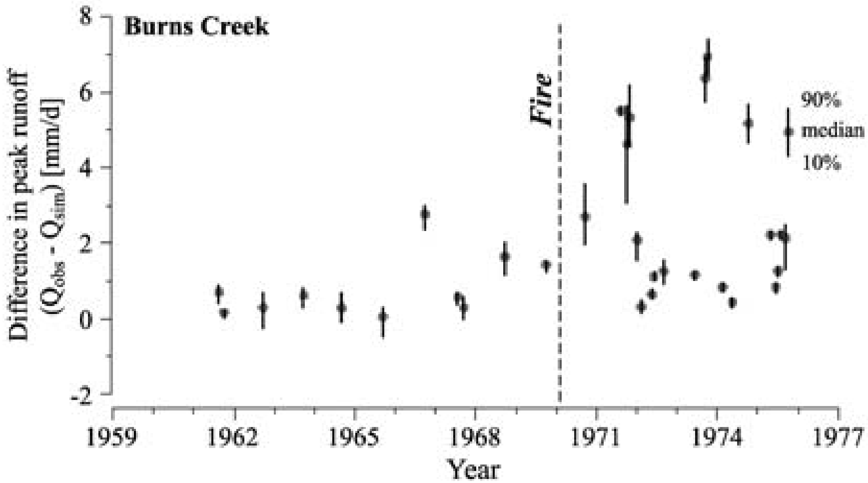



*Figure 9. Observed minus simulated runoff based on pre-fire parameter sets. Severe fire occurred on 24 August 1970. Data points are median values of the 100 best-fit parameter sets. Vertical bars represent the corresponding distribution of runoff values (Seibert et al. 2004).*

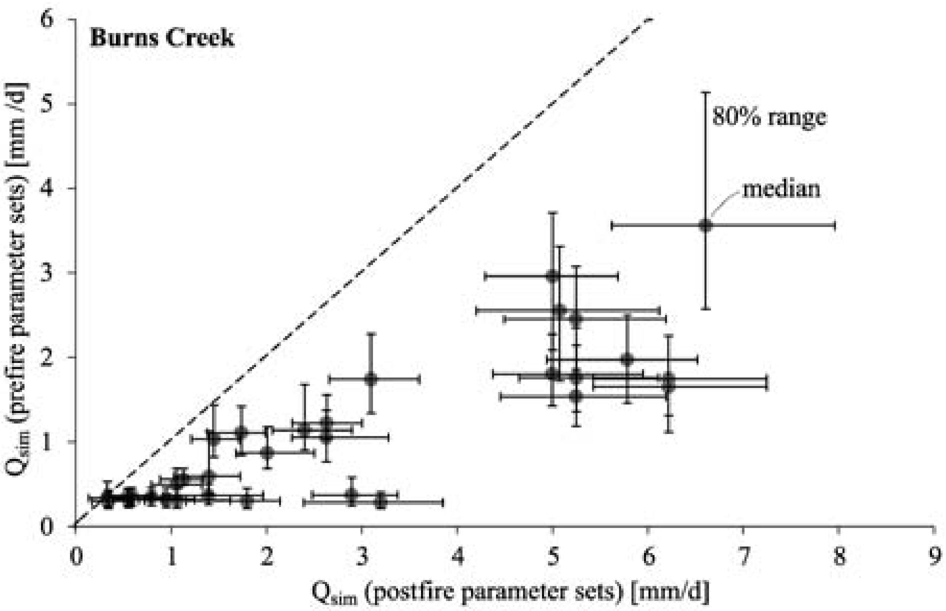



*Figure 10. Post-fire runoff simulated from post-fire parameter sets vs. pre-fire parameter sets. Data points are median values of the 100 best-fit parameter sets. Bars represent the corresponding distribution of runoff values (Seibert et al. 2004).*

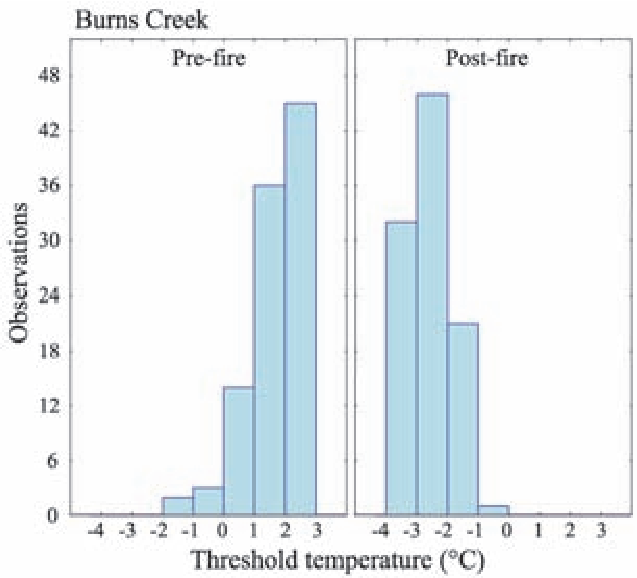
zero-change result. To directly contrast pre- with post-fire parameter values, separate parameter sets are calibrated, then pre- and post-fire values of central tendency of each parameter are contrasted (Seibert et al. 2004).

Each of these three approaches was applied to the EEF data. One million model runs were performed, and the 100 best fit parameter sets selected from these. The simulation vs. observation approach indicated a general increase in post-fire median runoff (Figure 9). Error bars in Figure 9 indicate distribution in runoff among the 100 best-fit parameter sets. Similarly, the simulation vs. simulation approach indicated a consistent increase in post-fire runoff (Figure 10).

Pre- and post-fire parameter sets were directly compared for all three EEF subwatersheds. Results indicated post-fire increases in soil moisture, reducing available storage for storm event water by approximately half. Modeling further indicated a 50% increase in the snowfall correction factor, implying greater snow accumulation, a 3°C post-fire decrease in temperature threshold (Figure 11), implying onset of snowmelt approximately one-month earlier than normal for the pre-fire period, and a 50% increase in rate of snowmelt calculated by the degree-day algorithm. These changes combined to produce modeled post-fire peak flow increases of 100% or more (Seibert et al. 2004). Our modeling results are in general agreement with findings of Helvey (1980) based on a conventional paired watershed approach, using the Chelan River as a control. Helvey computed measured minus predicted runoff based on pre-fire calibration, and determined that post-fire annual runoff increased from 1.7- to 3-fold relative to the pre-fire mean.

Although validation of the physical basis for these changes in adjustable parameter values is beyond the scope of this paper, the modeled shifts in values are physically reasonable. Fire related reduction in evapotransporation

*Figure 11. Distribution of the threshold temperature (TT) parameter among the 100 best-fit pre- and post-fire parameter sets (Seibert et al. 2004).*




should increase soil moisture; reduced canopy interception should lead to greater snow accumulation; and increased turbulent exchange at the snow-air interface should increase the efficiency of snowmelt processes leading to initiation of runoff at lower mean air temperatures (earlier in the season) and higher rates of snowmelt.

## Summary

In recent years interest in the hydrologic recovery of burned areas has increased. Effects of fire on soil and vegetation can lead to increased runoff, peak flows, flooding, water yield, erosion, sediment load, turbidity, mass soil movements, and debris flows that alter water quantity and quality and may threaten human life and property (Beschta 1990; Conedera et al. 2003; DeBano et al. 1998; Meyer et al. 2001; Robichaud et al. 2000; Swanson 1981; Tiedemann et al. 1979; Wells et al. 1979; Wondzell and King 2003). Despite increased interest, few data exist at the subwatershed scale that document the effects of wildfire on runoff characteristics. The EEF is the site of one of very few published studies that chronicle a "natural fire experiment" before and after wildfire.

Our objectives are to review and expand upon previous analyses of existing hydrologic data and to renew data collection and analyses in the EEF. We seek to increase understanding of the effects of severe wildfire and post-fire land management on water quantity, quality, and timing, as well as long-term hydrologic recovery following severe disturbance such as fire. Increased predictive capability regarding effects of severe wildfire and mechanisms and rates of hydrologic recovery will inform land management responses to these events. For example, improved knowledge of long-term hydrologic recovery following wildfire could help guide decisions regarding the relative value and advisability of various post-fire rehabilitation approaches. Increased understanding of catchment hydrology at the subwatershed scale will improve evaluation of hydrologic change associated with a variety of land management practices. Availability of gaging records for the Entiat River subbasin creates an opportunity to scale up this new knowledge from the subwatershed scale to larger areas within the ICRB.

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# Discharge and Sediment Loads at the Kings River Experimental Forest in the Southern Sierra Nevada of California

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The Kings River Experimental Watershed (KREW) is now in its third year of data collection on eight small perennial watersheds. We are collecting meteorology, stream discharge, sediment load, water chemistry, shallow soil water chemistry, vegetation, macro-invertebrate, stream microclimate, and air quality data. This paper primarily examines discharge and sediment data from six watersheds between 1600 m and 2400 m in elevation in the Sierra Nevada, California. The discharge discussion focuses on water year (Wy) 2004, which was relatively dry. The sediment discussion examines bulk mass data from Wy2001 through Wy2004, and presents some detailed analysis of the sediment load beginning with the Wy2003 dataset. Sediment loads in kilograms per hectare were low with the exception of Wy2003. Meteorology data from two stations at the top of the watersheds and two stations at the bottom is presented. Between 2007 and 2009, six of these eight watersheds are planned be harvested, undergo prescribed burns, or both, to quantitatively measure the effects of these USDA Forest Service land management practices.

Keywords: *watershed management, hydrologic processes, sediment yield, fire, thinning, stream ecology, streamflow*

## Introduction

Sixty percent of California's water originates from small streams in the Sierra Nevada, yet there is very little information about how these streams are affected by land management activities near the source. Sierra Nevada stream water is considered some of the highest quality water in the state. The quality of aquatic and riparian (near-stream) ecosystems associated with streams is directly related to the condition of adjacent uplands within their watersheds. Past management actions such as timber harvesting, road construction, and fire suppression have altered the vegetation structure of watersheds and have affected headwater streams. Forest Service management believes that prior to European settlement, circa 1850, the western slope of the Sierra Nevada was more open and had predominantly uneven-aged stands. This historic stand structure was extremely resistant to stand-replacing wildfires. Restoration of the Sierra Nevada's forest watersheds to historic or desired conditions requires active management, such as reintroduction of frequent, cool fires and removal of accumulated fuel loads.

The Kings River Experimental Watershed (KREW) is a long-term watershed research study being implemented on the Sierra National Forest to provide much needed information for forest management plans regarding water quantity and quality (Figure 1). This experimental watershed research is designed to: (1) quantify the variability in characteristics of headwater stream ecosystems and their associated watersheds; and (2) evaluate the effect of fire and fuel-reduction treatments on riparian and stream physical, chemical, and biological conditions. This is an integrated ecosystem project at the watershed scale and is part of a larger adaptive management study that began in 1994 as a collaborative effort between the Sierra National Forest, Southern California Edison, and the Pacific Southwest Research Station of the Forest Service. This larger study was designed to evaluate the effects of management actions aimed at recreating an uneven-aged forest that is resistant to wildfires. The KREW staff will evaluate the effects of mechanical thinning, prescribed

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***Figure 1. Kings River Experimental Watershed is located on the Kings River, which drains into the San Joaquin River basin. It is part of the Kings River Project, Sierra National Forest, which is a 60,000 ha collaborative study between research and management.***


fire, and thinning with fire combination treatment on the watersheds.

Stream monitoring is a well-developed science; however, the majority of work addresses large streams and rivers. Watershed research has been conducted in the United States since the early 1900s, but none of the long-term studies are in ecosystems similar to the Sierra Nevada, and most studies were designed to evaluate severe management actions such as clearcuts and stand-replacing fires. Critical information is lacking because few integrated ecosystem studies exist (Naiman and Bilby 1998). Such studies are essential for understanding stream-watershed ecosystem processes and functions for adaptive management.

The Kings River Experimental Watershed consists of eight watersheds that vary in size from 49 to 228 ha. The Providence Site is composed of four adjacent watersheds (1,500 to 2,000 m in elevation) in mixed-conifer forest – D102, P301, P303, and P304. The four Bull Site watersheds, ranging in elevation from 2,100 to 2,500 m (B201, B203, B204, T003) are in mixed-conifer forest with a large red fir (*Abies magnifica*) component approximately 15 km southeast of the Providence Site. These elevation bands were selected because this is where most Forest Service management activity in the Sierra Nevada has traditionally taken place. The KREW staff is collecting the standard watershed measurements of discharge, sediment load, and a suite of meteorology measurements; the first years of this baseline data are presented in this paper.

Other watershed and stream characteristics are being studied because KREW is an integrated watershed study. Stream water, soil water, and snowmelt are analyzed for various anions and cations every two weeks, and more often during peak spring runoff and storms. Air quality is monitored for ozone, ammonia, and nitric acid. Riparian and upland vegetation and stream macroinvertebrates are surveyed annually. Fuel loading and channel morphology will be measured prior to treatment implementation and periodically once the treatments are completed.

## Methods

### Discharge Methods

Stream discharge is measured with Parshall-Montana flumes (Figure 2). The KREW streams have approximately a 500-fold difference between lowest and highest flow over a 20-year time span, but Parshall-Montana flumes can capture accurately only a 50-fold difference; therefore two flumes, one large and one small, are on each stream. The two-flume design permits precise flow measurements (from standard tables) from 0.75 L/s (0.03 cfs) to 900 L/s (32 cfs). Less precise, but still acceptable, measurements over the range from 0.3 L/s (0.01 cfs) to 1,400 L/s (49 cfs) will be used. All of theWy2004 data from the four Providence streams and most of the data from the two Bull streams are from the small flumes, with 7.6 and 15.2 cm throats respectively. All discharge, meteorology, and sediment data are reported based on the water year which begins on 1 October of the previous year and ends on September 30 of the stated year (Wy2004 runs from 1 October 2003 to 30 September 2004).

Isco®[1] 730 bubblers were chosen to measure stage on the small flumes because freezing does not destroy the instrument. The bubbler relays data to an Isco 6712 sampler, which also takes water samples for chemical analyses. The Isco sampler and bubbler receive electricity from a 12V DC system powered by a 50W solar panel. The stage data is relayed via radio telemetry back to the Fresno office. The backup device on the Providence small flumes is a Telog® WLS-31 pressure transducer. The KREW staff measure stage in the large flumes (61 to 122 cm throat width) using Aquarods that sit in stilling wells. Both the Telogs and the Aquarods are downloaded to a laptop on a monthly basis. Visual stage readings are recorded every

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

*Figure 2. The two-flume design on the B201 stream allows KREW staff to precisely measure a wide range of flows. The 3-inch Parshall Montana flume (foreground) measures most flows, and the 2-foot Parshall Montana flume (background) measures large rain events.*

two weeks except during spring runoff when the sites are visited weekly. All data is stored and managed in the Isco Flowlink® program.

All of KREW's eight watersheds are located within the rain to snow transition zone where many precipitation events drop a combination of rain and snow. In order to better understand the factors that control stream discharge, this paper uses meteorology and discharge data to examine aspects of the water cycle. For this analysis the discharge from the Wy2004 hydrograph was divided into the following four categories: baseflow, rain event flow, snowmelt flow, and soil water. Baseflow was determined by looking at the discharge for the lowest flow period of Wy2004, 1 September to 15 September. Baseflow for the year is derived by multiplying this daily average by 366 (2004 was a leap year. The authors expect this water has been in the ground for at least six months and originates in perennial springs.

Rain event flow (quickflow) is all runoff above baseflow that occurred from the start of each rain event until the flow drops back to where it started, or 24 hours after the rain stops, whichever comes first. Rain events that did not increase the hydrograph by at least 20 percent were ignored. Using the above criteria, six rain events occurred in most of the KREW watersheds. In the Wy2004 hydrograph, these six events and their associated tails had a combined duration of approximately 300 hours. Snowmelt flow is runoff above baseflow that occurs between the start of spring runoff (7 March 2004) and two weeks past the date on which the snow depth sensor at the closest meteorology station indicates zero. The D102 watershed had two distinct snowmelt periods and was handled slightly differently. The authors believe that the snowmelt flow water resides briefly in the shallow soil as it moves to the stream. Soil water was determined by taking total discharge for Wy2004 in each watershed and subtracting baseflow, snowmelt flow, and rain event flow as defined above. We expect that this water is stored in the soil between two weeks and six months.

### Meteorology Methods

KREW has four meteorology stations; a station is located at the bottom and the top of each group of four watersheds (Figure 3). Seven parameters are measured at 15-minute intervals: temperature, relative humidity, solar radiation, wind speed, wind direction, snow depth, and precipitation. In Wy2004 there was one functioning snow pillow that measured snow water equivalence. Meteorological data are logged and processed by Campbell Scientific, CR10X data loggers and relayed back to Fresno via radio telemetry. The KREW staff visit each meteorological station once each month and record manual measurements to ground truth the sensors.

*Figure 3. Sensors on a 6-meter tower at the upper Providence meteorology station measure temperature, relative humidity, solar radiation, wind speed, wind direction and snow depth (left). The 3-meter high Belford® gauge measures total precipitation (right).*

Rainfall amounts reported here are typically an average value of the four precipitation gauges. For the six large events the totals generally vary by 10-15 percent between meteorology stations. The small events (< 25 mm) were more difficult to present in a comprehensive manner, as different sites recorded, and most likely received, very different amounts of precipitation. For small events, the data from the Upper Providence station, which is at a middle elevation for KREW, is presented instead of an average of all stations. Brief showers (< 5 mm) were excluded from the precipitation dataset because they generally did not occur at all four meteorology sites and several load-cell sensors do not exhibit sufficient precision to measure minute changes.

**Sediment Methods**

Sediment catchment basins exist on all eight streams, but only five of these had been constructed and were being analyzed in Wy2003 and Wy2004 (Figure 4). The basins vary in size from 25 $m^2$ to 200 $m^2$ and are slightly more than one meter deep at their deepest point. They are all lined with pond liner to make sure each year's sediment is clearly defined. These ponds are dug out by hand each September. After a total wet weight is measured, a representative sample is dried and used to determine the dry mass for each basin.

Starting in Wy2003 the organic and mineral fractions were determined. The organic fraction is made up of three components: large organic matter such as sticks that are removed by hand, coarse organic matter such as twigs that are floated off of an oven-dried sample, and fine organic matter that is burned off for 24 hours at 500°C. The dry weights of the three components are added together to arrive at a total organic fraction.

A representative sample of the mineral fraction is dried at 110°C until the sample loses less than one percent weight between hourly weighings (usually after 12 hours). A standard sieve analysis is then performed to determine a particle size breakdown using 2, 1, 0.5, 0.25, 0.125, and 0.065 mm sieves.

***Figure 4. The B204 sediment catchment basin, lined with commercial pond liner, traps sediment behind a 1.2-meter-high log structure. Sediment is removed each fall, weighed wet and subsampled. A dried subsample is analyzed to determine organic and mineral fractions and particle size distribution.***

## Results and Discussion

**Discharge and Meteorology Results**

The 2004 water year had two large storms (>125 mm of precipitation); storms of this magnitude may produce bankfull flows and move sediment. The 25 December 2004 storm came primarily as rain at all elevations and moved minor amounts of sediment, while the 26 February 2005 storm delivered snow (Figure 5). The timing, magnitude, and duration of these events was statistically normal. Four other storms each provided about 50 mm of precipitation. Whether these smaller precipitation events deliver rain or snow, the soil can usually absorb the majority of the moisture, and surface runoff is limited to rock outcrops and human-compacted areas such as roads. While there was a normal distribution of these events from November through February, a typical year would have seen about three more equivalent events in March and April.

The 80 mm of rain in November recharged the shallow soil moisture but did not produce discharge peaks associated with surface flow. The smaller December events also had little effect on the hydrograph. The hydrograph response to fall storms varies very little by watershed elevation or size, so the water from the distal portions of the watershed (> 50 m from the stream) is not rapidly arriving at the stream.

The large 25 December 2004 event produced between 5,000 and 7,000 cubic meters of water in each of the four analyzed watersheds (Figure 5); this converts to about 5 mm of depth spread over each watershed. Only 5 mm of the total 130 mm that fell as precipitation was measured as discharge in the streams. The next three precipitation events were snow. The last major precipitation event on 25 February 2005 fell as snow in all except the lowest elevation areas (D102 watershed).

Water that drained out of the watersheds as a direct result of rainstorms was on average only about 7 percent of the total yearly discharge (Figure 6). This value is strongly correlated with watershed elevation, with the lower elevation watersheds having the highest percentage of their discharge derived from rainstorms. Water that originated in melting snowpack accounts for an average

*Figure 5. For water year 2004, the hydrographs of four watersheds are very similar in the fall and early winter, but differ in the spring. The precipitation record (lowest graph) shows only two large storms ( >125 mm) and four mid-sized events ( >50 mm).*

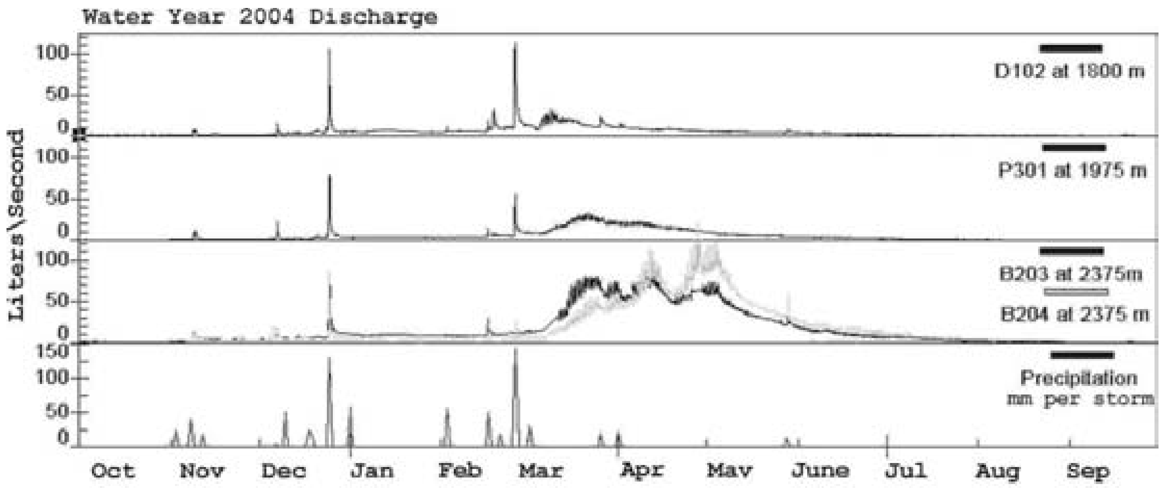
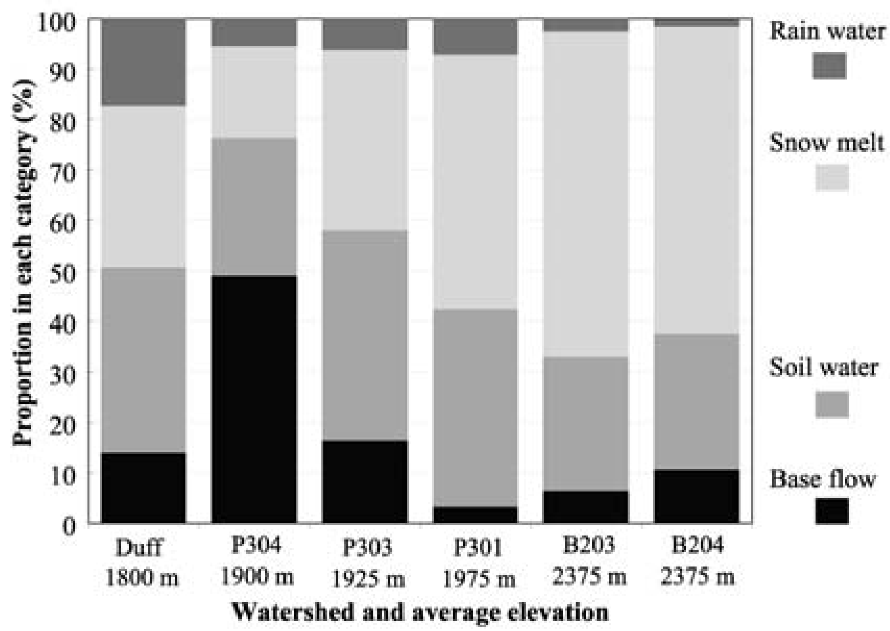



*Figure 6. The annual discharge from six watersheds is divided into source components. The percentage of water from snow melt correlates with increasing elevation. Rainwater is a relatively small percentage at all elevations.*




of 37 percent of the total discharge from the four lower watersheds, and was also strongly correlated with elevation, but in a reverse direction from rainfall water. Because the two highest watersheds (B203 and B204) produce twice the annual discharge of the lower watersheds, and because 68 percent of their discharge is generated by melting snowpack, 57 percent of the total water from the six analyzed watersheds came from snowmelt.

The average baseflow contribution to the annual discharge is 17 percent, but this value was skewed by P304, where baseflow accounts for 56 percent of discharge. If P304 is excluded, baseflow contributes an average of 11 percent of the annual discharge in the other five watersheds. Small perennial watersheds may have a larger baseflow component, because without good groundwater sources they would not be perennial during the late summer in the Mediterranean climate that characterizes the southern Sierra Nevada. The lower elevation watersheds rely almost entirely on baseflow from 1 July through 1 October. While these baseflows are important to stream biology, macroinvertebrates, and riparian plants in the lower elevation watersheds (P303 and D102), the last three months of the water year produced less water than the three days around the 25 December storm.

Water derived from the soil is difficult to estimate. The soil percentages (Figure 6) do not show a clear pattern, but the amount of water contributed per hectare from soil is similar for all watersheds. During Wy2004, soil water estimates for Providence watersheds varied from 462 $m^3$/ha in D102 to 711 $m^3$/ha in P304. For B203 and B204, shallow soil water contributed 1,085 $m^3$/ha and 984 $m^3$/ha respectively. The soil profile stored and then released approximately 6 cm of moisture at 1,900 m of elevation and approximately 10 cm of moisture at 2,375 m. While we have not yet developed a full water budget, it can be concluded that very little of the moisture that entered the soil's lower profiles was released back to the streams.

In watershed P303, monthly total discharge never exceeded precipitation (Figure 7). Of the total precipitation during Wy2004, only 13 percent contributed to streamflow. At higher elevations at B203, 40 percent of the total precipitation flowed down the stream (Figure 7). From a regional viewpoint, the watersheds at 1,900 m can not be expected to contribute significantly to storage in California reservoirs during dry years. At 2,375 m, slightly more precipitation falls, but a much larger percentage of that water will flow into the reservoirs.

We acknowledge that this data is a snapshot of one dry year which had only 70 percent of the average annual precipitation. It was not an extremely anomalous meteorological year, as there are 14 drier years during the 90-year period of record at Huntington Lake precipitation gauge, approximately 25 km north of KREW and at a similar elevation. Three-week-long dry periods, such as the one that occurred in January, are not unusual in the southern Sierra Nevada.

### Sediment Results

Sediment loss rates per hectare vary by three orders of magnitude among the five watersheds over the four-year dataset (Figure 8). Within a single watershed the rates vary by a factor of 100 during the four years. Between neighboring watersheds, but in the same water year, rates also vary by a factor of 100.

*Figure 7. Watersheds vary in the amount of precipitation that becomes discharge. In watershed P303 at 1,925 m elevation, only 13 percent of the incoming precipitation results in discharge (top graph), whereas in watershed B203 at 2,375 m 40 percent of precipitation contributes to discharge. (bottom graph). Precipitation greatly exceeds discharge until March when spring snow melt begins.*

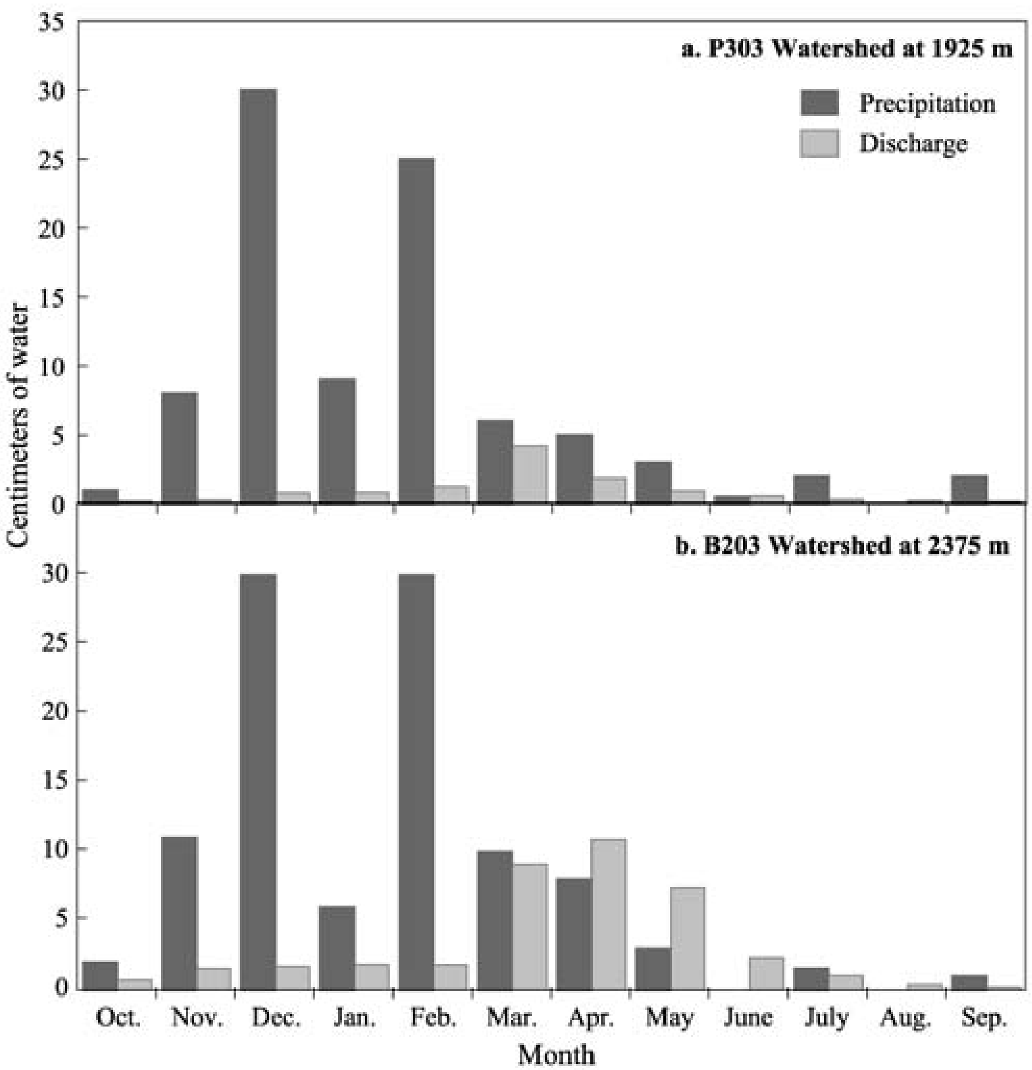
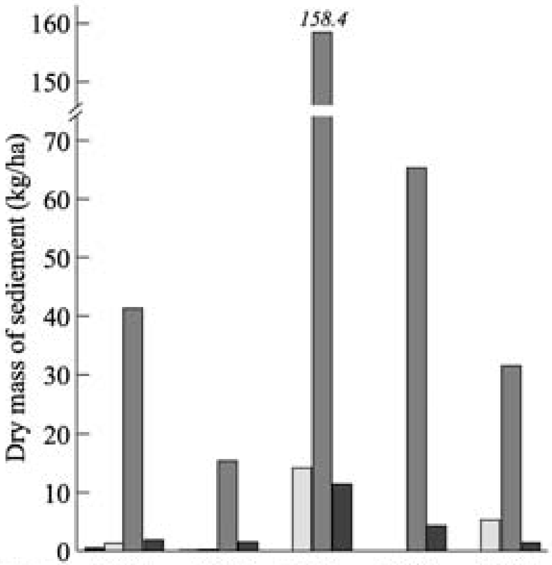


*Figure 8. The dry mass of sediment captured in each basin varies by orders of magnitude between years and between adjacent watersheds.*




| Watershed / *Water year* | P301 | P303 | P304 | D102 | B201 |
|---|---|---|---|---|---|
| 2001 | 0.5 | 0.1 | - | - | - |
| 2002 | 1.3 | 0.2 | 14.2 | - | 5.3 |
| 2003 | 41.3 | 15.4 | 158.4 | 65.3 | 31.5 |
| 2004 | 1.9 | 1.5 | 11.4 | 4.3 | 1.4 |

These data indicate only 0.002 mm loss of soil depth each year (average of all basin data and an average soil density of 1.2 g/cm$^3$). Based on this four-year period, one might conclude that it would take 500 years to loose a millimeter of soil depth. This conclusion is misleading because erosion can be almost non-existent and then greatly increase during infrequent but intense rainfall events.

On average the basins captured 17 times more sediment in Wy2003 than in Wy2004. The total rainfall was similar (a 300 mm difference); however, the magnitude and intensity of the single largest event was very different. In Wy2003, 290 mm of rain fell in 30 hours during the 7 November storm. For a steady rainfall, that amount averages to 9.7 mm per hour, but 27 mm actually fell during the most intense hour of this storm. In Wy2004, 142 mm fell in 60 hours during the 24-25 December storm. This amount represents an average of 2.3 mm per hour, but only 11 mm fell during the most intense storm hour (Table 1). With hard rain falling (> 5 mm per hour), we observed no overland flow in undisturbed areas of the watersheds under the forest canopy. The overland flow and sediment movement seen in Wy2004 probably came predominantly from roads, unstable stream banks, or erosion just below large rock outcrops. The percentage of precipitation that falls as rain versus snow also affects soil loss.

The datasets from the P301, P303, D102, and B201 sediment basins show similar patterns in their organic fraction and mineral fraction particle size (Table 1). The organic component was between 20 and 30 percent in both years, with the total average mass of organics contributed per hectare small: 5 - 10 kg/ha in Wy2003 and 0.5 kg/ha in Wy2004. Since the magnitude of the largest rain event in Wy2004 was small, we suggest that the organic matter was primarily leaves and sticks falling off the trees directly above the stream rather than material being transported by overland flow.

In the future KREW staff will present data from all eight watersheds and track changes in the size distribution of the mineral fraction. Seventy sediment fences were constructed in 2003 and 2004 to quantify erosion from graveled roads, natural surface roads, and undisturbed hillslopes. Fourteen headcuts were surveyed in 2003 and will be resurveyed in the future. The combination of these efforts will give us a better understanding of where sediment originates and how it moves through the watershed.

## Conclusions

The KREW project has the instruments in place to continue with baseline data collection at eight streams and watersheds, four meteorological sites, and 70 sediment fence locations. At the Bull Site, spring snow melt supplies the majority of the discharge. At the Providence Site, baseflow is a significant contributor to the P304 hydrograph and rain water is important to the D102 hydrograph. Such knowledge allows us to adjust our sampling for other attributes such as stream chemistry and efficiently plan field visits based on response characteristics. Spring snow melt began several weeks earlier than usual in Wy2004 at all elevations; this is a trend that has been observed during the last 50 years in the southern Sierras and has been predicted to continue with climate change (Brown and Binkley 1994). The five sediment catchment basins constructed prior to Wy2004 showed that rates of soil loss vary greatly between watersheds but are all correlated to the peak discharge. We will have sediment data for the additional three streams starting with Wy2005.

Burning and thinning treatments are scheduled to occur between 2007 and 2009 with the Providence Site starting in 2007 and the Bull Site starting in 2008. By that time, KREW will have baseline datasets of sufficient duration and precision to discern whether there are measurable changes that result from these low-severity treatments. This watershed experiment is designed to improve our knowledge of how headwater ecosystems function, and to

*Table 1. The mass of mineral and organic fractions in annual stream sediment loads and the median particle size are reported with respect to peak discharge and storm intensity. During pretreatment years, organic matter is consistently between 20 and 30 percent of the total dry weight in the KREW sediment basins.*

| Water Year 2003 | P301 | P303 | P304 | D102 | B201 |
|---|---|---|---|---|---|
| Mineral mass / area (kg/ha) | 28.0 | 12.0 | 113.8 | 49.3 | 26.5 |
| Organic mass / area (kg/ha) | 13.3 | 3.4 | 24.6 | 16.0 | 5.0 |
| Median particle size (mm) | 0.500 | 0.500 | 0.125 | 0.250 | 0.250 |
| Peak discharge (L/s) | 110 | – | 120 | 170 | 100 |
| **Water Year 2004** | **P301** | **P303** | **P304** | **D102** | **B201** |
| Mineral mass / area (kg/ha) | 1.7 | 1.4 | 6.7 | 3.8 | 1.2 |
| Organic mass / area (kg/ha) | 0.6 | 0.4 | 7.5 | 1.6 | 0.5 |
| Median particle size (mm) | 0.500 | 0.500 | 0.125 | 0.250 | 0.125 |
| Peak discharge (L/s) | 80 | 85 | 44 | 113 | 22 |

| Averages for all Measured Watersheds | Bulk Mass *(kg/ha)* | Peak Discharge *(L/s)* | Largest Storm Event *(mm/hr)* | Most Intense Hour *(mm)* |
|---|---|---|---|---|
| WY 2002 | 0.3 | 33.0 | – | – |
| WY 2003 | 58.4 | 125.0 | 9.7 for 30 hours | 27.0 |
| WY 2004 | 5.1 | 68.8 | 2.3 for 60 hours | 11.0 |

support extensive modeling exercises for the watersheds both before and after treatments. Modeling will include soil erosion, stream discharge, nutrient fluxes, and air pollution and climate change effects. Eventually comparisons between treatments and responses can be made for KREW and other long-term, forest watershed experiments in the western United States. Such comparisons are important to identify differences and similarities among stream and watershed responses for different ecoregions, to increase our understanding of ecosystem processes and thus facilitate the customization of standards and guidelines for adaptive management.

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# Section 3. Watershed Protection and Restoration

## Part 1. Monitoring and Restoration

Overleaf:
Bond Falls, West Branch Ontonagon River, Ottawa National Forest, Upper Peninsula of Michigan. Photo by Gary Whelan, Michigan Department of Natural Resources, Fisheries Division.

# The Role of BMPs in 303(d)-Listed Waters: A New Alternative to TMDLs

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Total Maximum Daily Load Analyses (TMDLs) are being conducted nation-wide to address 303(d) listed waters. The TMDL strategy can be broken into two basic phases; first is the detailed calculation of a permissible load that will attain state water quality standards. Second is the creation and execution of a plan to achieve load reductions identified in phase 1. Currently, most states are focused on the first phase in order to meet court ordered deadlines. Implementation is usually deferred pending completion of the court's decree, which will make more resources available for phase 2. However, determining TMDL targets has proved problematic in wildland forest environments when applied to non-point source pollutants such as sediment, because discerning between anthropogenic and natural sediment is difficult, and because a reliable quantification of instream loads is complex. Natural sediment discharge is highly variable as a result of various watershed interactions driven by stochastic disturbance events (fire, drought, flood, wind, insects, disease, and others). The expense of data collection needed to reliably establish numeric targets can easily exceed the cost of simply fixing the obvious problems. July 2004 Environmental Protection Agency [EPA] guidance states that where an existing regulatory program, such as watershed restoration and implementation of Best Management Practices (BMPs), is expected to achieve water quality standards, a TMDL is not required (Category 4B) (USEPA 2004a). While the 4B option has been used very infrequently, the potential benefits of streamlining the TMDL regulatory process to focus on remediation instead of the dubious quantification of permissible loads is obvious.

Keywords: *total daily maximum load (TMDL); 303(d) listed waters; watershed restoration; best management practices (BMPs); Category 4B*

## Introduction

Under Section 303(d) of the Clean Water Act (CWA), states are required to identify waters where existing water quality does not meet state water quality standards. Most states have interpreted this direction and listed waters degraded by nonpoint sources without regard for whether any existing regulatory process is in place. All National Forest System (NFS) lands require the implementation of best management practices (BMPs) to identify and treat existing water quality problems and to prevent future ones (Forest Service Manual 2532.03). Currently, 18,318 NFS stream segments or 2,201 streams have been included on state lists of impaired waters, often with little or no quantitative information (EPA, unpublished 1998 data – as of October, 2004, this was the most recent complete compilation of 303 data). Generally, listing has not considered existing BMP and ongoing watershed restoration programs designed to achieve the same result. These lists of impaired waters are formally updated by the states every two years. Once on the list, the landowner must either show that the listing is in error or submit to the establishment of a Total Maximum Daily Load (TMDL) and eventually a restoration plan. Some within the various state water quality regulatory community feel that Forest Service programs are inadequately funded to achieve restoration in a timely manner. They may see the TMDL process as a lever that will result in accelerated restoration. In practice on NFS lands, just the opposite may occur, as fixed resource dollars are spent on needlessly complex TMDL assessments, leaving even less for the repair of often easily identified water quality problems.

Guidance issued by EPA in July 2004 pursuant to Sections 303(d) and 305(b) of the Clean Water Act for reporting assessment and listing of stream status (USEPA 2004a) contains information on the components of the required report for 2004. The states are required to place water bodies in one of five categories:

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Category 1: All designated uses are met;
Category 2: Some of the designated uses are met, but there is insufficient data to determine if remaining designated uses are met;
Category 3: Insufficient data to determine whether any designated uses are met;
Category 4: Water is impaired:
4A – a TMDL(s) has been completed,
**4B – existing control measures are expected to result in the attainment of water quality standards (WQS) in a reasonable period of time, a TMDL is not needed,** and
4C – waters are impaired entirely by something other than a pollutant.
Category 5: Water is impaired: a TMDL is needed.

As mentioned earlier, EPA's 1998 data lists 18,318 impaired segments on NFS lands. Often, multiple segments are located on a single stream, so the active number of listed streams is 2,201. The situation is particularly acute in Montana, which is reported to have nearly one half of all 303(d) listed segments in EPA's Region 8 (including North Dakota, South Dakota, Nebraska, Wyoming, Colorado and Utah [Personal communication, Julie DalSoglio, EPA Region 8, 8 June 2004]).

NFS streams have had a particularly high incidence of listing across the country, principally because they represent a very high percentage of monitored small streams, not necessarily because they represent poor water quality. Real problems exist on NFS lands, but the listing process in combination with ambiguous state standards for sediment and temperature have resulted in some very questionable results.

In Montana, each watershed with one or more Category 5 segments may require preparation of a TMDL. A TMDL is the calculation of the amount of pollutant that a waterbody can receive from point and nonpoint sources, plus natural background and a margin of safety, without exceeding water quality standards. In Montana, for example, the TMDL assessment process uses a watershed approach that may include multiple impaired segments. To reach a reasonable level of scientific credibility, the process has evolved into a complex study with many of the same data requirements as the six-step watershed assessment process currently employed in the USDA Forest Service (RIEC and IAC 1995). Costs for completing approved TMDLs in Montana have generally ranged between $150,000 and $300,000, and completion and approval can take more than two years (personal communication, Ron Steg, EPA R-8). These represent all state and federal costs to create the TMDL but do not include restoration and monitoring. Estimated federal costs are approximately $50,000 per TMDL, which represents the cost of collaboration with state agencies.

Point sources are derived from a specific location while nonpoint sources are derived from the general landscape rather than a discrete discharge point. The actual TMDL equation also includes provisions for a margin of safety and future human growth.

On NFS lands in the western United States, sediment, temperature, or both, are most commonly the pollutants of concern. In cooperation with the Montana Department of Environmental Quality (MDEQ) and EPA Region 8, personnel from national forests in Montana have contributed large amounts of time to assist the state in meeting a court-imposed schedule for TMDL completion [See 20 September 2000 Court Order in Friends of the Wild Swan, Inc. v. US EPA, No. CV-97-35-M-DWM (D. Mont.)]. In some cases Forest Service personnel have written the entire TMDL and in others they were active contributors to the process. Where available, both EPA and MDEQ have provided supplemental funding. The following forests are currently working with EPA and MDEQ on TMDL projects:

Helena National Forest
- Participant in the Blackfoot Headwaters TMDL

Kootenai National Forest
- Funded by EPA to complete the Yaak TMDL

Lolo National Forest
- Collaborator on Upper Lolo TMDLs
- Funded by MDEQ for the St. Regis TMDLs
- Team member and partially funded for Prospect Creek TMDL
- Participant in Bobtail Creek TMDL

Flathead National Forest
- Developed the Big Creek TMDL
- Funded by EPA to complete TMDLs for the Flathead Headwaters
- Participated in the Swan TMDL

Beaverhead National Forest
- Team member on the Ruby TMDL

Though these ten projects represent a large effort on the part of forest staff, a number of additional TMDLs will be written for NFS watersheds over the next five years.

## Evolution of the BMP Alternative

State and Congressional interest in pursuing opportunities for speeding up the TMDL process on national forests grew following a United States District Court ruling in Montana (Sierra Club Inc.; Alliance for the Wild Rockies v. Deborah Austin as Lolo National Forest Supervisor), which stated that a project involving timber harvest and watershed restoration could not continue until the TMDL was completed because, without knowing the maximum allowable load, there was no standard to judge impacts against. This decision was appealed to the 9th Circuit Court, and the TMDL portion of the case was eventually overturned. However, litigants have indicated continued interest in pursuing TMDL related issues, and since implementation and monitoring are still on the horizon for most TMDLs, future grist for litigation seems assured.

These events caused the Montana State TMDL Advisory Group (appointed by the state Governor) to request that MDEQ begin exploring alternative ways to speed the TMDL process. Montana's Senator Max Baucus became interested and assigned a Congressional Fellow to help resolve the issue. As a result, a meeting was held on 4 and 5 May 2004 with representatives from the Washington offices of EPA and the Forest Service, Senator Baucus's office, MDEQ, Montana State Lands, and the Northern Region (R1) of the Forest Service. Placing waters into EPA Category 4B was discussed as one alternative that could be useful in speeding the recovery of degraded waters.

Preliminary investigation of the 4B process and its possible benefits showed that there were theoretically widespread benefits. There were a number of 303(d) listed waterbodies on NFS lands that several members of the review team were familiar with, where it was highly likely that the cost of treating the pollutant sources using existing restoration BMPs would be significantly less than the cost of producing the TMDL. Bristow Creek on the Kootenai NF and Taylor Fork on the Gallatin NF were identified as initial test watersheds.

As a result, discussion and development of the Taylor Fork Category 4B report was begun. Identified restoration needs were funded and the majority of needed work was completed in the 2005 field season. The final Taylor Fork 4B report was submitted to Montana DEQ in August 2005. This effort could result in a significant breakthrough in the regulatory process, since it redefines the role of restoration, BMP application, and monitoring to significantly speed the recovery of degraded waters, though other priorities have slowed MDEQ's review and approval of the report.

## Category 4B as Described by EPA

The choice of whether to pursue Category 4B remains with the states and affected agency. Current regulations do not require TMDLs for all listed waters. When to establish TMDLs and when they are not appropriate is described by EPA guidance (USEPA 2004a). It states "....it best serves the purposes of the Act to require the State to establish TMDLs and submit them to EPA for approval only where such TMDLs are needed to 'bridge the gap' between existing effluent limitations, other pollution controls and water quality standards (WQS)." For waters with sufficient controls, EPA states "...establishing TMDLs would not contribute to accomplishing the goals of the Act and could draw resources from areas where there are water quality problems [50 FR 1775, 11 January 1985]. To use category 4B, the state must demonstrate that "other pollution control requirements (e.g., best management practices or needed restoration) required or agreed upon by local, state or federal authority" [see 40 CFR 130.7(b)(1)(iii)] are expected to address all water-pollutant combinations and attain all WQSs [water quality standards] in a reasonable period (USEPA 2004a)."

What does the Forest Service have to do to demonstrate that Category 4B applies to a given situation? Recent EPA guidance (USEPA 2004a) identifies the information necessary to support a determination that waters may be moved to Category 4B:

1. Identification of the controls to be relied upon: What are the problems and what BMPs or restoration will be prescribed?
2. A description of the authority under which the controls are required: Are BMPs required as a component of Forest Plans or other relevant National Environmental Policy Act [NEPA] documents?
3. Documentation that the controls are adequately stringent to result in attainment of applicable water quality standards within a reasonable period of time. In most cases this can be a straightforward literature review or practical examples of similar restoration applied to similar situations, however, more extensive modeling can also be done if warranted.
4. Assurances that the controls will be implemented. A watershed restoration plan with a line officer's signature and a proposed schedule, for example, will usually suffice.

The TMDL approach and BMP application have substantial overlap as well as important distinctions. However, the practical differences are few. First, the watershed restoration-BMP (4B) approach does not require the calculation of a TMDL. Second, the 4B approach requires the identification and repair of the problem immediately or within a reasonable timeframe. The TMDL approach defers restoration work until phase 2, and in many states, actual restoration is voluntary. Third, both approaches require monitoring sufficient to attainment of water quality standards. In either case, should monitoring show inadequate improvement, additional measures can be implemented. If standards are not achieved, the state retains the authority and option to require a TMDL.

Both the TMDL and 4B approaches demonstrate the need to assure that either the load reductions identified in the TMDL, or the watershed restoration and BMPs identified as 4B controls, are stringent enough to achieve water quality standards. According to EPA's guidance on development of sediment TMDLs (USEPA 1999), this "linkage" analysis can range from simple to complex. The more simple approaches mentioned in the guidance include linkage analyses based on empirical, index, or inference approaches. The more complex methods rely on mathematical or process models. The appropriate level of analysis depends upon several technical and practical factors such as the pollutant at issue, the hydraulic characteristics of the waterbody, the relevant temporal and spatial representation needs, the level of accuracy needed, and stakeholder interests. Ideally, the linkage analysis will be supported by monitoring data, allowing the analysis to associate waterbody responses with flow and loading conditions. When dealing with natural background loadings as well as wide fluctuations in pollutant loadings from nonpoint sources, the professional judgment of resource experts is often used to construct the linkage analysis. This approach relies on established principles as well as any new approaches documented in the literature relevant to the pollution situation in question. Where qualitative approaches to linkage are used, all assumptions, theories that provide the basis for linkage, expert and literature citations, and provisions for follow-up monitoring should be identified (USEPA 2004b).

The following steps would be taken after a waterbody is moved to category 4B:

1. Monitor the implementation of the restoration measures and BMPs to ensure they are completed and correctly put into practice.
2. Monitor the effectiveness of the restoration measures and BMPs towards achieving standards. This could include monitoring the effectiveness of the BMPs and restoration practices in meeting compliance with water quality standards, or through monitoring of appropriate surrogate measures such as upslope or in-channel measures. A statistically valid sub-sample or benchmark site could be used in the monitoring design. The Northern Region proposes adopting the R-1 Draft Aquatic Ecological Unit Inventory Technical Guide for physical channel measurements (tiered to PACFISH/INFISH Biological Opinion protocols, the aquatic conservation strategies for federal lands). These data can then be compared to other similar watersheds from the greater population of measured streams.
3. Based on monitoring results, either redesign or add new watershed restoration measures or BMPs where needed, or provide information on the need to modify the water quality standards target.

If monitoring shows that controls are not implemented or they are not effective (e.g., BMPs are not implemented fully, or the monitoring data shows no trend towards meeting standards), the control measures would be adjusted or redesigned where needed. If after modifying or adapting controls, progress towards water quality standards is not taking place, consideration will be given to re-instating the waterbody back into Category 5 of the state's Integrated Report. In some cases it may be determined that modification of the water quality standard or target is appropriate because local natural geologic or thermal conditions preclude ever reaching the established numeric criteria.

## Summary

TMDLs will only be developed for waters classified as "Category 5". Placing waters in Category 4B rather than conducting TMDL analysis may hold several advantages. First, Category 4B may prove more cost effective and result in more rapid restoration of water quality. Second, the approach may also reduce the threat of projects being litigated for not having TMDLs in place. To date, few if any agencies have attempted to place waters in Category 4B.

EPA and MDEQ are currently working with the Northern Region of the USDA Forest Service to develop a list of Category 4B waters on NFS lands. This approach could greatly speed the recovery of water quality and reduce costs by eliminating TMDL preparation by emphasizing thorough identification of restoration needs, conducting the restoration, and designing a pragmatic approach to monitoring. Managers are likely to also find this approach attractive since it is more efficient, fosters new partnerships, provides agencies more flexibility when administering multiple use responsibilities, and builds upon existing BMP and restoration programs.

The Gallatin National Forest Taylor Fork Category 4B report was formally submitted to Montana DEQ under a Regional Forester cover letter in August 2005. Due to other priorities, the state has not given an official response to the report. However, all essential restoration projects have now been completed, and it is anticipated that ongoing monitoring will demonstrate water quality standard attainment and the waterbody will be reclassified as Category 1 (all designated uses are met). As a result, there will no longer be a need for completion of a TMDL and the Taylor Fork 4B will become a tangible demonstration of the effectiveness of the Category 4B approach.

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# Best Management Practices (BMP) Implementation Monitoring: Keys to Success and Pitfalls to Avoid

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Implementation Monitoring determines whether Best Management Practices (BMP), mitigation measures, and standards and guidelines were applied to a project as planned. The Clean Water Act, Forest Plans, the National Environmental Policy Act (NEPA), and the Forest Service Soil and Water Conservation Handbook provide the legal framework and guidance for Implementation Monitoring. Since the early 1990s, BMPs have been an integral part of the NEPA process. NEPA decisions rely heavily on stated and implied assumptions of BMP implementation and their effectiveness in achieving the goals of state water quality standards. Implementation Monitoring tracks whether or not a given practice was successfully applied from project planning through completion, and when or where in the process implementation may have failed. Conclusions are carried directly into accountable actions, creating a feedback loop to improve procedures if necessary. An interdisciplinary monitoring approach fosters trust, respect and communication between specialists and project administrators. The feedback loop works best when an interdisciplinary team evaluates a project that they planned, and when local line officers convey tangible support for the process. At a minimum, participants should include watershed specialists and project administrators. It is not an accusatory process and must focus on maintaining meaningful feedback. Excessive focus on numeric ratings may sabotage the feedback loop. A database with querying capabilities aids efficient reporting of results. The implications of effectiveness monitoring results depend on whether the BMP was implemented successfully. Tracking BMP implementation, and subsequently effectiveness, is fundamental to our credibility as land and water stewards.

Keywords: *Best Management Practices, BMPs, water quality, watershed management, monitoring programs, interdisciplinary, hydrology/water*

## Introduction

The authors have spent a combined total of 18 years on the Tongass National Forest, Alaska, meeting the challenges of conducting reliable and repeatable Best Management Practices (BMP) Implementation Monitoring surveys. Our objective in giving an oral presentation at the San Diego meeting of 18-21 October 2004 was to share with others the keys to success that worked well for us, as well as defining pitfalls to avoid when developing or conducting a BMP Implementation Monitoring program.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

## Discussion

A Best Management Practice, or BMP, is defined by 40 CFR 130 as a practice, or combination of practices, that have been determined to be most effective and practicable in preventing or reducing the amount of pollution generated by diffuse sources to a level compatible with water quality goals. The Forest Service Handbook (FSH) 2509.22 defines BMP Implementation Monitoring as determining whether necessary BMPs were actually applied to an activity as planned. Put more simply and plainly, we can ask the question "Did we do what we said we would do?" Watershed specialists may be challenged, as we have been, to explain why BMP Implementation Monitoring is needed. Current direction and support for BMP Implementation Monitoring occurs at the national, regional, state, forest, and project levels, and includes:

- the Clean Water Act [As amended through P.L. 107-303, 27 November 2002]

- the National Forest Management Act [1976]
- National Environmental Policy Act [1970]
- the EPA Water Quality Standards Handbook [(EPA-823-B-94-005) August 1994]
- the USFS Soil and Water Conservation Handbook [FSH 2509.22, See *http://fsweb.r10.fs.fed.us/directives/fsh/2509.22/*]
- state Non-point Source Pollution Control Strategies or Programs, as developed by individual states
- Memoranda of Understanding (MOUs) between the USFS and states
- Forest Plans, Environmental Analysis (EAs), Environmental Impact Statements (EISs), and Cumulative Effects (CE) documents

How do we do we conduct BMP Implementation Monitoring in such a manner that we expedite getting the job done; document that we did it; and create and maintain the documentation that we implemented the BMP as we said we would? Based on our experiences in developing the Implementation Monitoring process on the Tongass National Forest, we suggest eight important steps:

1. Ensure that Line and Staff support is in place.
2. Incorporate interdisciplinary input into the monitoring process.
3. Field test data collection form(s) and review for database management and analysis requirements.
4. Present the process to Line and Staff Officers.
5. Revise process and forms if needed after management review.
6. Select database managers; design and develop database considering intended uses of data.
7. Randomly select project(s) for monitoring; do the pre-work (project documents); conduct monitoring in an interdisciplinary group setting.
8. Enter data queries as needed to generate monitoring report(s).

Staff and Line support is critical to ensuring that the Implementation Monitoring process is initiated and maintained. Their support may encourage reluctant participants to be involved more constructively. The design of land management activities should never occur without interdisciplinary input, and conducting BMP Implementation Monitoring is no different. Without interdisciplinary input, the "feedback loop," which allows all of us to change how we do business, would be compromised from the start of the monitoring process. Field-testing of data forms and databases helps users to figure out what formats will be most efficient, effective, and accurate for recording information, data entry, and querying.

As the BMP monitoring process and forms evolve, review the progress in BMP implementation that is being made with management. Ensure that management's data information needs are being met. If input is received from management, or from other resource representatives, it is important to be flexible and willing to revise the forms and process as needed. This will help ensure that the process is useful, functional, and applicable to a variety of information needs. Once the data forms have been finalized, it is important to take the time to make sure that the design of the database is well thought out. Database entry screens should be the same as the data entry forms, to maximize efficiency of data entry.

The random selection of monitoring sites ensures equal treatment of projects. A quick and easy way to do this is to consecutively number all units, then use a random numbers table for selections.

Random review of data entry printouts should be conducted once data is entered. We suggest printing out 10-20% of the data to review for input errors by comparing to the original data entry forms.

The BMP Implementation Monitoring process starts with tracing the incorporation of BMPs in various project planning documents, long before they are implemented on the ground. As resource concerns are identified, they should be incorporated into field notes, planning documents, and contracts, all of which are completed prior to project implementation. During Implementation Monitoring, these documents form the basis for tracking the development of BMP recommendations from planning to on-the-ground project implementation. Before evaluating how well a BMP has been implemented on the ground, tracking its incorporation into planning documents and contract records should be completed.

The following example shows how BMP language may occur in NEPA documents:

> "Best Management Practices (BMPs) - Section 313 of the Clean Water Act and Executive Order 12088 require that Best Management Practices (BMPs) that are consistent with State Forest Practices and other applicable State Water Quality Regulations be used to mitigate the impacts of land disturbing activities. Site-specific application of these BMPs are designed with consideration of geology, land type, hydrology, soil type, erosion hazard, climate, cumulative effects, and other factors in order to protect and maintain soil, water, and water related beneficial uses. All appropriate Best Management Practices will be followed in the layout and harvesting of the selected units (USDA Forest Service 2004)."

Another example shows a more specific incorporation of a BMP into this EIS:

"Road 46631 - Site Specific Design Criteria, Erosion Control: An erosion control plan for construction and maintenance will be developed by the contractor and approved by the Contracting Officer (BMP 14.5). All areas of organic or mineral soil exposed during construction shall be grass seeded and fertilized (BMP 12.17, 14.8 [Alaska Region FSH 2509.22, see *http://fsweb.r10.fs.fed.us/directives/fsh/2509.22*, accessed May 2006])."

After BMP recommendations are made in the EIS, the next step is to incorporate them into the appropriate contract. The following example shows how the BMP is referenced as part of a road construction contract. Without this step, some BMPs cannot be tracked from planning to the project on the ground.

"Road construction shall be performed in accordance with all contract provisions and specifications as established in clause B 5.211. All areas of organic or mineral soil exposed during construction shall be grass seeded and fertilized (BMP 14.8 E1). During road construction, minimize sediment input into streams. Excess and/or unsuitable material excavated during bridge/culvert construction shall not be placed on the slopes adjacent to the stream or in the stream channel (BMP 14.17)." (excerpt from Road Construction Contract 12-11-010-1545-12, Road 6420-5, Tongass National Forest)

At a minimum, watershed specialists and project administrators should be involved in the BMP monitoring process. They should confirm what is being successfully implemented as well as identify areas of concern. This includes developing action items that define what needs to be clarified, improved or developed, and identifying personnel who will be involved in resolving each action item. All of this should be accomplished while out in the field, including all relevant documentation, to ensure accurate communication of issues and to avoid surprises. Ensure that a cooperative feedback loop using the results of monitoring has been developed. This will help ensure that the information collected, and recommendations made, are actually used to improve future projects.

Collecting all the information that has been discussed above on a single-page form is a challenge. What is a good format to use? We suggest a form that documents the item(s) monitored, whether or not the BMP is applicable in that setting, to what degree implementation occurred, corrective actions needed as a result of a failure to implement a BMP correctly, and where in the process implementation failed (see Figure 1 for an example). A variety of forms are currently in use across the nation, and a standard format may be developed through the Washington Office.

A simple but effective visual demonstration of the importance of properly implemented BMPs can be seen by comparing the results of two culvert replacement projects shown in Figures 2a and 2b.

*Figure 1: Example of BMP Implementation Monitoring Form.*

| Item Monitored | Applies | BMP Rating[1] | Corrective Action Needed? | Departure Occurred[2] | Comments |
|---|---|---|---|---|---|
| BMP 12.7/14.5/14.8 Measures to minimize surface erosion<br>- Erosion Control Plan<br>- Measures to limit sediment transport; ditch dams, sediment basins, silt fences<br>- Seeding | yes | Not implemented | Clean ditches, culverts, and seed cut-slopes | Contract, Project Administration | |

[1] BMP rating (rate after unit closure): Y (3, 4, or 5) = BMP fully implemented; D (2 or 1) = Departure from full BMP implementation; n (0) = BMP not implemented. Note: higher number designates a higher degree of implementation).

[2] Departure occured during Site Evaluation (SE), Environmental Analysis (EA), Contract (CT), Layout (LO), or Administration (AD).

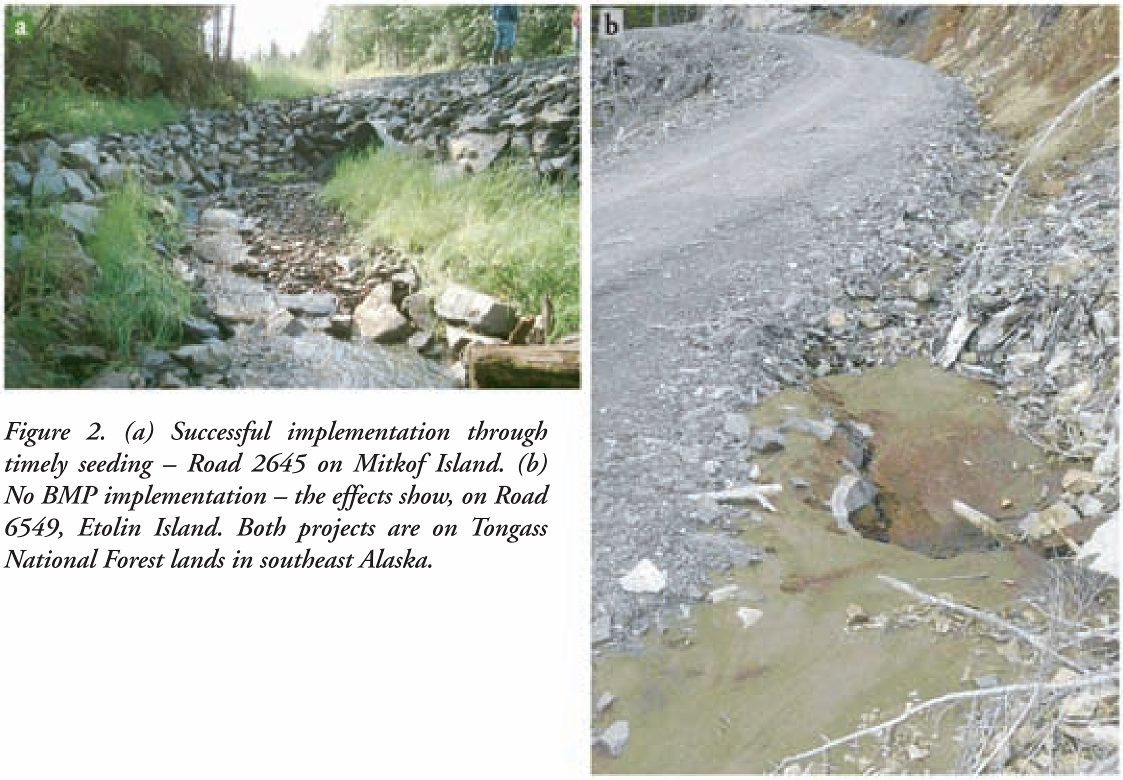


*Figure 2. (a) Successful implementation through timely seeding – Road 2645 on Mitkof Island. (b) No BMP implementation – the effects show, on Road 6549, Etolin Island. Both projects are on Tongass National Forest lands in southeast Alaska.*

The following quote illustrates the need for BMP clarification and lack of compatibility with existing road specifications, as defined by an interdisciplinary Implementation Monitoring team.

"Contract enforcement of erosion control is inadequate due to the disparity between BMPs and road construction specifications. The road construction contract did not incorporate enforceable time erosion control requirements for seeding…road segments are routinely accepted as final without seed and seed may not be applied until the following year (BMP Implementation Monitoring Report, Tongass NF [USDA Forest Service 1992])."

After defining an accountable action item, and those who need to be involved to define a solution, the next step is for those people to work together. In the Tongass NF example, the interdisciplinary monitoring team worked together to resolve a discrepancy between the erosion control BMP and road specifications. They developed the corrective on-site actions for seeding, evaluated and documented what went wrong in getting the seed applied, and revised the seeding specification to ensure that the BMP was enforceable.

Accountable action items and the "feedback loop" go hand in hand. A review of BMP implementation can find things that were done well, along with areas needing improvement. Accountable actions recognize both situations. Documenting where in the process implementation failed will help direct what type of outcome from the feedback loop is most needed to alleviate future problems. Outcomes could include commendations, BMP or contract revisions, training needs, increased communication, and specialist presence in the field.

In relation to the Tongass program, three elements were essential to developing and maintaining the process, which is still being used on the forest.

1. Engage managers.
2. Keep the process local and include project administrators.
3. Encourage and reward interdisciplinary co-operation, interaction, and innovation.

Involve district personnel in monitoring their own projects; they can tell the story of the project on the ground best as they often have helped develop and implement projects selected for monitoring. By involving both the specialists and the project managers, immediate feedback regarding BMP recommendations, design, and implementation is facilitated. Encouragement and reward go a long way toward fostering cooperation, improving trust and interaction, breaking down the perception of others being "territorial" about their disciplines, and fostering innovative ways to deal with resource concerns on the ground.

We identified four common pitfalls to avoid in implementation monitoring:

1. "Gotcha!" attitudes and surprises. Don't undertake monitoring with a mean-spirited, punitive, or fault-finding attitude.
2. Focusing on numeric ratings at the expense of meaningful feedback.
3. An excess of self-congratulation.
4. Waiting until you are back in the office to agree on major findings and needed actions – decide while you are still in the field.

The monitoring process is subjective; resist the temptation to "fight" for a particular rating or result (the Tongass NF uses a 1-5 scale). Strive for concise rating definitions. Make every effort to achieve objective evaluations of how well practices are implemented. Balancing the acknowledgement of good work versus identification of where improvement is needed can be tricky. Excessive praise could mean that there is something to hide.

Agree early and explicitly in the process that discussions will be respectful and focus on building credibility and trust. Talk about the problems, concerns, and the successes, while on the ground.

First and foremost, an established Implementation Monitoring program allows us to demonstrate our track record and verify our assertions that we are credible stewards of the land. With a feedback loop created as an integral part of the monitoring process, we ensure that issues are documented and accountable actions (solutions) are defined. This is essential not only to improving BMP implementation, but also to improving how BMPs are designed and written. A well-designed database provides the ability to query data efficiently and share information with other forest staff and the public. Interdisciplinary participation results in improved communication and trust, and therefore fewer "dropped balls" and crises to handle.

Another benefit of an established Implementation Monitoring process is that the stage is set for effectiveness monitoring. Effectiveness monitoring tells us how well the BMP worked, but its implications may differ depending on whether or not the BMP was fully implemented.

## Summary

There is substantial direction in place in federal and state regulations requiring BMP Implementation Monitoring. A well-established and repeatable implementation monitoring program sets the stage for effectiveness monitoring, and fosters interdisciplinary cooperation. Perhaps most importantly, BMP Implementation Monitoring is fundamental to our credibility as land and water stewards.

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USDA Forest Service. 2004. Three Mile timber harvest final Environmental Impact Statement. R10-MB-446b, Ketchikan, AK: Tongass National Forest.

# A Regional Protocol for Monitoring BMP Implementation and Effectiveness on Timber Harvest Operations


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The US Environmental Protection Agency (EPA) has cited a need for baseline monitoring information on forest harvesting to demonstrate compliance with the Clean Water Act and to respond to criticism of the silvicultural exemption. Historically, monitoring by state forestry agencies has been sporadic and anecdotal with little measurable evidence recorded. The Northeastern Area Association of State Foresters, Water Resources Committee initiated a project to develop and to test a standardized Best Management Practices (BMPs) protocol which provides the needed data for the 20-state Northeastern Area. A Phase 1 version of the protocol was developed in the fall and winter of 2001. Training and data collection occurred in nine states during the summers of 2001 and 2002, producing 97 samples and 21 quality control samples. Examples are provided to show the types of information that could be produced. However, they are not statistically sound because of the limited amount of data collected in each state. Beta testing is continuing through 2004 and 2005.



Keywords: *BMPs, Best Management Practices monitoring protocol, Northeastern Area*


## The Need for a Monitoring Protocol

The term Best Management Practice (BMP) was originally defined in the 1987 Clean Water Act (CWA) to refer to precautionary activities designed to protect water resources during timber harvests. Currently, timber harvesting activities are exempt from the permitting requirements of the CWA when BMPs are used to protect water resources. In response to litigation, the US Environmental Protection Agency (EPA) is required to show evidence that the requirements of the exemption are being implemented. As a result, the EPA has long sought a standard BMP monitoring protocol that would provide measurable data that are reliable and comparable among states.

In its Technical Bulletin #820 published in January 2001, the National Council for Air and Stream Improvement, Inc., stated: "Most States recognize the potential for water quality impairment from timber harvesting, especially soil erosion and sedimentation caused by roads and stream crossings. The States repeatedly report a serious lack of monitoring information, and generally fall back on widely accepted generalizations about the impact of timber harvesting on water quality (NCASI 2001)."

Beard et al. (1999) stated that there is a serious problem in environmental monitoring because of measurement inconsistency. Results are often criticized and open to various interpretations. The only way to assure reliable information is to gather it in a consistent and well-documented manner. Sources that influence data collection errors and the consistency of monitoring results include timing of the measurements, location, external environmental factors, and most notably, change in personnel. All of these factors must be considered in any BMP monitoring protocol to ensure consistency of data and compatibility for analysis.


Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Generally, state forestry agencies are in agreement that BMP monitoring should be implemented; however, barriers exist that hinder the states from having an effective monitoring program. Major hurdles have included costs, staff, time, variability of BMP practices among states, selection of practices to be monitored, activities monitored, and the method to be used to analyze the data.

## How This Protocol Differs

This monitoring protocol is designed to assess the effectiveness of BMP use with respect to water quality goals and further identify easily discernible benchmarks at which BMPs are considered acceptable for protecting water quality. It evaluates the use of BMP principles, not individual practices. The premise is that it does not matter ***which*** practice is used to slow and disperse waterflow, but that practices ***were*** used and were successful in meeting the desired goals, such as preventing erosion and sedimentation. The impact of sediment on water quality has been adequately researched elsewhere and is beyond the scope of this protocol. This monitoring protocol is not intended to replace instream or biological assessments, but to produce a consistent site evaluation of BMP use and effectiveness.

The BMP principle approach permits the evaluation of data from a variety of practices or a combination of practices across a region. BMP principle categories used in this protocol include planning the operation, controlling waterflow, stabilizing disturbed soil, controlling and disposing of chemical pollutants from machinery, and minimizing undesirable impacts on a water body, such as heat and slash. By usng BMP principles, individual states maintain control of their BMP practice specifications, thus meeting their needs while allowing for regional analysis of monitoring results.

Under this protocol, all data are collected based on standard measures of physical evidence. States determine the acceptability of the degree of water quality protection provided by BMPs based on their unique resource situations. The protocol monitors and measures what happens during and after a harvest, but the acceptability of the level of protection is determined by the individual States. For example, sediment levels acceptable in the Mississippi River may not be acceptable in Appalachian trout streams.

This method also fosters continuous improvement by allowing state forestry agencies and other educators to focus training efforts on identified problems or weaknesses in BMP implementation. Taken together, these characteristics add considerably to the credibility of BMP monitoring results.

## Protocol Components

***Data Dictionary.*** The BMP monitoring protocol consists of a series of questions with an array of answer choices, which functions much like a dichotomous key. The questions and related answer choices were programmed into a Trimble GEO 3 GPS unit[1], but have since been programmed into other data collecting units using Windows-based pocket PC software.

***Participants.*** During the pilot phase of this project, nine states and one industrial landowner were trained in the use of the protocol and the GPS data collection equipment. The participants included: New York City, Watershed Agricultural Council; state of New York, Department of Environmental Conservation; state of New Hampshire, Department of Resources and Economic Development, Division of Forests and Lands; state of Maine, Department of Conservation, Maine Forest Service; state of Maryland, Department of Natural Resources, Forest Service; state of West Virginia, Department of Commerce, Division of Forestry; Commonwealth of Pennsylvania, Department of Conservation and Natural Resources, Bureau of Forestry; state of Ohio, Department of Natural Resources, Division of Forestry; state of Indiana, Department of Natural Resources, Division of Forestry; and MeadeWestVaco, Maine.

## What is Monitored and Where?

The protocol focuses monitoring on the following logging, road construction, and road maintenance activities: At haul road water crossings; at skidder water crossings; at haul roads or landings within filter/buffer zones; within state-specified filter/buffer zones; and the slope distance outside the filter/buffer zone.

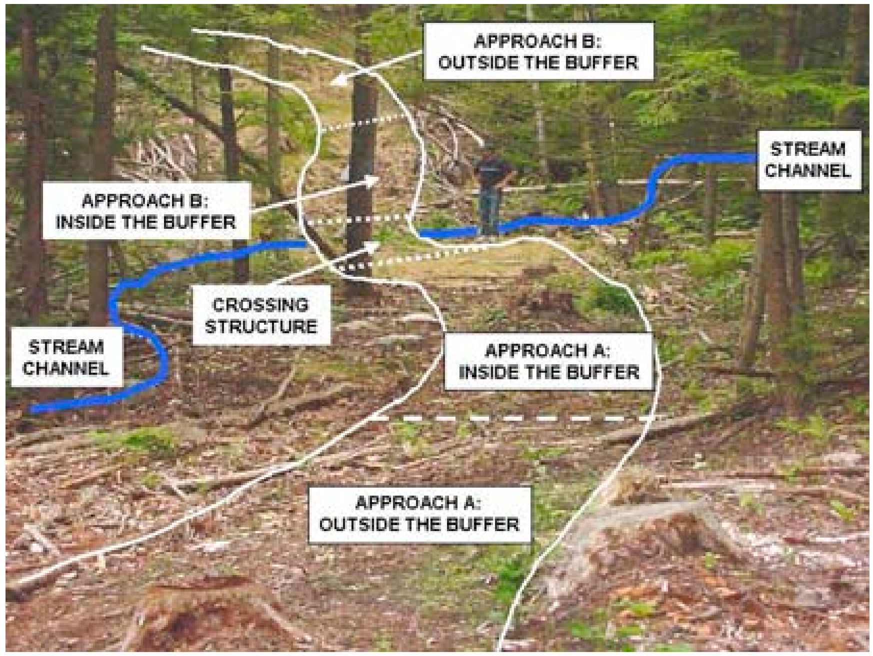
Monitoring activities within these focus areas will improve efficiency by focusing efforts in locations that typically have the highest potential to affect water quality.

***Focus Areas.*** The protocol is made up of a series of question sets relating to each of these focus areas (Figure 1). The outline of the protocol includes:

1. **General focus area.** This focus area gathers information on landowners, the timber sale contract, location and year logged, acres harvested, and other site information.
2. **Haul road water body crossing and attribute focus area**

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

*Figure 1. Protocol focus areas.*




Approaches "A" and "B", on either side of the stream
Inside and outside the buffer evaluation
Crossing structure evaluation (fords, bridges, and culverts)

3. **Skidder water body crossing and attribute focus area**
   Approaches "A" and "B", on either side of the stream
   Inside and outside the filter/buffer evaluation
   Crossing structure evaluation
4. **Filter/buffer focus area**
   Filter/buffer attributes
   Shade evaluation
   Woody debris recruitment potential
   Slash additions to water body evaluation
   Inside and outside the filter/buffer evaluation
5. **Chemical pollutants focus area.** Determines whether oil, gas, anti-freeze, brake fluid, battery lead, and other materials and containers were left at the site and if the products have the potential to reach surface water or groundwater.

***Sample Unit.*** A "sample unit" was defined to eliminate averaging the evaluations of multiple water crossings on large harvest sites.

A sample unit is a contiguous harvest unit that includes either a riparian zone or a water body crossing, or both (see Figure 2). It is bounded by any combination of water bodies and the boundary of the harvest area or a land ownership boundary. The sample unit starts when a water body is crossed or a riparian area entered. A new sample unit begins each time a water body is crossed and ends at the next water body, the edge of the harvest area, or the land ownership boundary, whichever is encountered first.

***Sampling.*** The first phase of the project was not intended to gather reliable data, but to test the protocol under a variety of site conditions throughout the Northeastern Area. Sampling was neither random nor unbiased. Each participating state chose ten sites to sample with the intent of testing the protocol on as many diverse sites and conditions as possible. The diversity of sample units was based on soils, topography, geography, or other characteristics that were identified as important to the individual state or company.

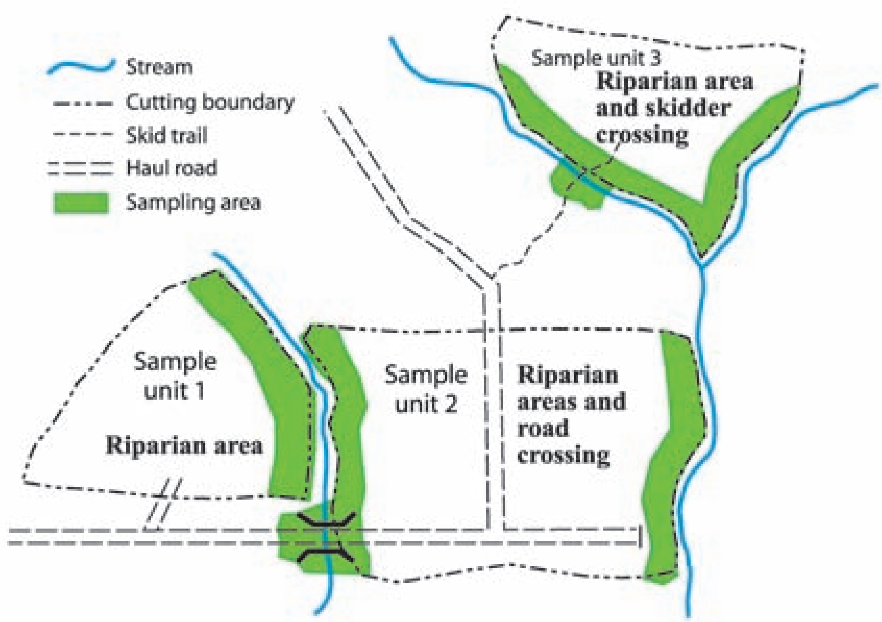
Different monitoring teams revisited three of the ten sites in each state to conduct a blind quality control sample. The returning monitoring team had access to only the general information section of the initial sample data in order to locate the sample unit. The quality control sample was used to determine which questions were producing consistent results and which questions needed to be clarified. The goal was to strive for a repeatable process, which returns consistent evaluations by different individuals.

## Electronically Managing Data

***Purpose.*** The protocol is intended to be used to collect field data across a wide geographic area and simplify data entry.

***Equipment.*** The question sets were programmed into Trimble GEO 3 GPS units using Pathfinder Office Software version 2.90. Revised question sets have since been programmed to run on several types of data collecting

*Figure 2. Sample Units.*




equipment using Microsoft WindowsTM pocket PC software.

***Collecting Data.*** Data were collected during the 2001 and 2002 field seasons. All GPS locations were collected based on the World Geodetic System (WGS) 84 datum and sent to the Maine Forest Service for analysis.

***Processing Data.*** The participants sent data files to the Maine Forest Service by e-mail or CD-ROM. Data processing was a little more time consuming than anticipated because of entry errors. However, this resulted in greater use of drop-down lists in subsequent versions of the protocol, streamlining the process and eliminating most recording errors.

Data from individual states were combined in ESRI ArcInfo and exported to Microsoft Excel for data comparison.

## Reporting Results Using the Pilot Project Data

***Note:*** *The data were collected in 2001 and 2002 to test the monitoring protocol and analyzed to demonstrate how the results could be illustrated. Therefore, these data are not a statistically meaningful representation of conditions on the ground, but simply a test of the procedure and examples of possible data outputs.*

Ninety-one sample units were observed. Of these, 79 were water crossings involving a culvert, bridge, or ford; 37 were haul road crossings; and 46 skidder crossings. Results of the data collecting can be grouped into six BMP categories (Figure 3).

In summary, the results show that:

- Sediment was not discharged on 25 of the 91 sample units.
- Fish passage was not blocked at 66 of the 79 water crossings.
- Stream channels were unaltered at 73 of the 79 water crossings.
- Plastic containers or chemical spills (Hazmat) were not found on 84 of the 91 sample units.
- Slash from the current harvest operation was not added into stream channels on 22 of the 41 riparian areas observed.
- There was less than 40 percent shade reduction on 7,356 m (24,135 ft) of the 9,808 m (32,180 ft) of surveyed filter/buffer strips.

The BMP implementation and effectiveness monitoring results (Figure 4) are based on 395 total observations in 91 sample units during the initial protocol testing in 2001. An "observation" should not be confused with a "sample unit." While conducting monitoring within a sample unit, many observations are made in Approaches A and B, inside and outside the filter/buffer, and at the crossing itself. Specific examples of results include:

- Soil was stabilized and waterflow was effectively controlled 80 percent of the time when BMPs were adequately implemented.
- The first three bars represent 198 observations that recorded no soil movement, i.e., those observations were stable. However, the remaining 197 observations indicate that there was either soil movement or a sediment discharge into a water body. For example, there was soil movement 26 percent of the time and discharge 40 percent of the time when BMPs were not applied (4th bar set).
- Although BMPs were applied, they failed to prevent soil movement 19 percent of the time.

*Figure 3. Overview of BMP categories by "sample unit".*

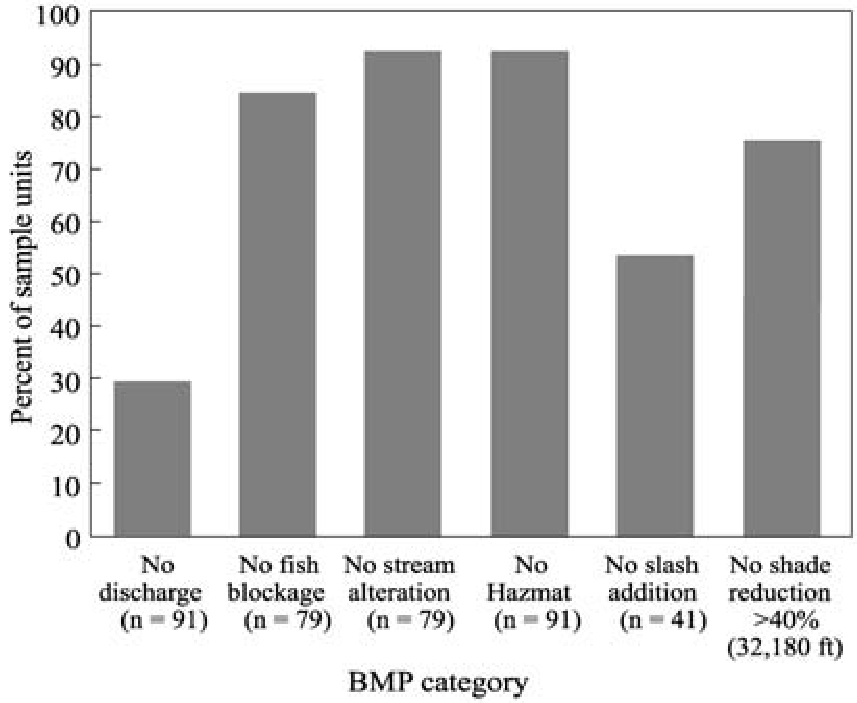
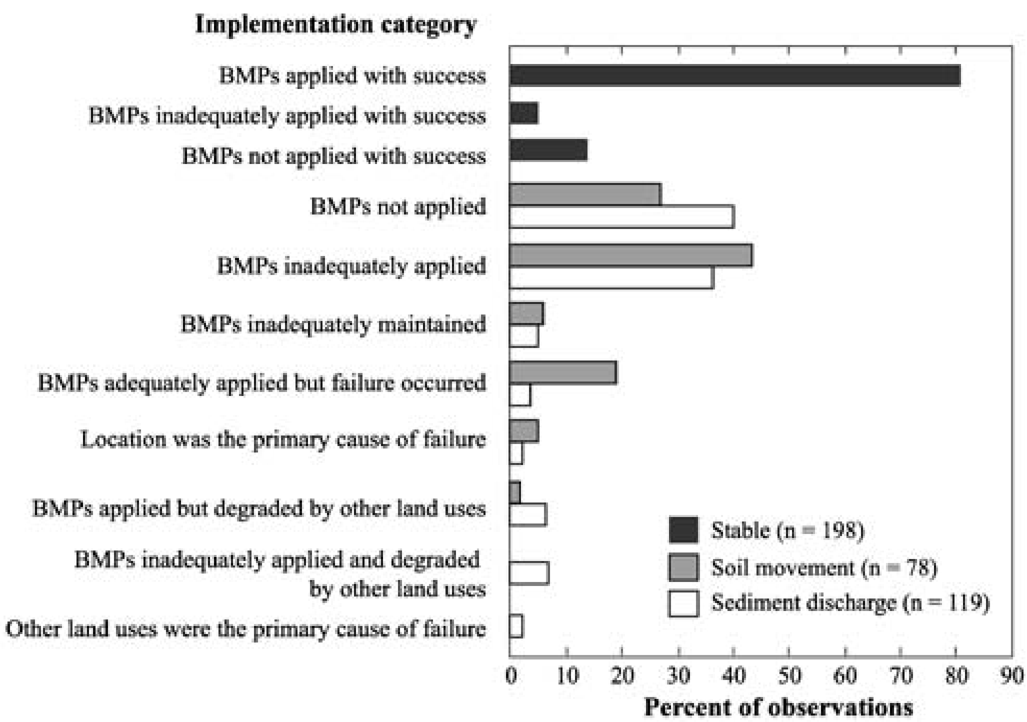



*Figure 4. BMP implementation and effectiveness for soil stabilization and waterflow control based on BMP practice functionality.*




- BMPs rarely failed due to impacts of other land uses (OLU).

***Haul road crossings.*** Data can be assessed by sediment delivery mechanism and primary cause of sediment discharge at haul road crossings. There were 37 sample units with haul road crossings. Sediment discharges resulted from sheet flow, soil slumping, and soil dropping into the water body at 20 locations (Figure 5). The second highest discharge category was direct ditches at seven of the locations.

For haul road crossings (Figure 6), the road structure or design was the primary cause of soil discharges (38 percent of discharges). Instability of the crossing structure (22 percent) and maintenance of the crossing structure (16 percent) were also noticeable contributors to soil discharges from haul road crossings.

Data input is done in the field using a variety of recording devices that use Windows software for portable PCs. Once

*Figure 5. Haul road discharges by discharge category.*

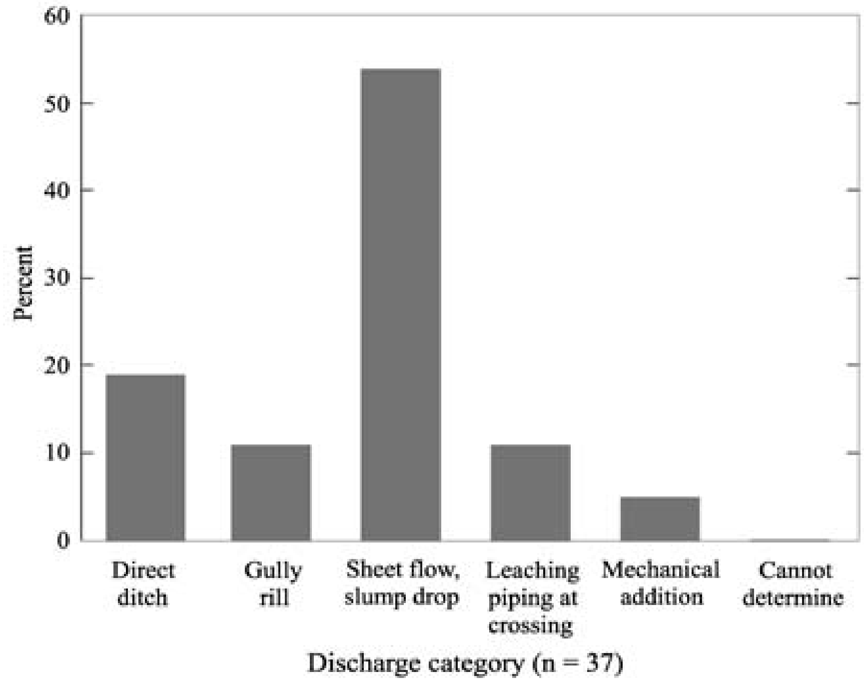
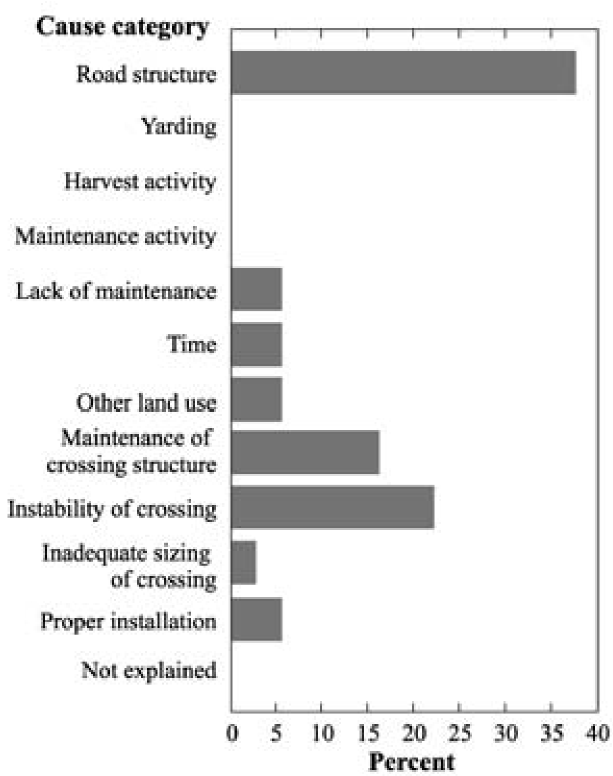



*Figure 6. Haul road discharges by cause.*




data are collected, the files are uploaded to a desktop computer and automatically combined with previous files in a Microsoft Excel spreadsheet. No additional office work is needed, which reduces error and saves time.

A standard data summary generator creates the types of data, which has been discussed above. Further refinement of the data will be possible with additional queries.

The results of the data can be used to focus training on improving BMP design specifications or installation and implementation errors. Specific examples include: Adjusting riparian buffer widths; using crossing structures with larger openings and open bottoms; and improving maintenance of roads and crossing structures.

## Conclusions and Recommendations

The approach to BMP monitoring using this BMP protocol appears to account for most of the topographic, soil, and geographic differences in the test area. Evaluation of BMPs based on their principles and desired function is a key component that allows the development of a standard BMP monitoring protocol which is workable across broad geographic and political variables.

An analysis was done comparing sample units with their quality control samples to determine how well different individuals independently evaluated the same site. We found that, for any given question, the participants usually came up with the same answer for the quality control sample as in the original sample. The goal was to attain a 90 percent match on most questions. The data show we fell short of our goal; however, based on comments during the training and suggestions after data collection, it appears that most of the improvements needed to obtain a 90 percent match can be accomplished by editing the text of some of the questions and answers. The other improvements regarding consistency among observers will come from training and added experience as the protocol is used.

There was a need to edit the protocol questions as well as to reduce and combine specific questions and answers. Improvements to user friendliness were accomplished by automating the movement to subsequent questions based on the selected answer.

Since the data were collected electronically in a compatible database format, there was no data entry other than the initial electronic entry in the field. This greatly reduces costs of data entry, reduces errors, and allows the data to be transferred easily by e-mail and entered directly into the main database.

Data collection with the Trimble GPS unit was successful overall during the 2001 and 2002 field seasons. It is our goal to reduce costs, increase user friendliness, and keep the amount of data entry required at the office to a minimum. At the suggestion of participants, the protocol has been adapted to more economical and user-friendly Pocket PCs, Palm Pilots, and other hand-held equipment.

Based on the data and participant comments, this project has moved to the next phase, which expanded the use of an edited version of the current protocol. Beta testing with new equipment and an updated version of the protocol was conducted during the 2004 and 2005 field seasons.

Once the data are analyzed, it is our hope that the participants and additional states will accept the standardized protocol to facilitate the gathering and assessment of data over the Northeastern Area. We will continue to assist states in the development of an effective BMP monitoring program and encourage states to conduct their monitoring using the protocol. States will be able to develop their own sampling design, generate automated reports, and maintain a database. The data should be of immeasurable value in improving BMP effectiveness and verifying enforcement of the CWA.

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# Monitoring Exposed! WARM:
# A Database Tool to Share and Query Watershed Resources Monitoring Information

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Forest specialists and managers often lack access to monitoring information collected within unit boundaries and across administrative units. The inability to effectively use existing monitoring results has led to repeated National Environmental Policy Act (NEPA) challenges, inefficient and ineffective best management practices (BMP) application, and poor feedback for the adaptive management process. The objective of the Watershed Resources Monitoring (WARM) database is to create an electronic repository for easy storage and retrieval of various monitoring information reports relevant to individual and multiple forests. Although originally developed to address monitoring information needs in the Intermountain Region (USDA Forest Service Region 4), the application is available to all national forests. The system was initially developed as a module within the Lotus Domino[1] database application for Wildlife, Fish, and Rare Plants (WFRP) reporting. Now a separate module, WARM houses reports generally referred to as "gray literature," including those produced by forest staff or partners and that do not appear in any other professional journal, book, or other library-available publication. This Forest Service Intranet-based tool allows users to locate actual monitoring information collected and documented within specific watersheds, across individual forests, or about specific management or conservation practices. Examples of database content and utility are illustrated, including an explanation of how information queried from the National Resource Information System (NRIS) and Infra[2] can be used and linked. Future module development may include creating an interactive map for querying and expanding support of the system and tools.

Keywords: *watershed, monitoring, data and information management*

## Introduction

Hydrology program managers in the USDA Forest Service Intermountain Region identified the need for a better way to share monitoring information among units. They acknowledged that our inability to effectively utilize existing monitoring results has lead to repeated National Environmental Policy Act (NEPA) challenges, inefficient and ineffective best management practices (BMP) application, and poor feedback for the adaptive management process. These deficiencies have prompted federal agencies to propose a new regulation that compounds and exacerbates the difficulties of project planning and implementation for various watershed activities.

In response to this need, Intermountain Regional Office staff collaborated with the Stream Team, Pacific Northwest Region and Pacific Northwest Research Station, and the Natural Resource Information System (NRIS) Water and Tools teams to prepare a project proposal for developing a tool to share monitoring information. The objective was to create a Forest Service Intranet-based system that allows users to easily store and retrieve various types of watershed resources monitoring information relevant to one or more districts, forests, or regions. The Watershed Resources Monitoring (WARM) database is the result of this effort.

## Watershed Resources Monitoring (WARM) Database

### What It Is and Isn't

The WARM database was built as a module of the Wildlife, Fish, & Rare Plants (WFRP) intranet reporting system. Using the front end development and

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.
[2] USDA Forest Service's Infrastructure information database

structure of the WFRP system leveraged the funding to offer users customized features including look-up tables, partnership documentation, a photo database, and querying capabilities. Another advantage of building on the WFRP system is that the platform made the module available to all National Forest System, units rather than only to those in the Intermountain Region.

The WARM module has recently been separated from WFRP, creating a stand-alone system. The intranet-based tool allows users to enter and edit monitoring reports and query the system for information collected within specific watersheds, across individual districts or forests, or related to specific management or conservation practices.

### Concept

The vision for the WARM database is that it will serve as corporate memory for monitoring information. Although there are several corporate databases in use, all of them deal with primary or factual data. These data are generally not useful to managers until they have been interpreted through some analysis process to extract meaningful assessments about a site or project. This interpreted information can now be stored in the WARM database so that authors, peers, managers, and other forest specialists have access to this assessment or monitoring information. Therefore, the WARM database bridges the gap to store interpreted information in one database that is currently not housed in other existing corporate databases (Figure 1).

### Database Features

The modular design of the WARM data entry features allows users to create new reports at any level of detail desired, from a single site evaluation to an annual forest monitoring report. There are some mandatory fields that establish a basic record, while all others are optional. The structured fields each include a description accessible by clicking on the term.

***Entering or Editing Reports.*** Users can create and store new or previously written reports. New reports can be generated on the spot by filling in the fields. This option is valuable for single event monitoring and brief monitoring reports. Existing reports can be stored by cutting and pasting text into the mandatory and summary fields, and creating a link to the full report (for this to work, the document must be link-accessible at least through the Forest Service Intranet). This option is best for very large or detailed reports and older ones that have good information but may take too long to enter. The linking capability reduces data entry redundancy and allows authors to reference other relevant documents, photos, or websites. By linking a photo directly into the system, it is captured as a corporate photo and is accessible by any other user through a browser tool.

All reports entered in the system are finalized (closed) upon the author's certification though an electronic signature. This step allows the author to enter information in multiple sessions, and allows others to review and provide feedback prior to indicating that the report is final. Appendix 1 depicts examples of the data entry and editing screens. The data fields supported by WARM are listed in Appendix 2.

***Querying and Reports.*** WARM accommodates two forms of querying and includes a standard report. Report records can be queried to find a specific, individual report, or to find sets of reports that meet the searcher's criteria. The report query enables the user to locate a specific report by entering the geographic area of interest and selecting a report from the list generated. This option is useful if the user knows the exact report wanted. For broader searches, the query tool allows the user to search based on location (district, forest, region, state), author, topic or keyword, hydrologic unit code, and primary/secondary lithology, as shown in Appendix 3. The query tool then returns a list of reports that can be copied and pasted into the text of an email and forwarded to others for viewing. This query tool option is more versatile than report query because users can search for multiple reports meeting a set of criteria.

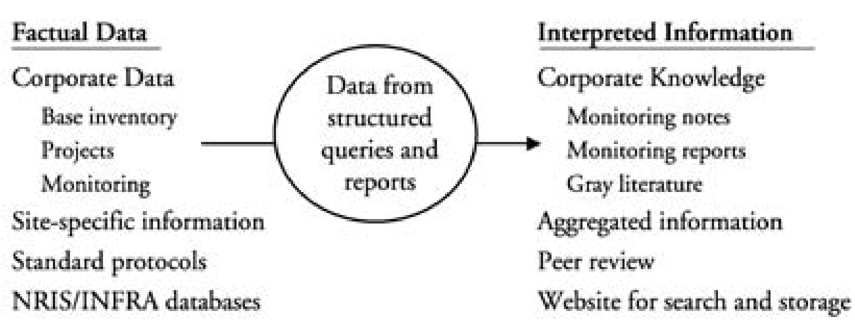



*Figure 1. Concept for how factual data is transformed to interpreted data for storage in the Watershed Resources Monitoring (WARM) database.*

One standard report form exists for all data entered, to maintain a consistent format across entries. Completed reports can be submitted to supervisors or partners to demonstrate accomplishments. An example report is shown in Appendix 4.

## Expected Benefits of Using the WARM Database

Several benefits of using the WARM database, as identified by USDA Forest Service program managers, include improving documentation, corporate memory, and information sharing. First, by querying for information relevant to a local project, National Environmental Policy Act (NEPA) documentation is expected to improve as specialists use applicable monitoring to document rational thought processes and support best professional judgment. Second, as watershed specialists move in and out of different positions, information stored within the WARM database will serve as the corporate memory for monitoring results and will facilitate efficient adaptive management processes. Third, monitoring information will be easily shared, since any employee using a Forest Service computer will have access to all completed monitoring reports. Access to such information is expected to improve understanding of management activity effects and allow specialists to better integrate monitoring activities across forest boundaries, improving efficiencies.

## Future Database Improvements

Since the WARM database is a new application, there may be opportunities to improve features, templates, look-up tables, and reports. The initial vision for the database included a mapping tool that would allow users to query for reports using an interactive map and based on hydrologic unit code, latitude and longitude, or UTM coordinates. As map querying tools continue to develop, this feature would be a desirable addition. The existing query tool could be edited to add or delete specific fields or to use look-up ranges. Existing look-up fields may contain only cursory choices, so the parent tables can be easily edited by a regional administrator. The site could also be expanded to share templates, examples, technical guides, and other databases as appropriate. Most possibilities for changes and improvements are limited only by funding availability and regional administrator approval.

## Accessing the WARM Site

Report viewing is open to all Forest Service computer network users, with data entry and editing privileges granted as determined by the regional office or forest. Authorized network users can enter the database using their internet name and password at the following URL: *http://wodata01.fs.fed.us/fsfiles/unit/wo/wfrp/wrproject.nsf*

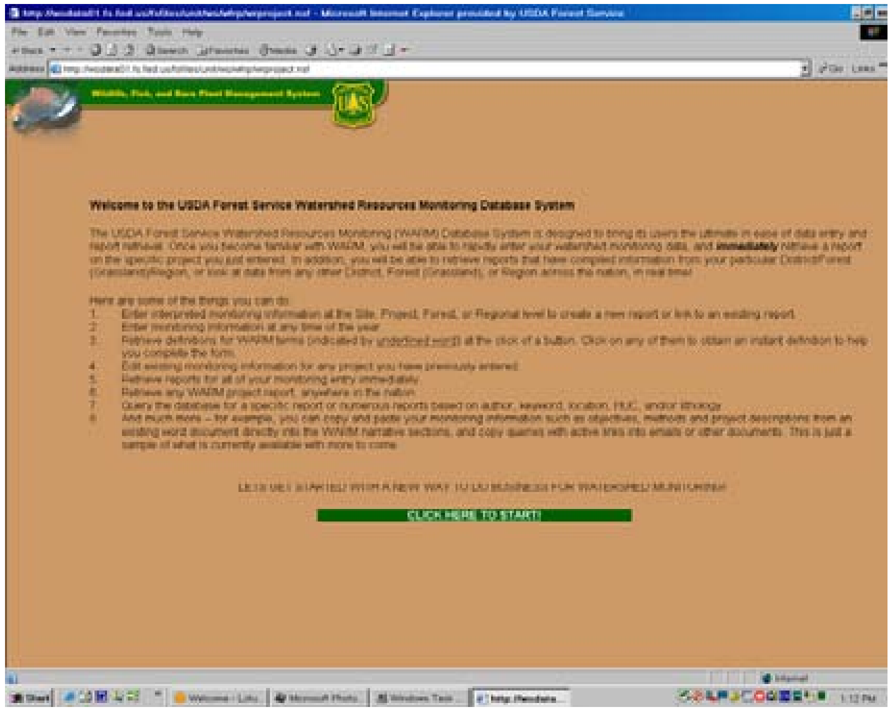
Additional instructions are available from the Intermountain Region FSWeb site, which includes how to obtain an internet password, a Microsoft PowerPoint™ slide show illustrating the features of the database, and the full documentation about the fields and look-up tables. The URL for the site is: *http://fsweb.r4.fs.fed.us/unit/bpr/watershed/fsweb/databases/databases.htm*.

## Summary

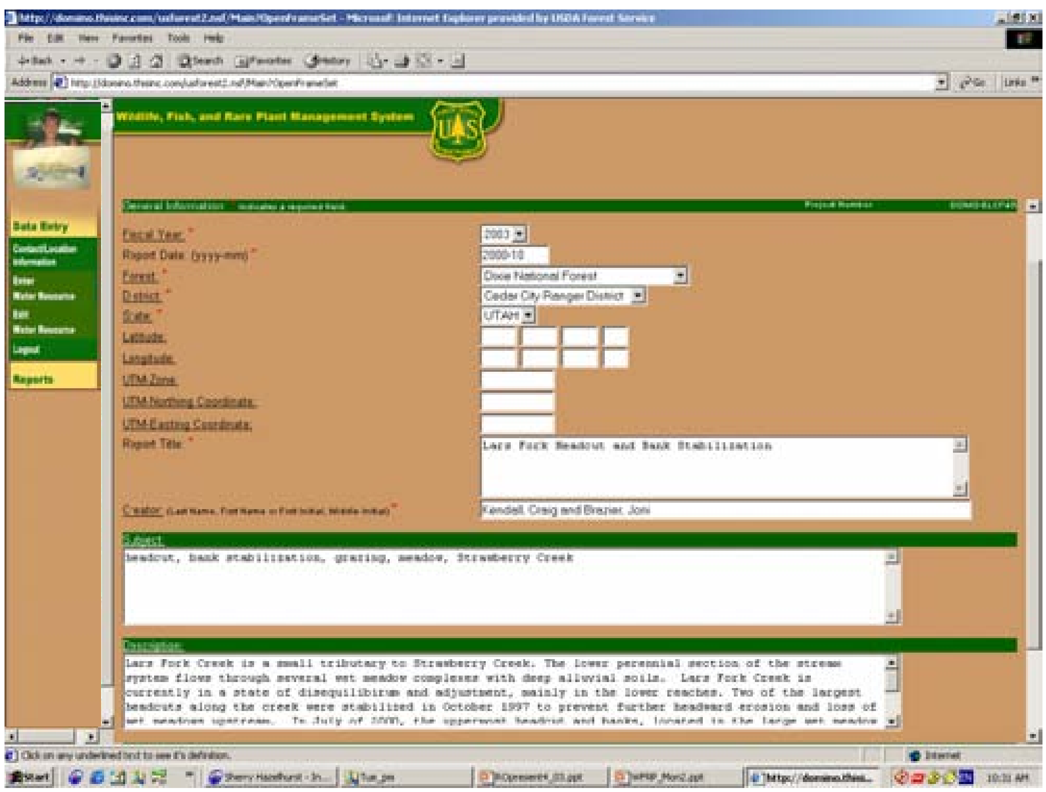
The WARM database provides a powerful tool for compiling, editing, storing, querying, and most importantly, sharing monitoring reports among Forest Service watershed specialists. If developed to its full potential, it may greatly assist in the assessment, monitoring, restoration, and management of watersheds on National Forest System lands.

*Appendix 1. Examples of Watershed Resources Monitoring data entry and edit screens.*

The initial sign-in screen will ask for your internet name and password. Once you have gained access, the following screen will appear:



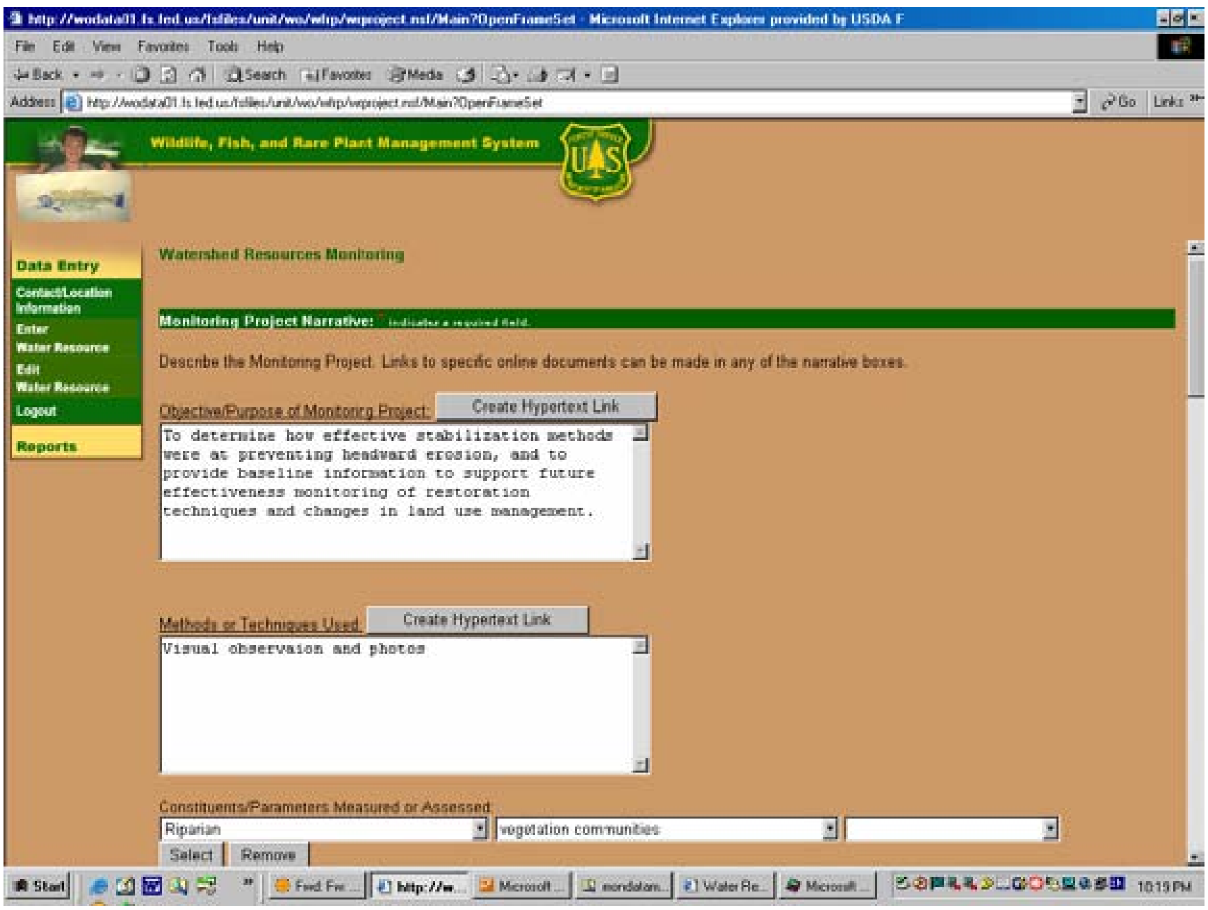

The first data entry/edit screen includes most of the header information common to most documents.



The monitoring extent and purpose screens allow multiple entries for each, with a purpose identified for each extent:



The first data entry/edit screen includes most of the header information common to most documents.



*Appendix 2. Watershed Resources Monitoring database documentation.*

## Watershed Resources Monitoring Database Documentation

### Objective

The objective of this database is to provide users a system for easily storing and retrieving various types of watershed resources monitoring information relevant to individual and multiple forests.
This intranet-based website allows users to locate actual monitoring information collected within specific watersheds, across individual forests, or about specific management or conservation practices.

### Data Entry Screens and Fields (Screen titles indicated by gray, shaded lines)

**General Information:**

**Fiscal Year:** Required

**Report Date:** Required (Format yyyy-mm)

**Region:** Required (automatically populated from your initial log-in information)

**Forest:** Required (may be automatically populated from your initial log-in information)

**District:** Required (may be automatically populated from your initial log-in information)

**State:** Required (may be automatically populated from your initial log-in information)

**Location Coordinates:** Latitude/Longitude may be entered in degree/minutes/seconds or decimal degrees (make selection). UTM coordinates may also be used to record location: enter Zone, Northing coordinate, and Easting coordinate for a complete record.

**Report Title:** Required

**Creator:** Required (Format: Last Name, First Name or First Initial, Middle Initial)
The person(s) or organization(s) responsible for making the content of the report.

**Subject:** Keywords, key phrases, or classification codes that describe the topic of the report.

**Description:** An account of the content of the resource, which may include an abstract, table of contents, reference to a graphical representation, or free-text account of the content.

**Partnership or Non-Partnership Project:** (Select one)

**Identify Partners:**

Partners may be selected from an existing list. An extensive partner list exists; however, if a new partners needs to be added, contact your regional administrator.

**Identify Monitoring Extent:**

Select one, or more than one, monitoring extent assessed. (Required)

- **Site:** photo point, reach, station, plot
- **Project:** e.g. restoration, road obliteration, road maintenance/upgrade, range, recreation, prescribed fire, wildfire, vegetation management, wildlife, multiple projects
- **Forest:** e.g. forest plan, cumulative effects, species viability
- **Region:** e.g. regional plan, cumulative effects, species viability

**For each selection above, Identify Purpose:**

**Identify Monitoring Purpose:**

Select one, or more than one, purpose for conducting the monitoring. (Required)

- **Baseline:** To characterize single or multiple constituents or parameters at a specific point in time.
- **Reference:** To characterize constituents or parameters over a period of time to serve as a basis for comparison.
- **Condition/Trend:** To determine changes in single or multiple constituents or parameters over a specified period of time, generally greater than 10 years.
- **Implementation:** To determine if the measure, practice, project, or plan was put in place as recommended/required.
- **Effectiveness:** To determine if the measure, practice, project, or plan accomplished intended/specified goals.
- **Validation:** To determine if assumptions made were correct.
- **Hypothesis Testing:** To test an unproven theory.

**Monitoring Project Narrative:**

Describe the Monitoring Project: Links to specific online documents can be made in any of the narrative boxes.

*Note: to avoid retyping text you have already written, you can simply copy text from an existing Microsoft Word document and paste it in many of these data entry fields.

**Objective/Purpose of Monitoring Project:** Clearly state your monitoring project objectives or purpose. A few sentences are all that is necessary. Number them if you like.

**Methods or Techniques Used:** State methods, protocols, or techniques you used to accomplish the monitoring project.

**Constituents/Parameters Measured or Assessed:** This is a three-level list of parameters from which you may select up to any 15. Selections can be made at any of the levels depending on the need to specify. To add parameters, please contact your regional administrator. The following headings are the first level from which the individual parameters are grouped:

Air Quality
Best Management Practices
Climate/Precipitation
Fisheries Habitat
Riparian
Soils
Species (communities, population, individuals)
Stream Channel Morphology
Water Quality/Quantity
Wetlands

**Monitoring/Sampling Frequency:** Select one item as listed from the following lookup terms: continuously, two or more times a day, daily, weekly, monthly, annually, seasonally, after storms, biennially or greater, randomly, other.

**Monitoring Duration:** Select one item listed from the following lookup terms: one time, one season, 2-3 seasons, one year, 2-5 years, 5 or more years.

**Primary Lithology:** Terrestrial Ecological Unit Inventory (TEUI) label most closely corresponding to one of the following: igneous extrusive, igneous intrusive, sedimentary, metamorphic, undifferentiated, unconsolidated, unknown

**Secondary Lithology:** Terrestrial Ecological Unit Inventory (TEUI) label most closely corresponding to one of over 400 types listed, e.g. Actinolite-Epidote Marble to Wyomingite.

**Land Type Association (LTA):** Description: Terrestrial Ecological Unit Inventory (TEUI) label corresponding to the landscape scale description.

**Hydrologic Unit Code(s):** The hydrologic unit(s) in which the monitoring was conducted. At least a 3rd-level HUC should be listed, and at least one HUC is mandatory. HUC levels 1-6 should correspond to USGS data standards. HUC levels 7-9 may be forest assigned, as no data standards exist for these levels.

**Results Summary:** State your results here.

**Report Peer-Review Status:** Reports may or may not be reviewed, depending on many factors including the resource(s) being addressed, issues, importance, uniqueness of data, monitoring plan, analysis rigor, etc. None = no peer-review. Local Review = at least one specialist at the district or forest has reviewed report for content, analysis, and accuracy. Broad Review = review from both a forest specialist and at least one other source, e.g., another forest, regional office, Washington Office, university, research group, or other credible scientist.

**Contact Name/Phone/Email:** List the name and contact information for the creator or data steward for this report.

**Links to Full Report and/or other information:** Internet or Intranet Web addresses with associated documents, maps, graphics, or presentations e.g. monitoring plan, forest plan, environmental analysis, ecosystem assessment, biological analysis, hydrologic condition assessment, total maximum daily load analysis or implementation plan, GIS map, Powerpoint presentation. Attachments should be in commonly accessible formats, e.g., Microsoft application files, HTML, PDF, MIME.

**Add Graphic Attachments:**

1. Select the file to attach (if separate from a previously linked report):
2. Enter an optional caption for the graphic (limit 50 characters):
3. Attach graphic to form:

Graphics may be attached elsewhere via links. However, those attached here will be printed in the report. Those linked will need to be accessed through the link. Graphics can also be retrieved from the master file by browsing with new captions added for your project. Graphics previously added may be deleted in the editing process.

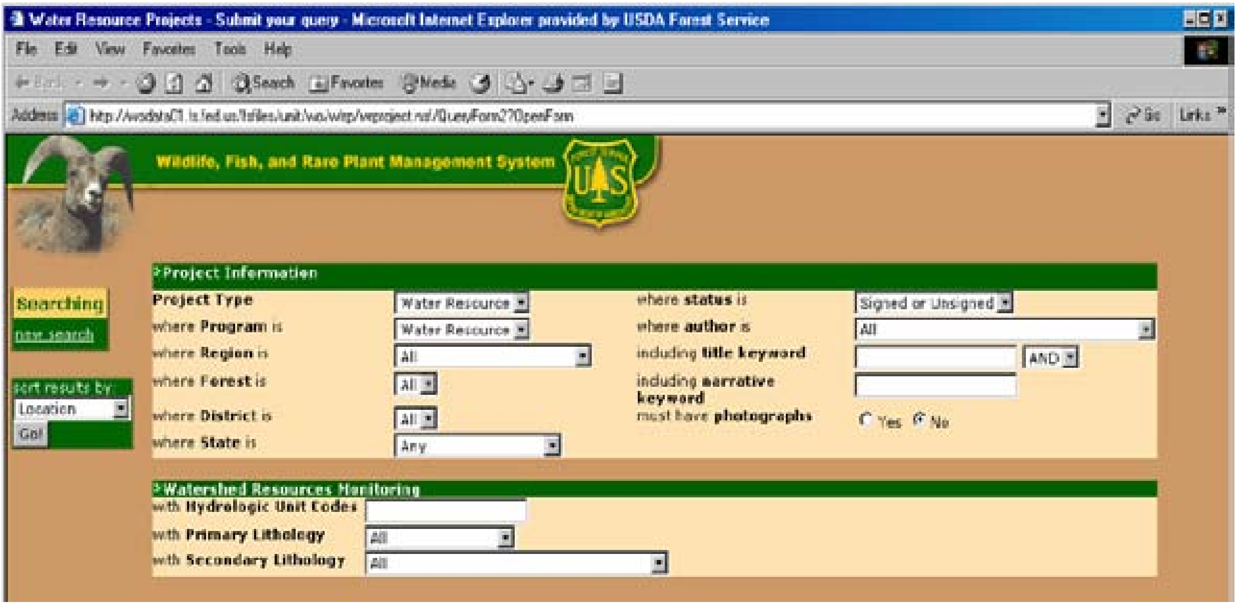
## Certification of Data Validation

Your signature is required prior to final data being entered into the database. This signifies that information on the form is accurate and based on project work plans, monitoring data, published literature and other information available at the District of Forest Office.

Select the "Save and Sign Final Data" button if you have completed entry and review.
Select the "Keep Data for Later" button to store provisional information until such time as it has been completed.

*Appendix 3. Example of Watershed Resources Monitoring query tool screen.*

he query tool was adapted from the Wildlife, Fish, and Rare Plants database and adapted for our use in Watershed Resources Monitoring:




An example of query output follows. The individual reports can be accessed by clicking on the title links.


Search Results for Form=("Choose Monitoring Extent" : "Choose Water Resource Partners" : "General Water Resource Information" : "Monitoring Project Narrative" : "Water Resource Instructions" : "WaterResourceSignature") & IncludeInReports="Yes"

Showing results 1-12 of 12 in Water Resource - Sorted by location

| TITLE | AUTHOR | PROGRAM | LOCATION |
|---|---|---|---|
| Culvert Condition Surveys along Forest HWY10 | Dan Gillikin | Water Res | Alaska Region, Tongass National Forest, Yakutat Ranger District, AK |
| Hubbard Glacier Assessment and Monitoring | Dan Gillikin | Water Res | Alaska Region, Tongass National Forest, Yakutat Ranger District, AK |
| Stream Identification and Classification using Remotely Derived Geospatial Information | Dan Gillikin | Water Res | Alaska Region, Tongass National Forest, Yakutat Ranger District, AK |
| Lars Fork Headcut and Bank Stabilization | Sherry Hazelhurst | Water Res | Intermountain Region, Dixie National Forest, Cedar City Ranger District, UT |
| White Pine Timber Sale | Adam Solt | Water Res | Intermountain Region, Fishlake National Forest, Richfield Ranger District, UT |
| Wildland Fire Use-Razorback Fire-- Saleratus Creek | Adam Solt | Water Res | Intermountain Region, Fishlake National Forest, Richfield Ranger District, UT |
| Na gah 3 Timber Sale Monitoring at Hancock Flat | Adam Solt | Water Res | Intermountain Region, Fishlake National Forest, Richfield Ranger District, UT |
| Idaho Forest Practices 1998 Monitoring Report | Ken Heffner | Water Res | Intermountain Region |
| NFK Sprague River Riparian Exclosure | Richard Pyzik | Water Res | Pacific Northwest Region, Fremont National Forest, Paisley Ranger District, OR |
| Watershed Condition Assessment for the Thunder Basin National Grassland | Paula GuentherGloss | Water Res | Rocky Mountain Region, Medicine Bow-Routt National Forests, Douglas and Thunder Basin Ranger District, WY |
| Mussel Survey of Horse Lick Creek | James W Bennett | Water Res | Southern Region, Daniel Boone National Forest, London Ranger District, KY |
| Test for the WO | Antoinetta Grant | Water Res | Washington Office, No Region, No District, DC |

*Appendix 4. Example Watershed Resources Monitoring report.*

## Lars Fork Headcut and Bank Stabilization
## Cedar City Ranger District
## Dixie National Forest
## USDA Forest Service, Intermountain Region

**Brazier, Joni and Kendall, Craig**
**2000-10**

**Description:** Lars Fork is a small tributary to Strawberry Creek. The lower perennial section of the stream system flows through several wet meadow complexes with deep alluvial soils. Lars Fork Creek is currently in a state of disequilibrium and adjustment, mainly in the lower reaches. Two of the largest headcuts along the creek were stabilized in October 1997 to prevent further headward erosion and loss of wet meadows upstream. In July 2002, the uppermost headcut and banks, located in the large wet meadow complex less than 1/4 mile upstream from headcut #1 & #2 were sloped back using a backhoe. The headcut and channel were armored with rock, and banks were covered with erosion cloth. Clumps of *Carex* were transplanted from the wet meadow to the creek bottom with the backhoe. A solar-powered electric fence was put up around the area to protect it from trampling and grazing until vegetation can get re-established. The site was monitored in October 2000 using visual observation and photos.

**Keywords:** headcut, bank stabilization, grazing, meadow, Strawberry Creek

**Hydrologic Unit Codes:**
160300010103

**Report Peer-Review Status:** Local Review

| Monitoring Extent | Purpose |
|---|---|
| Project | Baseline<br>Implementation<br>Effectiveness |

**Objective/Purpose of Monitoring Project:** To determine how effective stabilization methods were at preventing headward erosion, and to provide baseline information to support future effectiveness monitoring of restoration techniques and changes in land use management.

**Methods or Techniques Used:** Visual observation and photos

**Constituents/Parameters Measured or Assessed:**
Stream Channel Morphology bank characteristics/stability
Riparian vegetation communities

**Primary Lithology:** Unknown

**Secondary Lithology:** Alluvium

**Land Type Association:**

**Monitoring/Sampling Frequency:** annually

**Monitoring Duration:** 2-5 years

**Results Summary:** Up to this point, headcut stabilization seems effective. Vegetation from work done on headcut #1 and #2 in 1997 is slowly re-establishing, and the headcuts do not appear to be migrating. It is unknown at this time how effective the soil barriers will be in preventing high flows from flowing around the armored headcuts. Cattle broke through the electric fence protecting the upstream headcut, and some trampling of erosion cloth on the banks occurred. Some vegetation was noticed starting to sprout through the cloth when the site was checked on October 25, 2000. It is too early to tell how effective this project is at preventing further headward erosion. Some of the willow cuttings had sprouted new growth when checked on October 25. It is too early to tell how successful all of the cuttings have been at getting established.

**Photographs**

Figure 1: PP #7. Looking upstream on main channel (7/2000)

**Contact Name/Phone/Email:** D2 Hydrologist, Joni Brazier, jdbrazier@fs.fed.us, 435-865-3238

**Links to Full Report and Other Information:** On file at D2 Watershed Files; also included in 2000 Watershed Monitoring Results, Dixie National Forest (hard copy and CD). All photos attached to full report. *http://fsweb.r4.fs.fed.us/unit/bpr/watershed/fsweb/inventory_ monitoring/DNFLarsCk2000.doc*

# Aquatic Restoration Through Hydropower Licensing, Bond Falls Project, Michigan

Mark A. Fedora

*USDA Forest Service Eastern Region, Ironwood, MI*

Hydropower dams and diversions have the potential to alter many watershed and aquatic processes. The effects of multiple dams in a watershed can have negative cumulative effects at a watershed scale. The Federal Energy Regulatory Commission (FERC) originally licensed many hydropower dams in the Midwest US in the 1940s and 1950s, prior to the passage of legislation such as the Federal Power Act, as amended (1986). Today the facilities and operations of many of these hydropower projects are being reexamined as the original licenses expire. License proceedings, administered by FERC, provide an opportunity to gain a better understanding of cumulative effects on watershed processes, and to design measures to protect and restore specific features of the watershed in the future, including instream flows, substrate, channel stability, large wood, and water quality. The relicensing of the Bond Falls Hydroelectric Project on the Ottawa National Forest provided the opportunity for natural resource agencies and others, in conjunction with the licensee, to review the ongoing effects of the project, and to clearly define the resource conditions that the project must maintain or restore in the future. The licensing process was long and contentious with many competing interests. The new license was recently issued based on a negotiated settlement among the interested parties. The settlement provides for an improved flow regime, a mitigation fund to address project-related resource impacts, and a framework for the implementation team to work through issues using an adaptive management approach.

Keywords: *aquatic restoration, hydropower, negotiation, settlement, consensus*

## Background

The Bond Falls hydroelectric project is located in the Ontonagon River watershed in the western portion of Michigan's Upper Peninsula (Figure 1). The project affects approximately 250 kilometers of rivers and streams. Eighty-two percent of the rivers and streams affected are a part of the Ottawa National Forest (Figure 2). The Victoria Dam and powerhouse were constructed in 1931 on the West Branch of the Ontonagon River, the same year that the Ottawa National Forest was established. It is a 12.3-megawatt facility, or enough to provide power to about 13,000 residences at full capacity.

In 1937 the Bond Falls reservoir and diversion canal were constructed. The canal diverts water from the Middle Branch of the Ontonagon River to the West Branch via the South Branch, Sucker Creek, Bluff Creek and Roselawn Creek. Dams were constructed at the outlets of two


*Figure 1. The Bond Falls Project lies in the Ontonagon River watershed of Michigan's Upper Peninsula.*

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

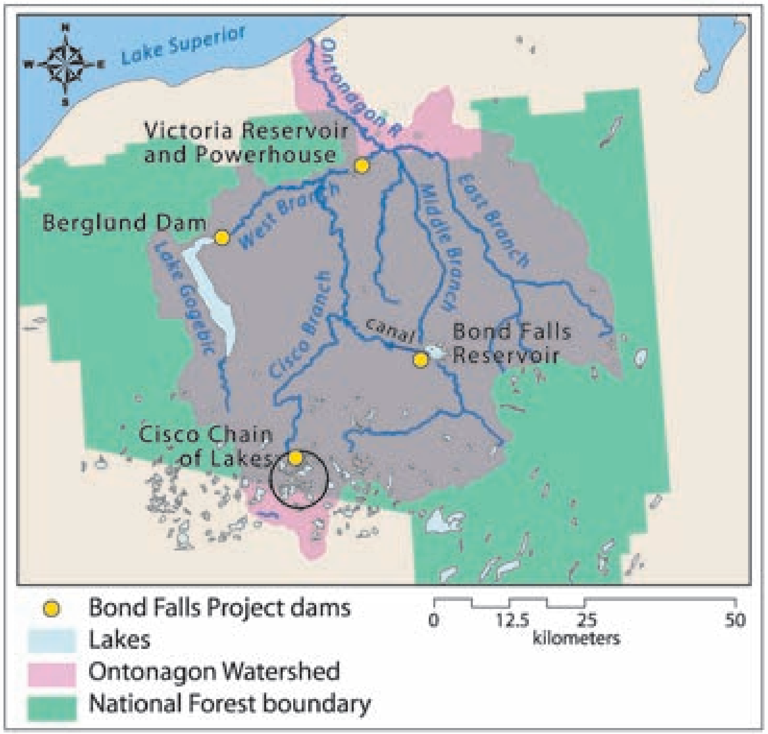



*Figure 2. Reservoirs and rivers associated with the Bond Falls hydroelectric project, within the Ottawa National Forest.*

other natural lakes, providing additional reservoir storage capacity for hydropower production. The total reservoir storage capacity available for use is 104.5 cubic kilometers. The mean annual daily discharge at the powerhouse is about 24.6 cubic meters per second (cms).

The original license for the project was issued in 1952 for the project for a 50-year term, retroactive to 1939. In 1985 the Federal Energy Regulatory Commission (FERC) initiated the re-licensing of the project by conducting agency and public meetings. Upper Peninsula Power Company (UPPCO) formally applied for a new license in 1987. The original license expired the following year; however, dam safety issues delayed the licensing process for another three years while the Victoria Dam was reconstructed to meet current safety standards, as required by the FERC. In 1992 several segments of rivers affected by the project were designated as recreational or scenic rivers under the Wild and Scenic Rivers Act (P.L. 90-542, as amended). Additional resource studies were conducted from 1992-1995, and the FERC declared that the project was "ready for environmental assessment" in 1996.

Resource agencies and non-governmental organizations (NGOs) recommended license conditions to the FERC that were much different from the way the power company proposed to operate the project. In 1997, the FERC encouraged the interested parties to enter into settlement negotiations in attempt to come to an agreement. The settlement agreement process had been previously used successfully in Michigan on another contentious hydropower project, and the decision was made by all parties to attempt to use a similar process for Bond Falls. The parties included agencies and NGOs that had widely divergent interests (Table 1). The Cisco Chain and Lake Gogebic Riparian associations and North Shore Riparian Owners chose not to participate in the settlement process.

In 1999, after approximately three years of difficult negotiations, the parties had reached a draft settlement. The final settlement was signed the following year, and the FERC developed draft and final environmental impact statements from 2001 to 2002. The license was issued in August of 2003, fifteen years after the original license expired.

## Issues

The key issue that the parties needed to resolve was water management. Specific issues included the timing, magnitude and changes in flow rates, and water level elevations in the reservoirs. The power company contended that any changes in the existing water management operations would adversely affect the project economics. Understanding how the components of the project had been historically managed and how resources are affected is critical to understanding the outcome of the negotiated settlement.

*Table 1. Parties to the negotiated settlement and their primary interests.*

| Party | Primary Interest(s) |
|---|---|
| Cisco Chain Association | Water levels at Cisco Lake |
| Keweena Bay Tribe | Natural resources, tribal rights |
| Lake Gogebic Riparian Association | Water levels at Lake Gogebic |
| Michigan Department of Natural Resources | Fisheries, wildlife, recreation |
| Michigan Department of Environmental Quality | Water quality |
| Michigan Hydro Relicensing Coalition | Represented the interests of six conservation non-governmental organizations |
| North Shore Riparian Owners | Water levels at Lake Gogebic |
| Upper Peninsula Power Company | Project economics |
| USDA Forest Service | National resources |

### Victoria Reservoir, Bypassed Reach of the West Branch, and the Ontonagon River

Victoria Dam is a 13.7-meter high concrete structure, constructed just upstream from a natural waterfall. During its initial licensing period, the powerhouse was operated as a "peaking" facility, with discharges ranging from zero to 22.7 cms on a daily basis. The power plant was operated during periods of peak energy demand, depending on inflows. A flume bypasses 2.6 kilometers of river between the dam and the powerhouse. Because there was no minimum flow requirement for the bypassed reach, it was often dewatered. A reproducing population of the State Threatened and Forest Service Sensitive lake sturgeon (*Acipenser fulvescens*) occurred historically in the river below the project (Schoolcraft 1821). The Michigan Department of Natural Resources has a goal of restoring this population. The waterfall is a migration barrier to fish; therefore, upstream fish passage was not an issue. The bypassed reach is relatively steep with cobble to bolder substrate, potentially suitable spawning habitat for lake sturgeon.

### West Branch of the Ontonagon River and Lake Gogebic

Bergland Dam, at the outlet of Lake Gogebic, regulates the water level of the 57 square kilometer lake. The dam has raised the elevation of the natural lake by 1.2 meters. Many private residences surround the lake; a priority under the original license was to maintain a full pool during the summer recreation season. By placing a priority on lake water elevations, the river below the lake would frequently be reduced to leakage flows (about 0.1 cubic meters per second) during the summer resulting in adverse effects on the aquatic system downstream. During the winter UPPCO was allowed to draw down the reservoir 0.6 meters (to be used downstream for hydropower generation) and refill the lake in the spring.

The lake is about 19 km long and oriented approximately north-south. When the lake is at or near full pool and there is a strong wind from the south, waves pound against the north shore contributing to shoreline erosion. North shore residents have complained that they are losing their shoreline and have asked UPPCO to lower the water levels and mitigate the damage by installing erosion control structures. Meanwhile, residents on other portions of the lake said that they would be adversely affected by lower water levels, as lower levels would expose navigation hazards and their docks would be in water that was too shallow for boat access.

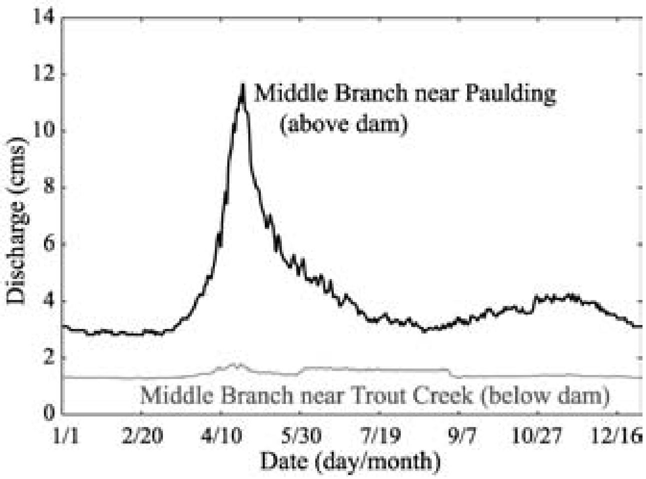
### Cisco Chain of Lakes and the Cisco Branch of the Ontonagon River

The Cisco Chain of Lakes consists of about a dozen lakes that are interconnected. The 3.4-meter high dam at the Cisco Lake outlet controls the water level in all lakes. Water levels are very important to the residents on the lakes to provide for navigation between the lakes. Similar to Lake Gogebic, lake water levels took precedence over streamflows in the original license, frequently reducing flows in the Cisco Branch to leakage (about 0.01 cms). During the winter UPPCO would draw down the lakes 0.3 meters to gain 4.9 cubic kilometers of water for power production.

### Bond Falls Reservoir, Middle Branch of the Ontonagon, and the Diversion Canal

The Bond Falls Reservoir is a 13.7 m earthfill dam on the Middle Branch of the Ontonagon River, just upstream from Bond Falls. The natural flow of the Middle Branch joins the Ontonagon River downstream from the Victoria powerhouse. Water is diverted through a constructed canal that discharges to tributaries to the South Branch. The

*Figure 3. Median of daily mean discharge values upstream (Middle Branch near Paulding) and downstream (Middle Branch near Trout Creek) of Bond Falls Reservoir, 1942-2003.*




South Branch joins the West Branch above the Victoria Reservoir. Discharges in the canal varied from zero to 10.8 cubic meters per second (cms). The effects of the diversion on the mean daily flows below the Bond Falls reservoir can be readily observed using data from the upstream and downstream gages (Figure 3). The additional flows in the small tributary streams created tremendous changes in stream channel morphology. Rapid fluctuations in flow eroded streambanks, resulting in an unstable stream system with adverse effects on benthos and fish populations (Taft 1995).

Annual water level fluctuations at the Bond Falls reservoir were as much as 7.3 meters. The reservoir provides habitat for the Federally Threatened bald eagle (*Haliaeetus leucocephalus*). Other species of interest that may be affected by reservoir elevation fluctuations include the State-Threatened and Forest Service Sensitive common loon (*Gavia immer*) and trumpeter swan (*Cygnus buccinator*). The entire assemblage of plant and animal species that depend on the near-shore environment can also be adversely affected by large fluctuations in water levels.

### Other Issues

A number of other issues were considered in the negotiation process, including sub-standard recreation facilities, water quality, wildlife habitat, fish passage, fish entrainment, nuisance plants, and woody debris management. Recreation facilities were mostly old and did not meet current standards regarding accessibility or adequacy. Water quality concerns included meeting state standards for dissolved oxygen and temperature below project facilities. Wildlife habitat issues raised included how land and vegetation would be managed around the reservoirs to provide the needed wildlife habitat – particularly old-growth habitat. The Bond Falls Project area provides habitat or potential habitat for 46 threatened, endangered or sensitive species. Upstream fish passage was an issue only at the Bergland and Cisco dams, as the other dams are located directly above natural waterfalls. A fish entrainment study conducted as a part of the licensing process found that about 235,000 fish per year were entrained (drawn into the generating flow) and the turbines killed approximately 71,000 fish (RMC Environmental Services 1996). Resource agencies and NGOs also wanted UPPCO to take responsibility for the prevention, inventory and control of invasive plants (primarily purple loosestrife [*Lythrum salicaria*] and Eurasian watermilfoil [*Myriophyllum spicatum*]). Woody debris management concerns surrounded the fate of debris that accumulated in the reservoirs at the dams that otherwise would have continued to move downstream. Recreation issues, including fishable and boatable rivers, were closely related to the aquatic issues concerning the volume and timing of flows and water levels.

## Negotiation and Settlement

The Forest Service formed a small interdisciplinary team to review reports, conduct independent analyses, conduct water quality monitoring, and participate in the negotiations leading to settlement. The Forest Service team included a wildlife biologist, a fisheries biologist, a hydrologist and a recreation specialist. Other agencies and NGOs were more narrowly focused in their interests and generally had only one representative. The power company had a lot at stake in the negotiations and was primarily represented by three to four individuals, including a contracted consultant at some meetings.

The strength of the Forest Service negotiation position stemmed from several laws that had been enacted since the original license was issued. Most notable was the Federal Power Act (FPA), as amended in 1986. Section 4(e) of the FPA allows the Forest Service to condition the license to assure the operations of an existing or proposed hydroelectric project are consistent with the goals established in the Forest Land and Resource Management Plan. The 1986 Ottawa National Forest Plan established many goals related to aquatic and recreation resources that were not being met under the original license (USDA Forest Service 2002).

The negotiations were long and contentious. The parties initially met about every six weeks during the negotiation process. But with little pressure from the FERC and an apparent lack of strong commitment to the process by

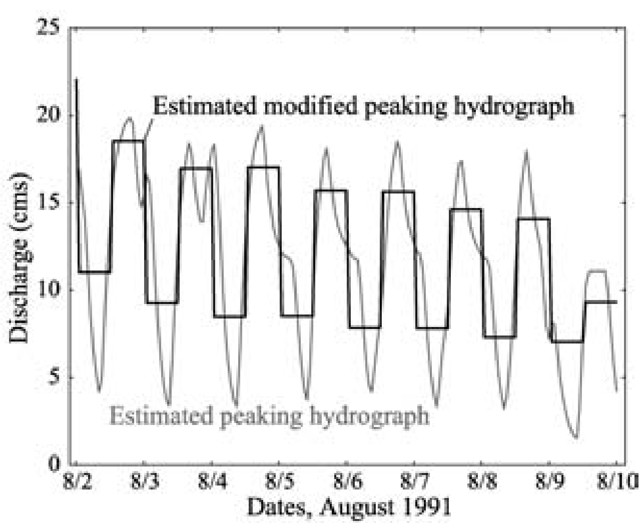
UPPCO, meetings were sometimes cancelled or dates slipped further. With the passage of so much time between meetings, the parties would often have to go back and review everything that was agreed to previously. The process was further delayed after Wisconsin Public Service (WPS) acquired UPPCO in 1998. With the introduction of new faces at the negotiation table, the process slowed as agreements had to be reviewed, explained and discussed again.

The parties tackled the minor issues first, to gain confidence and build trust in each other. They followed an outline that eventually led them to negotiate the most difficult issues – flows and water levels. Flows and water levels were modeled to try out various operating scenarios. Results from the operations model were combined with aquatic habitat modeling to estimate the effects of differing operations on habitat and recreation values. The power company used the modeling results to estimate economic impacts. The parties used the models as a basis for communicating interests and to help solve the complex problem of allocating resources. Using modeling results and independent analyses, negotiations continued for more than three years before a settlement was reached.

## Results of the Negotiated Settlement

Some of the most significant results of the settlement included more natural flow levels in the rivers, reduced fluctuations in reservoir elevations, and the establishment of a mitigation fund and an implementation team to meet other resource needs.

*Figure 4. Estimated discharge below the Victoria hydroelectric plant and simulated discharge under a "modified peaking" condition. Simulated discharge was based on the rules defining "modified peaking" according to the terms of the settlement.*




### Flows in the Middle Branch of the Ontonagon River

The flows in the Middle Branch are linked to the water levels and canal discharges from the Bond Falls Reservoir. The Middle Branch flows were the most contentious issue, as this river had perhaps the highest resource potential of the various project river segments, and had been severely affected by operations under the previous license. From the perspective of UPPCO/WPS, every drop of water that goes down the Middle Branch is a drop that does not go through the turbines at Victoria. Studies were conducted using the Instream Flow Incremental Methodology (IFIM) to determine flows that would support viable populations of aquatic species and recreational uses of the river. Flows in the Middle Branch are dependent on water levels in the reservoir and discharges in the canal. Water level fluctuations and canal discharges had to be moderated in order to achieve a more natural runoff pattern in the Middle Branch.

The parties agreed to a minimum flow that varied through the year to better emulate a more natural hydrograph and meet the needs of aquatic species and recreation. The winter drawdown of the reservoir was limited to 2.4 meters and the maximum discharges to the canal were limited to 5.0 cms. These changes served to allow for higher flows in the Middle Branch during the spring to provide channel-maintenance flows.

### Victoria Dam and Power Plant Operations

The parties agreed to change the operations of the power facility from a peaking facility to a run-of-river operation during sturgeon spawning season, and a "modified peaking" facility during the remainder of the year. Modified peaking was defined as the minimum discharge on any day had to be at least half of the maximum discharge of the previous day (Figure 4). This provision assured that the stream channel below the facility would be constantly wetted and aquatic resource values protected.

During the sturgeon spawning periods, minimum flows of 4.2 cms would be released into the bypassed reach to provide sturgeon-spawning habitat. Flows would be maintained through June 15 to assure that young fish would reach rearing habitat in Lake Superior.

### West Branch Minimum Flows

Operations at Bergland Dam at the outlet of Lake Gogebic would be modified under the terms of the settlement to provide a minimum flow of 0.9 to 1.4 cms, depending on water level elevations. Minimum flows would be reduced as water levels decline in the reservoir.

The minimum flows were designed to provide adequate, if not optimal, habitat to protect aquatic, aesthetic, and recreation resource values of the river.

### Mitigation and Enhancement Fund, Implementation Team

A mitigation and enhancement fund was established to provide resources to address other issues through the term of the license. The settlement provided for the establishment of an implementation team, consisting of representatives of all parties to the settlement. The team operates by consensus to determine priorities for funding proposed projects. Potential projects include recreation improvements, fish entrainment prevention, water quality monitoring, fish passage facilities, wildlife and fisheries habitat improvements, erosion control, telemetry for gaging, wildlife and fisheries studies, and nuisance plant inventory and control. The licensee will contribute monies to the fund on an annual basis, amounting to $2.46 million (year 2000 dollars) over the 40-year term of the license.

## Implementation

Issues regarding the implementation of the terms of the license arose immediately. In 2003, drier-than-normal conditions during late summer meant that flow conditions and water levels could not be met at the West Branch Ontonagon River and Lake Gogebic, respectively. Provisions within the settlement call for the power company to consult with the implementation team when conditions cannot be met. The team then makes a decision and notifies the FERC. When the same conditions could not be met the following year, the team met and decided on temporary changes in target elevations and "trigger" water levels for 2005 to help alleviate the problems. This adaptive management strategy will help the team to work through the complicated provisions of the settlement to best meet the needs of the affected parties and resources.

Since the license was issued, the team has reviewed and agreed to the content of many implementation plans prepared by UPPCO/WPS including: the management of water quality, recreation resources, wildlife habitat, Threatened and Endangered species, woody debris, erosion, and project operations and monitoring. The plans will help guide the team in the coming years as priorities are set and projects are implemented.

***Acknowledgments.*** I would like to thank Bob Evans for his unwavering and excellent work on this project from the very beginning of the licensing process, for inviting me to work on this project, and for his review of this manuscript. I'd also like to thank my mentor, Dale Higgins, for his fine work in conducting hydrologic modeling for this project.

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# TRTR Funds–Successes in Watershed Restoration in the Eastern Region

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Eastern national forests are largely comprised of lands that were cut over, burned, farmed and mined. In over 100 years of National Forest System management we have made great progress in improving the condition of the "lands nobody wanted," but considerable work remains to address impacts to the aquatic component. Sediment continues to be the primary contaminant of concern in our aquatic systems. High historic sediment levels are sustained by persistent contemporary input, primarily from roads and trails. To improve the condition and health of our eastern watersheds, we need to address the delivery of sediment from our gravel and gravel-sand roads and trails. In addition to being a source of sediment, many of the road and trail crossings are impediments to passage by aquatic organisms. The Roads and Trails for States (TRTR) program, which returns to the Region ten percent of the prior year receipts collected from National Forests, has enabled the USDA Forest Service Eastern Region to make significant progress in addressing many of our road and trail stream crossing problems. Our TRTR program uses an integrated process to address sediment problems at many of our high priority road and trail stream crossings. TRTR projects range from improving high use hiking trails on the White Mountain National Forest (New Hampshire) to replacing open slotted bridges on the Chippewa National Forest, Minnesota. Our landownership pattern presents challenges but also offers numerous opportunities for partnering with others to achieve success. Many forests have leveraged their TRTR funds with partners to achieve transportation, recreation and riparian-habitat objectives.

Keywords: *watershed restoration, sediment, aquatic habitat impairment, stream crossings, transportation management*

## Background

Eastern national forests differ markedly from the larger forests west of the 100th meridian. The Eastern Region of the USDA Forest Service (Region 9) is vast, extending from Minnesota to Maine, south to West Virginia, and west to Missouri. While the western forests are prominent on the landscape, eastern forests seem like mere flecks scattered across the eastern half of the nation (Shands 1979). Land ownership within national forest boundaries is fragmented and the percentage of federal ownership varies by forest.

While there is some public domain land in the East, eastern national forests were formed primarily of land purchased following passage of the Weeks Act in 1911. The Weeks Act authorized Congress to appropriate money to purchase forest reserves for the purpose of conserving forests and the water supply (Conrad 1997). No single law has been more important in the return of the forests in the eastern United States. The lands acquired to build the region were the "lands nobody wanted" (Shands 1977). Historical logging and burning, farming and burning, and mining and abandonment, left behind vast acreages of stump fields, severely eroded hillslopes with numerous gullies, thousands of acres of drained wetlands, and miles of sediment-clogged stream channels and lakeshores.

In 1920 there were 1,402,000 acres (567,800 ha) of national forests in what is now the Eastern Region (USDA 2004a). Today this figure is 12,061,766 acres (4,885,015 ha) or approximately 55 percent of the land within the administrative boundary (USDA 2004a). Ownership within watersheds varies from over 90% on the White Mountain National Forest in New Hampshire to less than 1% for some of the watersheds on the Wayne National Forest in Ohio. These intermingled lands that comprise a national forest are owned by states and counties, as well as private individuals and timber companies.

Today, because of high human population densities and relatively small public land acreages in the East, national forests here have been called "islands of green in a sea of people." Many Eastern Region national forests are within a day's drive of major metropolitan areas such as St. Louis, Minneapolis, Chicago, Cleveland, Detroit, Pittsburg, Philadelphia, Washington, DC, New York and

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Boston. People seeking recreational opportunities can readily travel to these national forests. Off-highway vehicle use, motorbike riding and horseback riding have increased significantly in recent years, and the demand for these uses is a major forest plan revision issue on most forests.

Recreational activities involving aquatic resources have also increased and present significant resource management challenges. The Eastern Region, with more than 962,000 acres (389,600 ha) of lakes and more than 15,300 miles (24,600 km) of streams, has more of these resources than any Forest Service region outside of Alaska (Schmal 2004). Lakes and wetlands dominate the forests in Minnesota, Wisconsin and Michigan, with streams dominant in Missouri and West Virginia. All Eastern Region forests contain both free flowing and flat water. It is public interest in accessing and using the eastern national forests that sets the stage for potential impacts to the riparian and aquatic resources, ultimately effecting watershed function and health.

**The Problem**

The intermingled land ownership patterns of eastern national forests bring challenges and opportunities. Transportation management is one of the challenges. There are approximately 30,000 miles (48,300 km) of inventoried Forest Service roads and more than 12,000 miles (19,300 km) of inventoried Forest Service trails in the region (USDA 2003). In addition to what has been inventoried, there are many unauthorized and unmanaged user-developed roads and trails. The existing network provides access to recreational areas and serves as a conduit for the harvest of wood products. But the existing roads and trails were not initially designed to address aquatic and riparian resource needs.

Many existing roads follow old railroad beds and have surfaces of native gravels and sands, often with stream crossings at the lowest elevation in the watershed. Drainage structures comprised of corrugated metal pipes are common and many bridges are open-slotted (the bridge travel surface is not solid). In parts of the region, crossing structures are non-existent, and low water crossings or fords are used instead. These existing crossings are major contributors of sediment to the aquatic resources.

Excessive sediment has both physical and biological effects. The addition of sediment can alter stream channel morphology (e.g., increase width-depth ratios) and reduce the carrying capacity of the channel. During high runoff periods, the crossing may be overtopped, causing subsequent removal of road surfacing material and erosion of stream banks. High sediment levels rarely kill adult fish, but can harm eggs and juvenile fish. Many streams with important fish habitat in the forests of the Great Lakes region are Rosgen “C” types. These are perennial streams with sinuous, low-gradient, low-relief channels, and well-developed floodplains (Rosgen 1996). Much of the deposited sediment stays in the channel where it can bury important food, spawning, and cover habitat.

Consider the “Brill Cream” slogan that was popular twenty years ago, “A little dab’ll do ya.” If you are a fish or other aquatic organism living in a low gradient stream or a stream with numerous undersized culverts or open-slotted bridges, “A little dab of sediment will do you in”. Fish habitat studies in Michigan and other parts of the country have shown that the addition of inorganic sediments can seriously alter habitat conditions, thereby affecting food sources which can then limit reproductive potential of certain fish species (Hansen et al. 1982). Fish and other aquatic organisms need pools for cover and the addition of inorganic sediment fills the pools, further altering the stream channel and habitat.

Older culvert crossings frequently impede aquatic organism passage. While most culverts were designed to meet the hydraulic design criteria, they are undersized when consideration is given to debris, sediment and aquatic organism passage. These culverts may effectively pass water during moderate and high flow conditions but still serve to block or inhibit upstream aquatic organism passage due to increased velocity during high flows and insufficient water depth during low flows. Changes in stream configuration over time, including scour and ponding around the upstream end of culverts, have also resulted in raised inlets in many cases. The issue of raised inlets was noted as the second most significant issue identified from the integrated stream crossing inventories on the Huron-Manistee National Forests, Michigan (CRA and USFS 2004). Raised inlets are a significant concern because they block downstream passage of aquatic organisms during low flows and pond water upstream of the crossing. This can accelerate bank erosion and sedimentation.

Trail stream crossing problems are also prevalent throughout the region. Many of the existing trails were initially developed by users. Limited effort was expended on location, design or installation, and best management practices were not applied. While some trails have culverts, many more do not. The existing culverts were installed to provide drainage to protect the trail, but may not meet variable flow conditions or aquatic organism passage needs.

Across the Eastern Region, erosion of sediment from our existing road and trail network further alters streams working to recover from prior land use practices. This is especially true when viewed from a cumulative perspective across a watershed.

## Roads and Trails for States Program (TRTR) – "The Hero"

Interest in improving road and trail stream crossings in the Eastern Region began in the late 1980s and parallels the "Rise to the Future" initiative. This initiative was created in 1986 by Chief Max Peterson and implemented the following year by Chief Dale Robertson. In 1988, the Eastern Region started hiring fish biologists. Assessments of aquatic habitat conditions were initiated, followed by habitat improvement projects. An evolutionary process occurred in the Eastern Region. Fish biologists knew sediment was harmful to fish and their habitat. Early aquatic habitat restoration work focused on repairing individual sites, such as an eroding stream bank. These eroding stream banks were thought to be "the problem". This evolved to treating all actively eroding sites on a river. But still stream sedimentation and aquatic habitat impairment continued. Concurrent with concerns about sediment in the East, Dr. Jerry Franklin and other scientists were examining the relationship between the health of aquatic systems and what was occurring in the watershed (Franklin 1989; Verry 1992). From knowledge gained through discussions both within and external to the region, larger landscape inventories, and in many cases, watershed inventories were initiated. These larger-scale inventories identified road and trail stream crossings as major sources of sediment on most Eastern Region national forests.

While the Huron-Manistee National Forests led the region in this effort, other eastern forests also initiated road-stream crossing inventories. These road-stream crossing inventories identified over 14,000 culverts in the region, with large numbers of problem crossings-raised inlets, perched outlets, high flow velocity issues, low flow passage organism passage problems, to name a few (Schmal 2004). While the focus was on national forest lands, it was apparent that problem crossings were not exclusive to the national forests. The challenge was how to meet the need to address these problems and stay within existing program constraints.

Within the Forest Service, Soil and Water Resource Improvement funds can cover the installation of land treatment and structural measures for erosion control, rehabilitation of abandoned roads and trails, and stream bank and gully stabilization (USDA 2004b). But these funds are not appropriate to fund erosion control work or perform other maintenance, including replacing stream crossing structures on existing roads or trails. Maintenance work should be implemented using road and trail maintenance funds, but the need far exceeds our region's annual appropriations. This issue was not unique to the Eastern Region. Alternative funding sources were needed. In 1913, a statute was written that addressed this need. The original statute in 16 USC Sec. 501, Title 16, Chapter 2, stated that:

"On or after March 4, 1913, ten per centum of all moneys received from the national forests during each fiscal year shall be available at the end thereof, to be expended by the Secretary of Agriculture for the construction and maintenance of roads and trails within the national forests in the States from which such proceeds are derived".

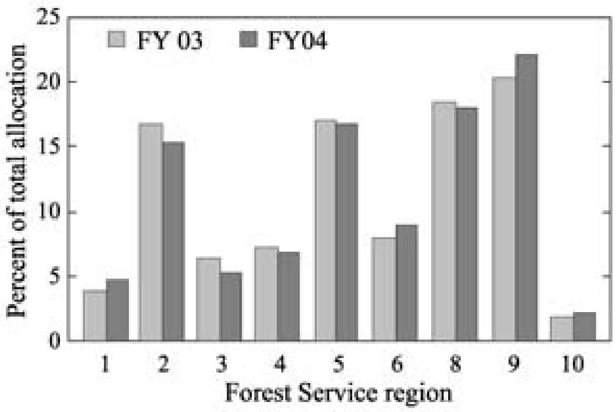
But it was not until 1996 that Congress authorized use of ten percent of the prior year's receipts from national forests, "…to repair or reconstruct roads, bridges and trails on national forest system lands…..for the purpose of reducing risks to human health and safety and public property, and to enhance ecological functions, long-term productivity, and biological integrity (USDA 1998). The program was called "Roads and Trails for States" and the agency assigned the program the "TRTR" fund code.

All regions started receiving TRTR funds in 1998. The TRTR funds were viewed as "the hero" in the Eastern Region because program direction enabled forests to use the funds to address environmental problems caused by existing roads and trails. Initially, the funds went back to the forest based on the forest's collection of receipts, but in subsequent years, regions were directed to select and fund the highest priority projects based on factors including watershed condition, watershed integrity, and partnerships, and other relevant considerations, regardless of which forest initially generated the funds (USDA 1999).

## TRTR Program in Region 9

The Eastern Region has been successful with the TRTR Program for several reasons. A number of forests had inventories of road and trail stream crossings that included assessment of problem crossings. Crossing needs were known, and project designs to address both the transportation and aquatic resource needs existed or were nearing completion. Secondly, the national program direction emphasized program integration. Implementation of the TRTR program offered support to those forests where engineering, fisheries, watershed and recreation were working together. The added value from this internal integration has been tremendous and will continue to have significant program benefits. Lastly, the region's percentage share of TRTR funds has been significant (Figure 1). Our annual allocation of approximately 3 million dollars along with program direction that gives priority to projects with partnership potential, has opened the door to working across boundaries with a variety of partners. For partnerships to work, all partners need to bring

*Figure 1. Percentage share of TRTR funds for fiscal year 2003 and 2004 by Forest Service Region. Regions: 1. Northern, 2. Rocky Mountain, 3. Southwestern, 4. Intermountain, 5. California, 6. Pacific Northwest, 8. Southern, 9. Eastern, 10. Alaska*




something to the table. Without a stable source of funding, maintaining and expanding partnerships is difficult at best. Across the Eastern Region, most forests are working with external partners to address road and trail stream crossing needs. By leveraging TRTR funds with partner funds they are able to correct road-trail stream crossing problems and accelerate watershed restoration on "the lands nobody wanted".

There are many TRTR success stories in the Eastern Region that exemplify "working together" with both internal and external partners. Five projects described below provide representative examples of the region's use of TRTR funds to address environmental problems associated with our existing roads and trails.

## Chippewa – Woodtick Road Relocation (Figure 2)

The Chippewa National Forest in north-central Minnesota has been an active participant in the TRTR program. The forest has a long-standing commitment to restoring the health of watersheds from the impacts of past land use practices. While addressing road stream crossings has been a major focus of the TRTR program on the Chippewa, the success story involves the relocation of a road and the restoration of a large connected complex of wetlands.

Forest Road (FR) 2107 was a gravel-surfaced, system road open seasonally to public highway traffic (Figure 2a, c). The road bed was frequently flooded in the spring or during heavy rainstorms and required frequent maintenance. The road had been in place for many years and was partially located in a wetland. The purpose and need for the relocation project was to reduce long-term maintenance costs, improve safety, and restore water flow within the wetland through which the road passed. The project had been previously identified and listed on the Chippewa's road maintenance inventory. In 2002 the project was selected as the Forest's number one priority for TRTR funds because of the opportunity to address both transportation issues and watershed restoration concerns.

The proposed action involved relocating 3,500 feet (1067 m) of FR 2107 by constructing a permanent bypass for the portion of the existing roadway that ran through a wetland (USDA 2002c). The relocated roadway would provide a 22-foot-wide (6.7-m) driving surface with 3:1 side slopes. The bypass would traverse uplands that include open fields and forest. It would diverge north and west from the existing roadway to form a new junction with Minnesota Trunk Highway 371, approximately 1,000 feet (305 m) north of the current junction. The bypassed portion of the roadway would be removed and restored to approximate the topography and native vegetation that were present before the road was constructed.

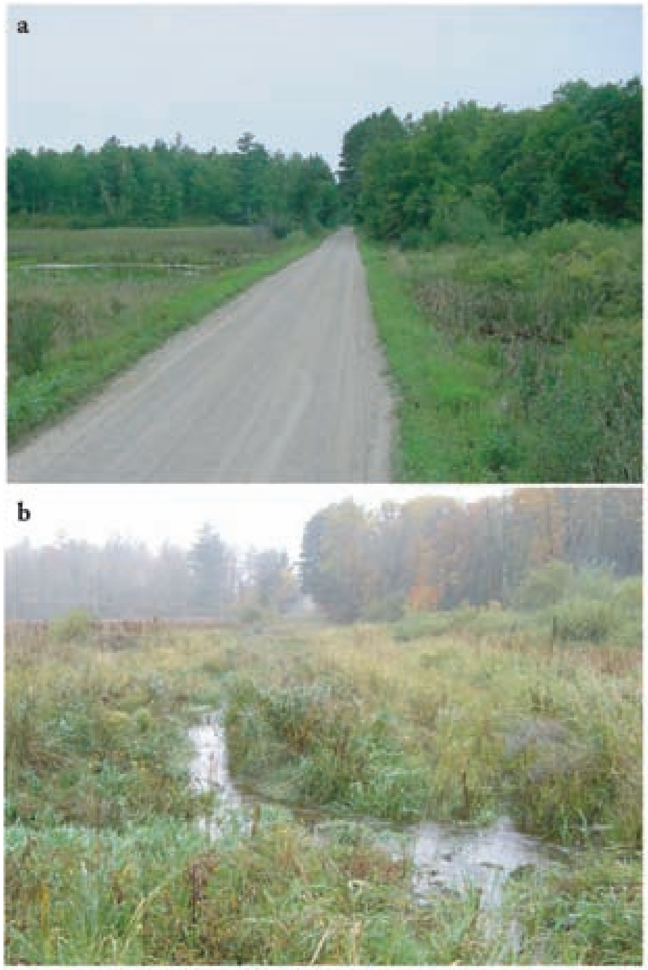
Construction of the new road segment cost $159,000 and was funded using TRTR. Removal of the old roadbed and restoration of the adjacent topography and vegetation was accomplished through a partnership between the Chippewa National Forest and Cass County (Figure 2b, d, e). The county paid for the removal of the grade in exchange for use of the fill on a nearby project and to obtain credit for wetland restoration that offset wetland losses on the Forest due to other county highway projects. The value of the County contribution was $25,000. The National Forest contributed $15,000 of TRTR funds to cover surface re-contouring, topsoil costs, and the creation of a few small sandy areas suitable for turtle nesting.

The strength of this project was the partnership that formed and helped to elevate the importance for the project. The result was an improved and safer access to national forest resources, the restoration of flow through 19 acres (7.7 ha) of wetland, and the direct restoration of almost two acres (0.81 ha) of wetlands.

## Hiawatha – Sturgeon River Bridge Replacement (figure 3)

The Hiawatha National Forest is located in Michigan's Upper Peninsula, between Lake Superior and Lake Michigan. As with other Lake States' forests, it has numerous lakes, wetlands and rivers. Many of the rivers are classified as wild and scenic rivers, including the Sturgeon River, the site of this success story.

The Sturgeon River Bridge crossing has long served as a chronic source of sediment to the Sturgeon Wild



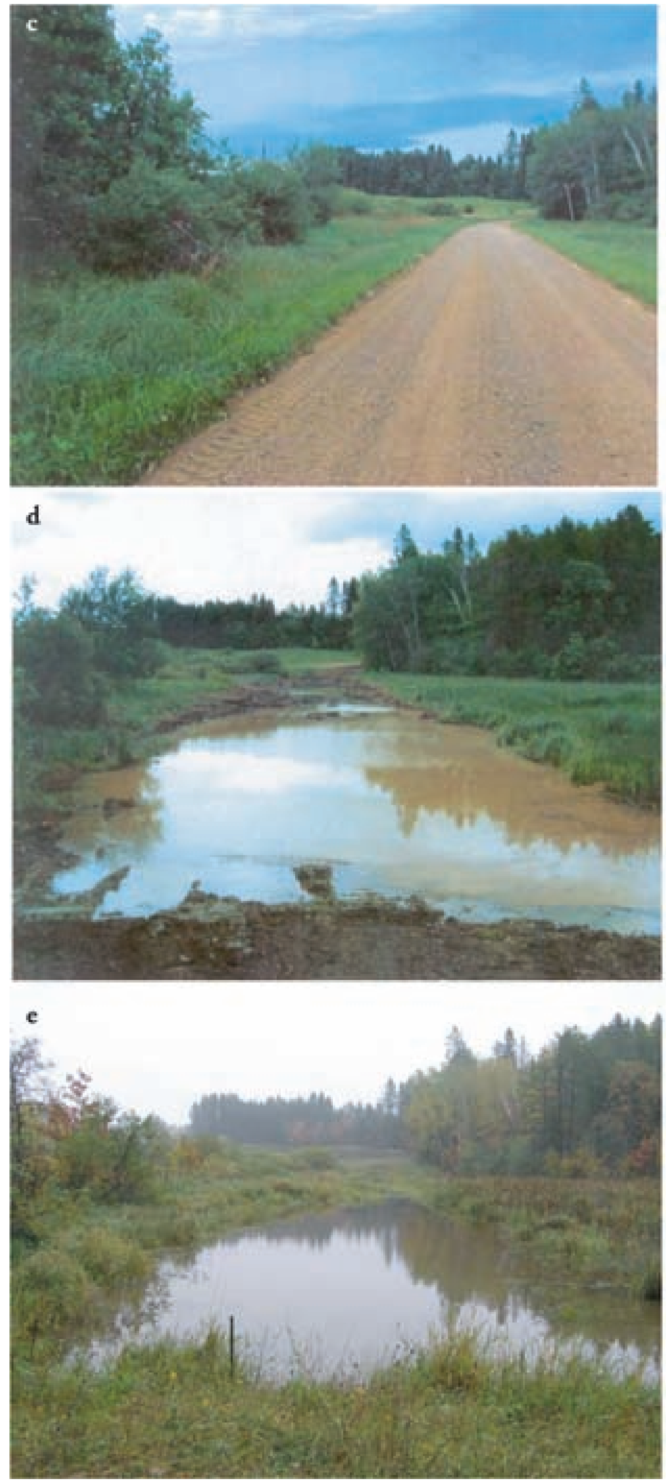


*Figure 2. Woodtick Road Relocation, Forest Road 2107, Chippewa National Forest, Minnesota. (a) Before, (b) Restored wetland after relocation. (c) Before, (d) After; the road was rerouted around the wetland; roadbed was removed from wetland area, and (e) natural drainage was restored. Photos by William Yourd.*

and Scenic River. Below the crossing, the river and its floodplain form the setting for a candidate Research Natural Area, elevating the importance of maintaining river and floodplain function. The east bridge approach was steep and confined, directing all eroded materials into the Sturgeon River. The western approach, though not as steep, also produced sediment that was transported to the river. In addition, the existing bridge had a center pier that continuously caught large woody debris being transported downstream by the river. The bridge abutments intruded into the bankfull area of the river, constricting the channel, with resultant upstream sediment deposition and increased width-depth ratio (Figure 3a).

Support for this project came from within the forest as well as from private contacts, including county and township road commissions. The Forest Hydrologist, Fish Biologist, Wild and Scenic River Planner and Recreation staff all worked together with the Forest Engineer to assess the site and to develop a conceptual design for the structure that met all the resource needs. Actual bridge design and National Environmental Policy Act (NEPA) documentation was contracted with a private engineering firm. Funding for the bridge came from the Capital Resource Improvement Program in addition to TRTR funds. The the entire project cost $521,000 and took four years to accomplish.


*Figure 3. Sturgeon River Bridge, Hiawatha National Forest, Upper Peninsula of Michigan. (a) Before, (b) After. Former road was narrow, with native road surfacing material; stream crossing was at the lowest elevation on the road and this allowed runoff to flow down the road and deposit sediment into the Sturgeon River, a cold-water, low gradient stream. The new crossing was slightly elevated, provided more sunlight to the roadbed; the bridge was replaced; the approaches and crossing were hardened and runoff drains were constructed. Photos by Richard Kell.*

The project included removal of the old structure, followed by installation of a single span bridge that spanned the entire bankfull width, establishment of functioning ditches and drainage relief structures, and hardening the road approaches to the river (USDA 2002b). Because of the magnitude of the project, the construction activities occurred over three years.

As a result of the work accomplished, the following benefits were achieved:

- a reduction in sediment delivered to downstream aquatic habitat,
- the restoration of the free flowing characteristics of the Wild and Scenic River, and
- a safer, wider bridge with regulation guardrails

The new Sturgeon River Bridge is now complete and an outstanding example of one of the larger, more complex stream crossing projects accomplished with TRTR funds (Figure 3b).

## Green Mountain – Catamount Trail Bridge Replacement (figure 4)

The Green Mountain is a small but very special national forest in southern and central Vermont. As with many eastern national forests, there are non-Forest Service recreation sites within and adjacent to the national forest. The Catamount Trail, a cross-country ski trail running the entire length of Vermont, is an example of a trail that has access points on the forest. One segment of the trail crosses Burnt Meadow Brook. This section of the Catamount Trail has been in existence for a number of years, and passes through the grounds of the Macartney House, a pristine country inn, which is operated under a special-use permit from the forest. The existing bridge was in need of replacement from a structural standpoint, and the approaches and decaying native log abutments were causing sedimentation (Figure 4a).

*Figure 4. Burnt Meadow Brook Bridge replacement, Catamount Trail, Green Mountain National Forest, Vermont. (a) Before, (b) After. Photos by Richard Gaiotti.*

As a result of discussions between the forest TRTR coordinator and members of the Catamount Trail Association, Macartney House and the State of Vermont, a partnership developed and plans were made to replace the Burnt Meadow Brook Bridge (USDA 2002a, 2002d, 2002e). The Burnt Meadow Brook Bridge was the largest of nine bridges replaced on the Catamount Trail on the Manchester Ranger District, during the summer of 2003. The Forest Service, using TRTR funds, agreed to share the cost of its construction with the Catamount Trail Association, which had received grants from the State of Vermont. The new Burnt Meadow Brook Bridge has a standard Forest Service trail bridge design with steel stringers and treated timber mudsills, railing, and decking. Heavy equipment was used to transport the stringers to the site and set them in place. All other work was performed by a ten-person Vermont Youth Conservation Corps (VYCC) crew, with Forest Service and Catamount Trail Association personnel. The Catamount Association, Forest Service, and Macartney House shared in providing logistical and technical support.

The new bridge (Figure 4b) met the resource needs and assured safe access across Burnt Meadow Brook while providing a worthwhile and rewarding project for the VYCC crew.

## Hoosier – Charles Deam Wilderness Trail Restoration (Figure 5)

The Hoosier National Forest comprises 200,000 acres (81,000 ha) on two units in southern Indiana. The northern unit of the forest includes the Charles C. Deam Wilderness, the only congressionally designated wilderness in the state of Indiana. This wilderness is a popular weekend destination for local residents from nearby Bloomington, Indiana, a city of 120,000 people. In the last decade, both horseback riding and hiking have steadily increased. Much of the wilderness is covered with lush second growth hardwood forests. The existing network of trails, many of which follow the old road system built in the late 1800s, has been maintained but was not designed to accommodate the increased horse traffic (Figure 5a). Many trails were originally built without adequate cross-drainage. There were numerous damaged areas with increasing concern for erosion, runoff, and subsequent sedimentation to Monroe Reservoir, the municipal water supply for Bloomington, Indiana.

An Environmental Assessment released in 2001 analyzed several trails in the Charles C. Deam Wilderness (USDA 2001). The Environmental Assessment focused on improving trails where improper drainage and flooding was causing sedimentation into the Monroe Reservoir. Knowing that any trail restoration work must comply with wilderness requirements, the forest began contacting western forests with mule strings that might be available to assist with the work. The Bridger-Teton National Forest in Idaho reported they had two mule packers and eight

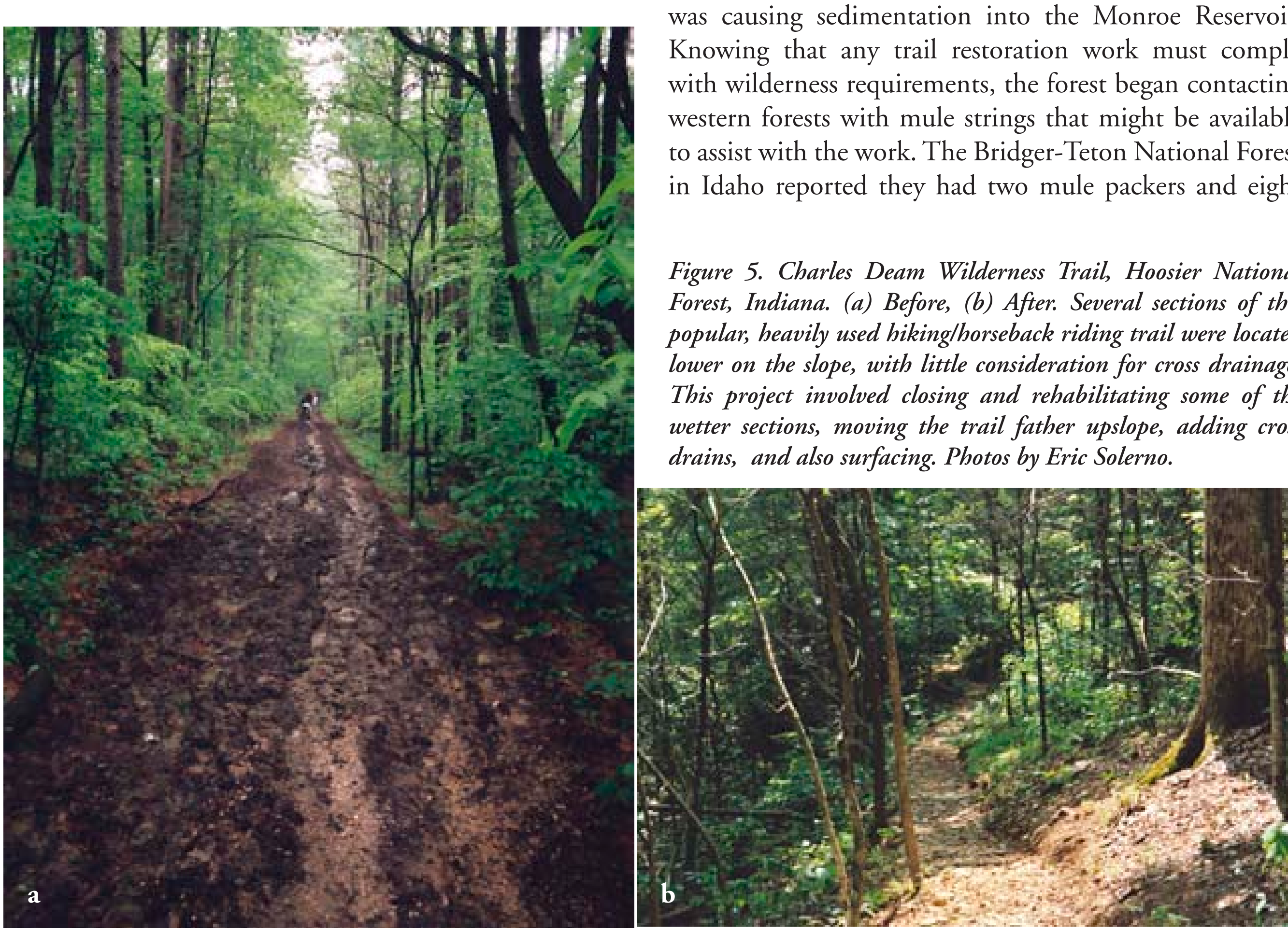


*Figure 5. Charles Deam Wilderness Trail, Hoosier National Forest, Indiana. (a) Before, (b) After. Several sections of this popular, heavily used hiking/horseback riding trail were located lower on the slope, with little consideration for cross drainage. This project involved closing and rehabilitating some of the wetter sections, moving the trail father upslope, adding cross drains, and also surfacing. Photos by Eric Solerno.*

mules that handled their trail restoration work during the summer season. But during the winter and late spring, these resources were available and willing to work. A partnership formed between the forests, and since 2000, two packers and eight mules have spent the month of May on the Hoosier National Forest performing trail restoration work both inside and outside wilderness. In that period, 11.5 miles (18.5 km) of trail have been constructed or reconstructed to move them up out of the low areas and more than 500 tons (453 metric tons) of gravel have been hauled by mules and placed to harden the trail surface (Figure 5b).

This partnership is both innovative and definitely a "win-win" situation for both national forests and the resources.

### Huron-Manistee – Landscape Approach Through Partnerships (figure 6)

The Huron-Manistee National Forests' motto is "United by Rivers". The forests' location in central Lower Michigan makes them accessible to over 60 million people who are within a day's drive (Leefers et al. 2003). A prized feature is the deep groundwater-fed rivers that support world-class fishing, as well as providing habitat for a variety of endangered, threatened, and sensitive species. Viewing the mixed land ownership patterns within the watersheds as an opportunity, the forests took a collaborative approach using partnerships to tackle problems on a landscape scale.

In the mid 1990s, the forest partnered with local Resource Conservation and Development Councils, and initiated watershed-wide inventories focused on stream crossings (NMRC&D and USFS 1992; NMRC&D and USFS 1994; HPRC&D and USFS 1996; CRA and USFS 2004). The partners developed a rating system to assess potential for sediment delivery and fish passage impairment. Over 1170 crossings were identified at the watershed level (within 5th-level Hydrologic Units). A majority of crossings were off the national forest; only 220 were on National Forest System lands. Sediment was the most frequent problem, with county roads accounting for a majority of the problems. Of the county crossings, 70% were rated "severe" or "moderate". In addition to sedimentation problems, 160 crossings had fish or aquatic organism passage problems.

Using the inventory results, the forest has successfully integrated the TRTR Program into their watershed restoration efforts. During the period 1998-2002, 46 projects have been completed with nine different county road commissions, upgrading road-stream crossings, addressing aquatic organism passage, and improving roads in riparian areas (Figure 6). Almost $2.7 million has been expended, of which 40% or $1.1 million has been contributed by the partners. Benefits include over 92 miles (148 km) of stream habitat improvement downstream from the projects. The partners' funding has come from multiple sources including Clean Water Act, Section 319 grants, Department of Transportation Intermodal Surface Transportation Efficiency Act [ISTEA, 1991] and Transportation Equity Act for the 21st Century [TEA-21, 1998] funds, and Clean Michigan Initiative funds.

*Figure 6. Road improvements on the Huron-Manistee National Forest, Lower Michigan. (a) Before, photo by William Fowler, (b) After, photo by Robert Stuber. Former road was narrow, with native material for road surfacing; drainage structures were undersized with many acting as barriers to aquatic organism passage. Road surfacing was hardened; alignment improved, some of the crossings were elevated; drainage structures were replaced with at least one bridge added; side slopes were stabilized and outlet drains provided to catch and direct runoff. This was a 2-mile long project that occurred over three years.*

Working together, the forest and its partners have been able to leverage funds to accomplish work that no one partner could do alone, providing multiple benefits to the public, the resources and to the watersheds. There is still more work to do and it continues annually, with the goal of improving aquatic habitat and watershed function.

## Closing

Eastern national forests are largely comprised of lands that were cut over, burned, farmed and mined. In over 100 years of managing these national forests we have made great progress in improving the condition of the "lands nobody wanted", but considerable work is still needed to address impacts to the aquatic resource. The Roads and Trails for States program has enabled the Eastern Region to address many of the existing road and trail stream crossings that are contributing sediment and restricting aquatic organism passage. Continued implementation of this program using integrated teams and partners ensures that the transportation system can co-exist with maintenance of valuable riparian and aquatic habitats.

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Hiawatha NF: Ruthann Trudell - Forest Hydrologist; Richard Kell - Forest Engineer

Hoosier NF: Eric Solerno - Engineer, TRTR Coordinator; Brad Lidell - Forest Engineer

Huron Manistee: William Fowler, Hydrologist, TRTR Coordinator; Robert Stuber - Fish Program Manager

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# The Alkali Creek Story: 40 Years of Gully Control

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In the early 1960s, Burchard Heede of the Rocky Mountain Forest and Range Experiment Station designed and implemented a whole-basin (356-hectare) gully restoration plan in Alkali Creek, Colorado. This modest experiment and its results still serve as some of the benchmark research in gully control 40 years later. The project elements included perimeter fencing for cattle exclusion, check dams in a variety of forms, headcut control measures, revegetation, and conversion of several gullies to vegetation-lined waterways. These original designs are presented along with a discussion of findings after approximately twelve years, as well as the present status four decades after project implementation.

Keywords: *watershed restoration, gully control, check dams, vegetation-lined waterways, riparian vegetation*

## Introduction

Many of the specific details of the Alkali Creek experiment are chronicled in detail in a number of publications by Burchard Heede (e.g., Heede 1976, 1977). Therefore this paper focuses on how the project came into being, what was done and why, and the resulting changes after four decades.

## Study Area

### Location

The study site is located in the headwaters of Alkali Creek on the Rifle Ranger District of the White River National Forest, approximately 32 km south of Silt, Colorado. Alkali Creek is a tributary to West Divide Creek, which enters the Colorado River at Silt. The 356-hectare study site ranges in elevation from 2,320 to 2,560 m.

### Climate

The annual temperature varies from a maximum mean monthly temperature of 27°C in July to a minimum mean monthly temperature of -16°C in January. Between 1962 and 1974 the project area received about 48 cm of precipitation annually. Precipitation throughout the year was fairly evenly distributed with a low of 3 cm in January to a high of nearly 6 cm in September (Heede 1977). Snow is typical between October and April.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

### Vegetation

The project area is representative of the oakbrush-sagebrush-grasslands of the western slope of the Rocky Mountains in Colorado. Sagebrush (*Artemisia* spp.) and grasslands primarily occupy the valley bottoms and southern aspects while thick stands of oakbrush (*Quercus gambeli*) dominate the upper parts of the northern aspect. Typical grasses include Kentucky bluegrass (*Poa pratensis*), western wheatgrass (*Agropyron smithi*) and small amounts of introduced crested wheatgrass (*Agropyron cristatum*). Small amounts of serviceberry (*Amelanchier alnifolia*) and snowberry (*Symphoricarpos albus*) are present along with occasional groups of aspen (*Populus tremuloides*) near the valley bottom.

### Geology and Soils

The parent geology of the project area is the Tertiary Wasatch formation, which is composed of clay shale and sandstone. The sandstone varies from fine- to coarse-grained and, in places, is strongly calcareous.

The soils are formed predominantly from shale and beds of sandstone (Fox and Nishimura 1957). Mechanical analysis of the soil done in the mid-1960s showed the distribution of clay, silt, and sand averaged 52%, 28%, and 20%, respectively, with the clay content as high as 65% (Heede 1977). Coarse materials, such as gravel or boulders, are essentially absent from the gullies.

Soil properties were measured in the early 1960s during project design. The disturbed soils in the valley bottoms, where grazing pressure was concentrated, typically had infiltration rates that were 4 to 5 times lower than adjacent upslope oakbrush areas with relatively light grazing impacts. The compaction of valley floor soils decreased the amount of precipitation needed to generate overland flow and led to the subsequent erosion of gullies into the fine grained soil. Recovery of soil porosity and permeability would eventually be a key component in the stabilization of the drainage network.

## Gully Stream Flows

Stream flows in the gullies typically occur only during the spring snowmelt and at times of intense summer thunderstorms. During 1963 and 1964, the measured peak spring runoff in the project area was 0.57 to 0.71 $m^3/s$ (20 to 25 $ft^3/s$). Heede (1977) determined these to be normal precipitation years bases on regression with nearby long term weather stations in Collbran and Glenwood Springs, Colorado. Measured peak discharges in 2005, an average precipitation year, did not exceed 0.09 $m^3/s$ (3 $ft^3/s$). These measurements corroborate past observations in project file memos of considerable overland flow during snowmelt prior to project implementation versus little evidence of overland flow today.

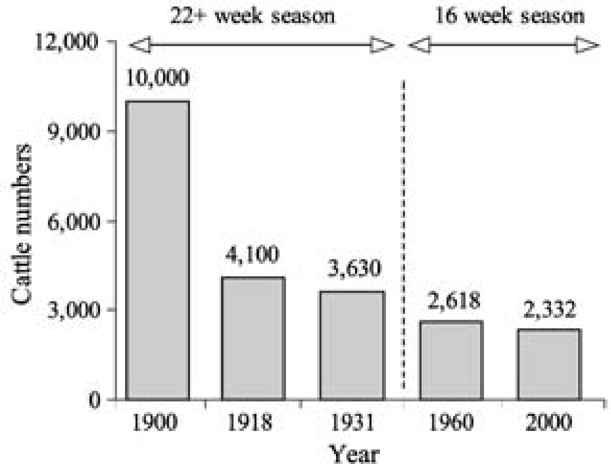
## Grazing History

The Alkali Creek watershed is a small part of the 182-$km^2$ West Divide cattle allotment. The south aspects of the project area also serve as winter range for elk (*Cervus elaphus nelsoni*) and mule deer (*Odocoileus hemionus hemionus*).

Cattle grazing likely began in the watershed commensurate with the settlement along the Colorado River and its tributaries in the late 1800s. Local ranchers estimate that as many as 10,000 head of cattle grazed the present allotment boundaries in the early 1900s. Figure 1 shows the change in cattle numbers within the West Divide allotment over time. A notable feature of Figure 1 is the reduction in the grazing season from 22 weeks to 16 weeks that occurred in the mid 1950s. This reduction occurred in the early part of the season, which kept the cattle off the soils soon after snowmelt when moisture content was more likely to be optimum for detrimental soil compaction.

As early as 1916 there are written accounts in the allotment files from the range conservationist discussing the poor condition of the watershed. This led to decreasing stock numbers through the 1940s. In the late 1940s, a range conservationist named Carl Henderson began documenting the range conditions in the Alkali watershed. There are numerous summaries and field reports in the allotment file that chronicle "excessive overland flow from depleted range." His recommendation was to cease grazing in Alkali Creek altogether. The proposal at the time was a 31 percent reduction in cattle numbers, which he described as "too little, too late." Figures 2, 3, and 4 show the conditions that Carl Henderson saw on the ground. The soil pedestal supporting the large boulder in Figure 2 illustrates the significant loss of topsoil (and therefore water storage) in the area prior to 1957.

*Figure 1. Bar graph of cattle numbers on the West Divide allotment. Data from the White River National Forest grazing allotment file records and from Heede (1977).*




The series of photos in Figure 5 depicts the type of changes that occurred on the landscape between 1915 and present. There are anecdotal accounts of being able to cross the gullies shown with on horseback or in a wagon in 1915 (note the line and dots for reference). Between 1915 and 1949 considerable gully incision occurred. The gully widened and stabilized with less bare ground visible by 2004.

## Project Development

The gully network, along with the efforts of Carl Henderson to elevate the issue of range condition to the District Ranger, led to the development of the Alkali Creek

*Figure 2. Soil pedestal supporting large boulder in 1957 photo. Note camera at the pedestal base for scale. Photo by P. Hauk.*

*Figure 3. Gully development through former cattle watering location at Mud Springs in 1949. Gully depth is approximately 5 meters. Photo by C. Henderson.*

*Figure 4. Main gully in 1947 near the downstream end of the eventual project area. Photo by C. Henderson.*

Soil and Water Project. The project had a scope larger than active gully control, and included the following:

1947-48 – Construction of stock ponds to distribute cattle away from streams.

1951 – Seeding of 49 ha of disturbed ground with grasses.

1952 – Contour trenching on selected hill slopes to enhance water infiltration.

1953 – Seeding of 53 ha of disturbed ground with grasses.

1958 – Perimeter fencing to exclude cattle from a 356-ha area in Alkali Creek.

1959 – Boy Scouts plant 500 New Mexican locust trees (*Robinia neomexicana*), all of which died.

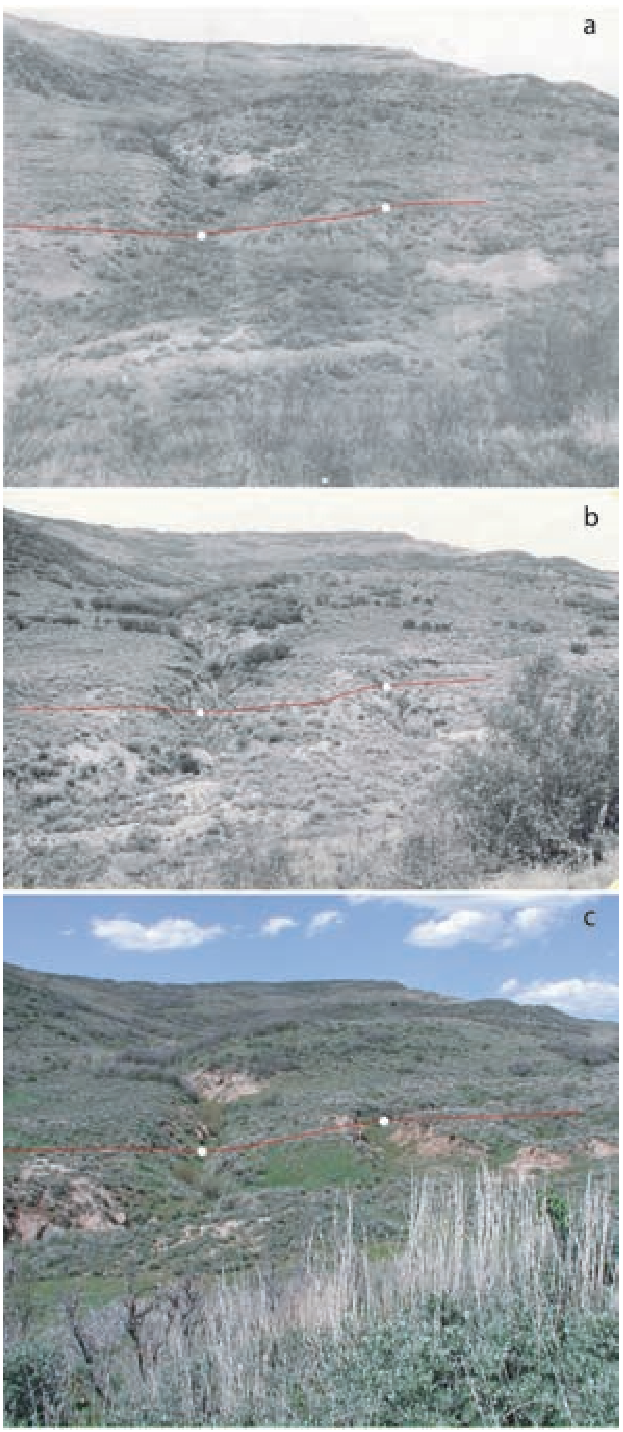
1960 – Cooperative agreement between the White River National Forest, the Rocky Mountain Regional Office (FS Region 2), and the Rocky Mountain Forest and Range Experiment Station for an experimental watershed/gully restoration project in the fenced area of Alkali Creek.

1961-1964 – Gully treatments installed.

Burchard Heede was the principal investigator from the Range and Experiment Station in Fort Collins, Colorado. He designed the gully restoration project, prepared the construction plans, and evaluated the results. The White River National Forest provided the labor and equipment needed to accomplish the survey work and project implementation. The Rocky Mountain Regional Office, Division of Watershed Management, provided funding for the project.

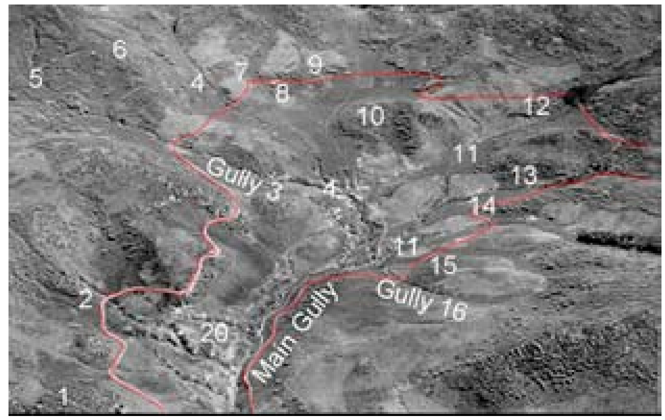
Initial survey and design work began soon after the agreement was in place and the first gully control structures were installed in 1961. A road was constructed in 1962

*Figure 5. (a) Gully No. 4 as photographed from control point CP-39 in 1915. Note that it can still be crossed by wagon or on horseback (see horizontal line and dots for location). File photograph. (b) By 1949 the gully had deepened considerably, with very steep side walls. Photo by P. Hauk. (c) By 2004, the gully had stabilized and the side walls had flattened and become more vegetated. Photo by M. Weinhold.*




to provide equipment access to the gullies higher in the basin. Figure 6 shows the location of the access road and the numbered gullies proposed for treatment. Project implementation was largely complete in 1963, with maintenance occurring throughout 1964.

*Figure 6. Oblique view of the Alkali Creek project area. The red line shows the alignment of the access road. The numbers identify gullies proposed for treatment. File photograph.*




Treatments included an assortment of check dams, headcut treatments, and vegetation-lined waterways. The type and number of structures are shown in Table 1. A variety of treatment types with different unit costs was intentionally used because cost effectiveness was a key component of the project evaluation program.

*Table 1. Gully treatment types employed at Alkali Creek, Colorado.*

| Structure Type | Number Used | See Figure No. |
|---|---|---|
| Precast concrete check dam | 1 | 12 |
| Loose rock check dam | 56 | 7, 13 |
| Gabion check dam | 7 | 7 |
| Single fence rock check dam | 12 | 8 |
| Double fence rock check dam | 40 | 9, 11 |
| Headcut control structure | 15 | |
| Vegetation-lined waterway | 4 | 10, 14 |

Gabion and loose rock check dams (Figure 7) are essentially the same type of structure, except that the former is wrapped in a wire fence mesh for added stability. Single fence check dams, shown in Figure 8, used steel fence posts and wire fence to support the rock fill on the downstream side to reduce the amount of rock required for construction. Similarly, double fence rock check dams (Figure 9) had post and wire fences on the upstream and downstream faces of the structure, with a 60-cm-thick layer of rock between. Headcut armoring consisted of

*Figure 7. Typical loose rock check dam, in this case wrapped in wire mesh for added stability. Photo by B. Heede.*

*Figure 8. Typical single fence check dam. Photo by B. Heede.*

placing a layer of rock over the flattened headcut with a loose rock check dam immediately downstream.

Four gullies were converted to vegetation-lined waterways. While this method had been successfully employed in flat farmland across the country, this was a new approach to gully restoration on mountain slopes. The existing gullies were filled and a new, wider sinuous channel was built. Increased sinuosity extended the length of the waterway and consequently reduced the gradient. The combination of a lower gradient and shallow, wide cross section decreased the erosive energy of the water so that a thick layer of vegetation would prevent gully development. The sequence of construction is shown in Figure 10.

## Results and Discussion

The photo pairs in Figures 11 through 14 clearly show the recovery that occurred in the Alkali Creek watershed over the last four decades. In each case, the initial photo was taken soon after project implementation in the early

*Figure 9. Typical double fence check dam. Photo by B. Heede.*

1960s and the second photo was repeated in 2004. An effort was made to reoccupy the same photo point and provide a person in the same location for scale.

A striking result of this project was that none of the 131 gully control structures failed permanently. This high rate of structure stability was unique for the 1960s when check dam failure was the order of the day. On the other hand, nearly half of these check dams required some sort of maintenance between 1961 and 1964. This maintenance was primarily targeted at filling pore spaces in the rock structures created by poorly graded, large rock that did not meet design specifications. No maintenance has occurred since 1964.

There are several reasons for the high success rate of the structures built in Alkali Creek. Perhaps the most important was vegetation management. This primarily occurred through grazing management with the construction of the perimeter fence around the project area in 1958. This not only allowed the vegetation to recover, but it allowed soil properties to recover as well. These two parameters, increased vegetation and increased infiltration, would ultimately reduce the amount of overland flow, the original driving force for gully formation and enlargement. The perimeter fence is still maintained today.

A second reason for success was that detailed structural and hydraulic designs were developed for each gully control structure. Careful attention was given to design flows, structure dimensions, keying structures into the gully sidewalls, and overflow scour protection. Burchard Heede was a hydraulic engineer and he approached the work of gully control very quantitatively. This is clear in his summary publications on Alkali Creek (Heede 1977) and gully control in general (Heede 1976) where literally all aspects of design and evaluation are captured in formulae. For example, he provides a formula for calculating everything from the notch depth in a spillway to the

*Figure 10. (a) Vegetation lined waterway construction sequence. Original gully configuration. (b) Shaping the new waterway after filling and compacting the old gully. (c) Completed waterway after establishment of vegetation. Note that the new flow line is offset from the original gully location. Photos by B. Heede.*

*Figure 11. (a) Double fence check dam at the base of the main gully (structure M0) during peak snowmelt runoff in the spring of 1964. Photo by B. Heede. (b) The same double fence check dam during the fall of 2004. Photo by M. Weinhold.*

number of fence posts needed to construct a double fence check dam.

A third reason that no structures failed is that, in retrospect, the project area was over-treated. Approximately 44 percent of all check dams did not see enough flow in the first 12 years to have measurable sediment deposits. Only 27 percent of the check dams filled entirely, and these were primarily located along the main gully. This over-treatment was related to a gully's position in the watershed: nearly two-thirds of second order streams collected no sediment. As such, confining check dams to third- and fourth-order streams would have reduced project costs by 30 percent (Heede 1977). Even gullies that were not directly treated saw some benefit due to the establishment of base-level control provided by treatments at the confluence with larger, more active gullies.

Another result of the Alkali project, which had been observed in other gully restoration projects, was that ephemeral flow in the lower reaches of the main channel became perennial seven years after treatment. This was likely due to the water storage provided behind the

*Figure 12. (a) Precast concrete check dam at the base of the main gully during spring runoff in 1964. Photo by B. Heede. (b) The same structure during the early summer of 2004. Photo by C. Hirsch. Note that the right half of the structure is covered by willows.*

*Figure 13. (a) Rock check dam on the main gully (structure M5) during spring runoff of 1964. Photo by B. Heede. (b) Same rock check dam in the fall of 2004. Photo by M.Weinhold.*

sediment-filled check dams along the length of the main gully.

The vegetation-lined waterways were not immediately stable, due to their dependence on a robust layer of vegetation prior to exposure to overland flow. In some cases, burlap strips were buried perpendicular to the thalweg of the waterways to slow the flow during the first few runoff seasons and prevent rill formation (see Figure 14a). The burlap rotted away after several years. Fertilization was also necessary at all waterway sites due to a lack of phosphorus in the disturbed soils. Fertilizer was reapplied to all four vegetation-lined waterways in spring 2005 and minor headcuts were filled with small rock.

## The Legacy of Burchard Heede and Alkali Creek

Gully control has been an ongoing process in the United States since the late 1700s. Burchard Heede created his legacy in that field by bringing gully control to the mountains and to the Forest Service. Even though gully control had been occurring on national forests in the southeast prior to Burchard Heede, he made substantial gains in quantifying the science of gully control and making that research and design guidance available to users in the Forest Service and beyond. He was an advocate for treating gullies as a system, with special attention paid to gully formation processes.

The printed legacy of the Burchard Heede's Alkali Creek experiment is extensive. Publications began rolling off the press within a year of project completion. Below is a partial list of the project related publications; complete references are contained in the bibliography.

- 1964. A pavement breaker attachment to drive steel fenceposts.
- 1965. Multipurpose prefabricated concrete check dam.
- 1966. Design, construction and cost of rock check dams.

*Figure 14. (a) Vegetation-lined waterway No.16 in early 1960s with burlap strips in place to disperse flow. Photo by B. Heede. (b) The same waterway in the early summer of 2004. Photo by C. Hirsch.*


- 1967. Fusion of discontinuous gullies: A case study.
- 1968. Conversion of gullies to vegetation-lined waterways on mountain slopes.
- 1970. Morphology of gullies in the Colorado Rocky Mountains.
- 1971. Characteristics and processes of soil piping in gullies.
- 1974. Stages of development of gullies in western United States of America.
- 1975. Submerged burlap strips aided rehabilitation of disturbed semi-arid sites in Colorado and New Mexico.
- 1976. Gully development and control: The status of our knowledge.
- 1977. A case study of a watershed rehabilitation project: Alkali Creek, Colorado.

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Heede, BH. 1967. Fusion of discontinuous gullies: A case study. *Bulletin of the International Association of Scientific Hydrology*. 12:42-50.

Heede, BH. 1968. Conversion of gullies to vegetation-lined waterways on mountain slopes. Res. Pap. RM-40. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 11 p.

Heede, BH. 1970. Morphology of gullies in the Colorado Rocky Mountains. *Bulletin of the International Association of Scientific Hydrology.* 15:79-89.

Heede, BH. 1971. Characteristics and processes of soil piping in gullies. Res. Pap. RM-68. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 15 p.

Heede, BH. 1974. Stages of development of gullies in western United States of America. *Z. Geomorphol.* 18(3):260-271.

Heede, BH. 1975. Submerged burlap strips aided rehabilitation of disturbed semi-arid sites in Colorado and New Mexico. Res. Note RM-302. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 8 p.

Heede, BH. 1976. Gully development and control: the status of our knowledge. Res. Pap. RM-169. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 42 p.

Heede, BH. 1977. A case study of a watershed rehabilitation project: Alkali Creek Colorado. Res. Pap. RM-189. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 18 p.

# The Once and Future Streams: Re-creating Bailey and Karnowsky Creeks, Central Oregon Coast Range, USA

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The Bailey Creek Project reconstructed over one mile of meandering stream channel in a low-gradient valley on the central Oregon Coast. The original channel was moved, straightened and diked to accommodate agriculture over the last century. After it was straightened, the channel velocity increased, leading to incision and bank erosion, degrading water quality and fish habitat. The project's focus was restoring wetland, stream and floodplain functions to a stream that once provided excellent rearing habitat for coho salmon (*Oncorhynchus kisutch*). The new, meandering channel was built in 1999 and water was introduced in 2000. From 1999 through 2003, native trees and shrubs were planted and wood was added to the stream. Monitoring results document five times the number of juvenile coho in the project area compared to a control reach. Lessons learned from Bailey Creek were applied to Karnowsky Creek, a tidally influenced, Siuslaw River tributary with a channelization history similar to Bailey Creek. Over two miles of meandering main-stem channel were constructed in late summer 2002. In 2003, ditches were filled, water was turned into the new channel and over 130 large whole trees were placed in the new channel and floodplain by helicopter. A variety of native trees and shrubs have been planted on the valley floor. In 2004-2006, two tributaries with valley gradients of 3-5% are being restored by building new channels with step-pool morphology. Project monitoring consists of 22 channel cross-sections to track changes in the new channels' geometry, groundwater wells, photo points, low-elevation aerial photography, spawning surveys and juvenile fish snorkel counts.

Keywords: *coarse woody debris, coho salmon, channel geomorphology, fish habitat, riparian vegetation, stream reconstruction, stream restoration, wetlands*

All photos, maps and figures were taken/created by authors.

## Introduction

The Siuslaw National Forest, Oregon, in collaboration with partners, has restored two low-gradient, channelized streams in the central Oregon Coast Range by constructing new, meandering streams to replace the existing ditches. Bailey Creek flows through Enchanted Valley into Mercer Lake, and then about five miles (8 km) out to the ocean just north of Florence, Oregon. Karnowsky Creek flows into the Siuslaw River estuary between the towns of Florence and Mapleton, Oregon, approximately nine river miles (14.5 km) from the ocean. Both streams flow through flat-bottomed valleys and share a similar homesteading history. The valley land was cleared for agriculture in the late 1800s, and in the early to mid-1900s the streams were channelized into ditches along the sides of these valleys to provide more pasture.

As a result of the channelization, sinuosity decreased, and stream gradients and water velocity increased. The stream downcut into the valley floor creating high, erosive banks. At Bailey Creek, sedimentation into Mercer Lake increased, creating a large delta into the lake. A repeated topographic survey of this delta from 1998-2000 showed that the delta grew over 3 meters laterally during this period. The Bailey Creek ditch was also attempting to re-create meanders in the ditch, which increased bank erosion and sediment production. At Karnowsky Creek, the larger tributary streams to the valley with gradients from 3-5% had also been channelized, and these tributaries had severely downcut three meters or more to match the main valley ditch incision.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

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In general, the restoration of these two streams involved a process that used reference data, local flow equations, stream classification, dimensionless ratios, and cross-checking using Manning's equation. It must be stressed that this process is iterative and not linear. Many of the steps loop back or occur simultaneously due to the complex interactions of stream processes that are being recreated. When one variable changes, so do all the others. The thought process weaves all the factors together at once as opposed to following a cookbook recipe.

For both Bailey and Karnowsky Creeks, questions to be answered included the following: What type of stream should be built to fit the valley type and landscape? What should the dimensions of the new channel be, including the width, depth, cross-sectional area, gradient, sinuosity and pool depth and length? In general, the steps in the design processes for both Bailey and Karnowsky Creeks are as follows :

1. Find a relatively undisturbed stream with similar characteristics to serve as a guide for the new channel design and measure its parameters.
2. Determine the bankfull discharge of the new channel.
3. Determine the cross-sectional area for the new channel, which determines the capacity of the stream to carry its flow and maintain the channel's dimensions.
4. Determine the new channel's slope and sinuosity, which may vary downstream through the valley. Slope is the main parameter influencing a stream's energy, which in turn determines the sediment transport capacity and potential for erosion.
5. Refer to Rosgen's (1996) stream channel classification system to see if the values chosen for the new channel fall within the range of variability for the chosen channel type. This step serves as a useful reality check.
6. Determine the minimum, maximum and average radii of curvature for the meanders in the new channel. The radius of curvature influences shear stresses on banks, and will partly determine the layout of the new channel.
7. Lay out the design on a base map, and then on the ground. An accurate survey is essential for this step. Test the design, checking the sinuosity, gradient, shear stresses, and capacity of the channel to carry the predicted bankfull flows. Manning's equation, among others, is useful for this step. The layout may have to be modified several times before a satisfactory design is finished.

## Bailey Creek Restoration

Enchanted Valley was acquired by the USDA Forest Service in 1991, and planning began on the Bailey Creek restoration project in 1995. Goals of the project included: improving rearing habitat for coho salmon (*Oncorhynchus kisutch*), a threatened species on the Oregon Coast; reconnecting the channel with its floodplain; restoring riparian vegetation; and reducing sedimentation into Mercer Lake, which was a major concern for homeowners along the lakeshore. Public concerns about the project included reduction of elk (*Cervus elapus roosevelti*) forage in the valley, skepticism of the project's purpose and need, and possible increased sedimentation into Mercer Lake caused by constructing a new channel. Six public working group meetings held in 1997 were aimed at working through these concerns with the public, and a compromise was reached where only the lower half of the cleared and channelized valley would be rehabilitated while the upper valley would be maintained for elk forage.

### Methodology

The first step in the planning process was gathering data on existing conditions, and comparing Bailey Creek to a similar stream that had not been cleared and channelized. We enlisted a professional Forest Service surveyor to create a topographic map of the valley floor with a one-foot (0.3-m) contour interval, and we used this topographic map as our base map. Other data collected included several cross-sections of the existing ditch, pebble counts at the cross-section locations, a longitudinal profile of the ditch, and cross-sections and pebble counts of Bailey Creek upstream of the channelized section. For reference on pre-channelized conditions, we had a 1955 aerial photo. Although channelization had already occurred, the original stream channel was still visible in the pasture of the upper valley. We used this photo to determine the historic sinuosity and meander geometry. We also measured cross-sections on Leitel Creek, which flows into Tahkenich Lake, another coastal lake south of Florence, Oregon. Although Leitel Creek is surrounded by early seral industrial forestland, the valley bottom has not been cleared for agriculture and the stream has not been straightened. Given that this valley has a similar geomorphology and setting to Enchanted Valley, Leitel Creek served as a reference stream for our design.

Determining the bankfull or "design" flow was the most challenging aspect of data collection, and we used several sources of information. A master's thesis by Giese (1996) correlated flow measurements to 16 years of rainfall records for Bailey Creek. This flow information was used along with discharge measured in the field during winter flow events, and with data from nearby gauged watersheds. Where reed canarygrass (*Phalaris arundinacea*) overhung straightened ditches at Bailey Creek, there were no discernable bankfull indicators, which greatly hampered determination of bankfull discharge in the ditch.

Once parameters of sinuosity, channel gradient, cross-sectional area, and design discharge were obtained, they were fit together into an appropriate channel geometry. Similar to our observed reference stream, Leitel Creek, the desired future condition of the new channel was one that floods frequently during the winter to re-establish seasonal wetland characteristics, but maintains a stable cross section that would not be prone to heavy bank erosion. A decision had to be made whether the new channel would be a Rosgen (1996) "C" (wide, shallow channel) or "E" channel type (deep, narrow channel). Based on the low gradient of the valley, the geomorphic setting (an old lake bed), and the cross-sections from Leitel Creek, a Rosgen "E" channel type was chosen.

To make sure that the stream frequently overtopped its banks during winter flows, riffle cross sections of the upper 1,341 meters (4,400 feet) of channel were designed 30% smaller than the existing ditch. Also, knowing that Mercer Lake backs up into the lower third of the project area every winter, the bottom 335 meters (1,100 feet) of channel was undersized by an additional 50% to facilitate inundation and sediment drop out in the floodplain. Pools and riffles were not built in the "pilot" channel at the lower end. See Tables 1-3 for the measurements of the pre-project ditch, the new design channel and the pilot channel.

The next step was translating the design parameters to a map view of the new channel. Using the newly surveyed topographic map of the valley floor as a base map, a piece of string was cut to the scale representing the length of the new channel and then taped to the upper and lower end of the project area on the map. The string was laid out so that the channel followed the low spots of the valley, and the meander length and radius of curvature averaged about 74 m (240 feet) and 16 m (52 feet), respectively. This step took several trials. Once satisfied with the layout, the "string" map was digitized onto an electronic map using a geographic information system. Points were added that represented stakes to survey on the ground. A surveyor then translated the staking points to coordinates based on the bench marks put into the original topographic survey. With these coordinates input into the total station survey equipment, the surveyor moved personnel into the stake locations by trial shots until the proper coordinates were located and center-line channel stakes were pounded in. When it was discovered that the new channel would cut through some high ground, resulting in banks that would be higher than the rooting depth of the grasses and sedges, that portion of the channel was redesigned and moved into

*Table 1. Enchanted Valley specifications.*

| | |
|---|---|
| Basin size | 11.4 km$^2$ (4.4 mi$^2$) |
| Bankfull flow | 5.1-6.8 m$^3$/s (180-240 ft$^3$/s) |
| Average high flow | Approx. 2.3-2.5 m$^3$/s (80-90 ft$^3$/s) |
| Average winter base flow | Approx. 0.7 m$^3$/s (25 ft$^3$/s) |
| Low summer flow | Approx. 0.03 m$^3$/s (1 ft$^3$/s) |
| Valley slope | 0.0034 |
| Valley length | 954 m (3100 ft) |
| Stream bank substrate | 60% silt/clay, 40% sand |

*Table 2. Bailey Creek measurements. (* based on cross-sections above channelized section)*

| Parameter | Historic Channel | Ditch | Design Channel (1,340 m) | Pilot Channel (335 m) |
|---|---|---|---|---|
| Sinuosity | 1.66 | 1.1 | 1.8 | 1.8 |
| Gradient | 0.0022 | 0.0032 | 0.0019 | 0.0019 |
| Bankfull width | 8.5-12 m (28.5-40 ft)* | 4-4.5 m (13-15 ft) | 6.4 m (21 ft) | 3.0 m (10 ft) |
| Belt width | 68-85 m (220-275 ft) | Not applicable | 46-77 m (150-250 ft) | 46-77 m (150-250 ft) |
| Meander length | average 77 m (250 ft) | Not applicable | average 73 m (239 ft) | average 73 m (239 ft) |
| Radius of curvature | average 25 m (82 ft) range 12-43 m (40-140 ft) | Not applicable | average 16 m (52 ft) | average 16 m (52 ft) |
| W/D ratio | No information | lower valley, 2-3 above channelized, 25 | 7.0 | 3.3 |
| Riffle cross-sectional area | No information | 8.4 m$^2$ (90 ft$^2$) | 6.3 m$^2$ (60 ft$^2$) | 2.8 m$^2$ (30 ft$^2$) |

*Table 3. Bailey Creek new channel design specifications, Enchanted Valley Stream Restoration.*

| | | | |
|---|---|---|---|
| Design flow | 2.8 m$^3$/s (100 ft$^3$/s) | Channel cross-section area | 5.6 m$^2$ (60 ft$^2$) |
| Flood frequency | 12-20 days per year | Bankfull width | 6.5 m (21 ft) |
| Design velocity | 0.3-0.4 m$^3$/s (1.0-1.3 ft$^3$/s) | Bankfull depth | 0.9 m (3 ft) in riffles, 1.5 m (5 ft) in pools |
| Channel length | 1,684 m (5,474 ft) | Width/depth ratio | 7 |
| Rosgen type | E | Meander wave length | 74 m (239 ft) |
| Sinuosity | 1.8 | Radius of curvature | 16 m (52 ft) (2.5 x channel width) |
| Slope | 0.0019 (overall) | Pool/riffle spacing | 32-45 m (105-147 ft) |


*Figure 1: Low-elevation aerial photograph of the new Bailey Creek channel before connection to stream flow. September 2000.*

the lower spots, being careful to maintain the calculated length and gradient of the new channel.

For the 1,341 meters of upper channel (design channel), a pool-riffle morphology was designed for the stream bottom, with the pools occupying approximately half of the stream length on the outside of meander bends. The entire new channel was excavated in late summer 1999, taking about a month to construct with an excavator and 18-yard dump truck (Figure 1). We used a laser level to check the gradient during the construction of the entire 1,676-meter-long channel. The outside bends of meanders were revegetated with willow (*Salix* spp.) stakes in early spring of 2000, and the new channel was connected to water in the October 2000. Also in 2000, the abandoned ditch was intermittently plugged with fill material that had been stockpiled during channel construction, leaving ponds in the unfilled areas. Since then, wood has been added to the channel, tributary channels from the valley side slopes have been connected to the main channel, and elderberry (*Sambucus racemosa*), red alder (*Alnus rubra*), Sitka spruce (*Picea sitchensis*), western redcedar (*Thuja plicata*), and several other native species have been planted in the riparian zone along the new channel.

**Monitoring**

Twenty-four permanently monumented cross-sections are surveyed and photographed each year to track channel morphology and vegetative changes. Low-elevation aerial photographs are flown semi-annually. Additionally, vegetation transects, spawning surveys and juvenile fish surveys are conducted yearly, and water quality surveys are done either yearly or concurrent with large storms.

**Results and Lessons Learned**

During the first two winters after connection, the stream overflowed its banks during peak flows, but not to the extent hoped for in the design channel section. Wood placed directly into pool cross sections in 2002 has significantly improved floodplain inundation in the design channel section. Ongoing bank erosion from the ditched channel above the project area inputs such high sediment loads during winter flows that point bars and mid-channel bars are being formed in the new channel. The channel is deepening in some places, and aggrading in others, but even as the shape of the bed adjusts, the overall cross sectional area remains fairly stable. After five years of tracking geomorphic changes in cross sections, the net overall change in cross-sectional area for the entire project reach is an estimated 0.02 $m^2$, well within measurement error (2004 Enchanted Valley Monitoring Report [USDA 2004]). See Figures 2-4 for changes to the constructed channel over time.

One area of concern is the connection between the old, downcut channel that was eight feet (2.4 m) below the valley floor and the new channel that is only three to four feet (0.9 to 1.2 m) deep. It was assumed that sediment would drop out upstream of the diversion point as water


*Figure 2: New Bailey Creek channel at photo point 7, in (a) 1999, and (b) 2004.*

*Figure 3: Over bank winter flow in Bailey Creek interacting with added large wood in channel, winter 2003.*

*Figure 4: Willows and conifers planted along the bank of the new Bailey Creek channel, 2003.*

slowed to enter the new channel at a lower gradient, and the old ditch would aggrade. Instead, a tail cut began to develop downstream of the diversion point, as the channel's longitudinal profile came into equilibrium between the two elevations (See Figure 5 for a cross sectional comparison). This situation is being monitored, but it may be necessary to remedy this cutting by adding larger substrate to the channel at the diversion point to smooth out the longitudinal profile and armor the channel bed. The existing stream bed at the old channel junction and in the rest of the constructed channel is silt loam.

Spawning numbers have been strengthening between 2000 and 2004, averaging 124 fish per kilometer per year compared to an average of 44 fish per kilometer per year during the four-year period before that (1996-1999). From 2002 to 2003 alone, there was an increase of 50 fish per kilometer. The 2003 spawning adults were the first juveniles reared in the project area that went to the ocean in the spring of 2001. The assumption is that juveniles of this year's class took advantage of both good rearing conditions in the new channel and good ocean conditions to produce the 2003 spawning numbers. Looking at other spawning counts in the surrounding area, Bailey Creek was one of the few areas that had an increase in 2003.

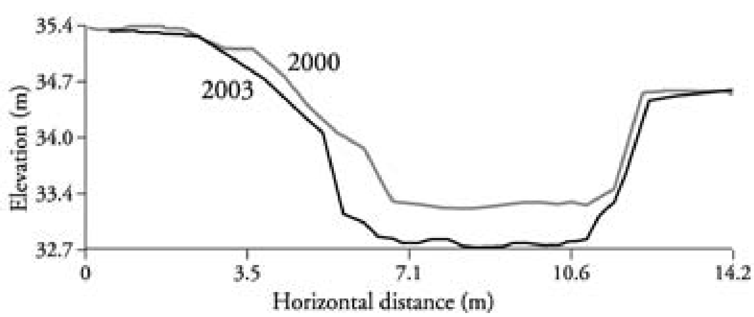


*Figure 5: Permanent cross-section #24 in new Bailey Creek channel just below diversion from the old ditch to new channel. Between 2000 and 2003, the new channel down cut into silt loam bed material approximately one-third of a meter.*

The new channel increased overall length by one-third, and the square meter pool volume doubled. Control data taken in the ditched channel above the project indicates that from 2001-2003, there were 1.5-2.0 times the number of juvenile coho compared to the two previous years sampled. At the same time, there was roughly a ten-fold increase in numbers of juvenile coho in the project area in 2001-2003. On a per-square-meter basis for 2003, the control estimate was 0.5 coho/$m^2$ while the project area estimate was 1.1 coho/$m^2$.

Although heavily browsed by elk, willows and planted vegetation are making progress in the riparian area of the design channel. Predictably, riparian vegetation in the pilot channel area has not done well due to the absolute dominance of reed canary grass in the lower valley that excludes all other species of plants, shrubs and trees. In the future, attempts may be made to establish willow in the pilot channel by using long willow stakes up to three inches in diameter pushed deep into the valley floor.

The Forest Service, Oregon Watershed Enhancement Board and the Oregon Department of State Lands spent $250,000 for the on-the-ground construction of 1.8 km (1.1 miles) of new meandering channel. The Forest Service spent another $250,000 on planning, design, implementation and monitoring through 2003 for an estimated total cost of $500,000.

## Karnowsky Creek

The Karnowsky Creek watershed was acquired by the Forest Service in 1992. From the start, partnerships with the local Siuslaw Watershed Council and Soil and Water Conservation District were developed to assist in the restoration of the watershed. This collaboration resulted in the hiring of a student intern team to develop a whole-watershed restoration plan for the Karnowsky Creek watershed during the summer of 2001. The student team researched the history of the area, the potential for fish and wildlife habitat and plant communities, and wrote a well-researched and illustrated restoration proposal. Using this proposal, the partnership applied for funds from the Oregon Watershed Enhancement Board and the National Forest Foundation to implement the plan.

The goals of the Karnowsky Creek restoration project are similar to those in Bailey Creek: increase the amount and quality of coho salmon rearing habitat, reconnect the channel with its floodplain, and restore riparian vegetation. In addition, a network of groundwater monitoring wells is being measured on a monthly basis to see if replacing a downcut ditch with a meandering stream successfully raises the water table. Unlike Bailey Creek, there is less concern about downstream sediment deposition, which allowed a higher degree of freedom in the design from permitting agencies.

### Methodology

As with Bailey Creek, the first step was producing a topographic map of the main valley and tributary valley floors with a contour interval of one foot (0.3 m) (Figure 6). Other data collected in the Karnowsky Creek watershed included several channel cross sections on the main ditch and tributary ditches, and discharge measurements taken during winter flow events. Part of the historic channel was still visible on a 1953 aerial photo, although much of that evidence of the historic channel had since been obliterated due to 70 years of agricultural use. Where the old channel was visible, it was used as a template for the new channel. Hoffman Creek was used as a reference stream, given that it is a nearby tributary of similar size and geomorphic setting that also drains into the lower Siuslaw River. Cross sections, pool dimensions, meander radius of curvature, pool/riffle ratio and reach gradient were measured throughout lower Hoffman Creek.

Unlike the pre-project ditch in Bailey Creek, there was more certainty that the main stem ditch in Karnowsky Creek had come into equilibrium with bankfull flows, and the size of the ditch would be a more accurate guide to the size of the new channel than using a flow equation. Bankfull discharge was calculated for the existing ditch by comparing results from a regional equation for small watersheds developed at Oregon State Univeristy (Adams et al. 1986), regional U.S. Geological Survey equations, and Manning's equation. As with Bailey Creek, a channel that overtops its banks frequently was the desired future condition, therefore, the new channel's cross-sectional area was designed 33% smaller than the ditch. It was assumed that the channel could more easily adjust to increase its cross-sectional area if it was undersized, than to decrease its cross-sectional area if it had been oversized.

Desired width/depth ratio, slope, and sinuosity of the new channel also had to be determined. The width/depth ratio is important, given that it is a major control on shear stresses on the banks and velocities within the channel. To determine whether the stream should be a Rosgen "C" (width/depth ratio > 12) or an "E" channel (width/depth ratio < 12) (Rosgen 1996), we used the width/depth ratio from Hoffman Creek (9.5), and referred to Rosgen's (1996) classification system to make our choice. We ran several width/depth combinations through Manning's equation and shear stress equations to compare the existing ditch's estimated discharge and shear stress with that calculated for the new channel. We decided on a width/depth ratio of 9.3; in other words, a relatively narrow channel. The

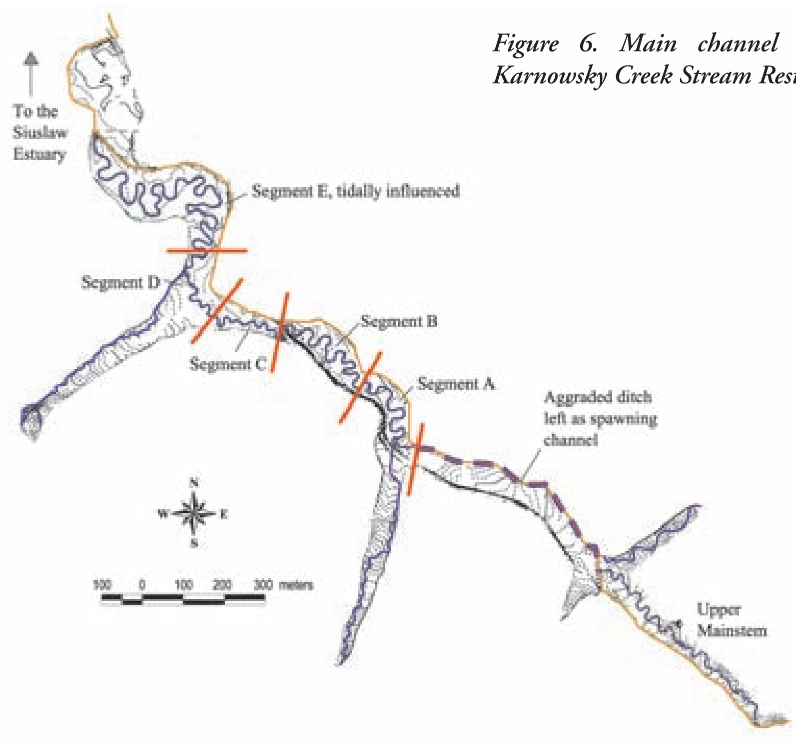


*Figure 6. Main channel design segments, Karnowsky Creek Stream Restoration.*

rationale was that the vegetation and root strength present in the valley will support the higher shear stresses and velocities found in an "E" channel, and a narrower, deeper channel would result in less direct solar heating in the stream in summer. Unlike the design for Bailey Creek, more variation in the size and shape of the meanders was included in the design for Karnowsky Creek (Williams 1986). Table 4 shows the new channel's dimensions and Table 5 shows the results of analysis with Manning's equation.

Slope and sinuosity are directly related. The upper part of the valley is slightly steeper, while the lower, tidally influenced part of the valley has a very low gradient. To fit the valley, the gradient of the newly designed stream gradually decreases from 0.39% at the homestead site to 0.11% in the tidally influenced zone. Sinuosity also increases down valley, from 1.9 to 2.8. In the tidally influenced zone, where frequent winter flooding occurs, we wanted to create as much fish habitat as possible. Therefore, two meanders were designed with narrow necks,

*Table 4. New Karnowsky Creek channel dimensions by segments shown in Figure 6.*

| Channel Segment | Width | Riffle Depth | W/D Ratio | Cross-sectional Area | Gradient | Sinuosity | New channel length |
|---|---|---|---|---|---|---|---|
| A | 4.3 m (14 ft) | 0.46 m (1.5 ft) | 9.3 | 5.6 $m^3$ (21 $ft^3$) | 0.0039 | 1.9 | 393 m (1,278 ft) |
| B | 4.3 m (14 ft) | 0.46 m (1.5 ft) | 9.3 | 5.6 $m^3$ (21 $ft^3$) | 0.0028 | 2.2 | 546 m (1,773 ft) |
| C | 4.3 m (14 ft) | 0.46 m (1.5 ft) | 9.3 | 5.6 $m^3$ (21 $ft^3$) | 0.0038 | 1.6 | 356 m (1,157 ft) |
| D | 4.3 m (14 ft) | 0.77m (2.5 ft) | 5.6 | 10.8 $m^3$ (35 $ft^3$) | 0.0020 | 1.6 | 226 m (733 ft) |
| E | 4.3 m (14 ft) | 0.77m (2.5 ft) | 5.6 | 10.8 $m^3$ (35 $ft^3$) | 0.0011 | 2.8 | 1,356 m (4,406 ft) |

*Table 5: Testing the design parameters for the new Karnowsky Creek channel with Manning's equation*.*

| Channel Segment | Hydraulic Radius ("R") | Slope | Discharge "Q", $m^3/s$ ($ft^3/s$) | Velocity "V", m/s (ft/s) | Calculated Ditch Bankfull Discharge $m^3/s$ ($ft^3/s$) | Percentage of Bankfull Flow New Channel Will Carry |
|---|---|---|---|---|---|---|
| A | 1.016 | 0.0039 | 14.93 (49) | 0.72 (2.35) | 26.51 (87) | 56 |
| B | 1.016 | 0.0028 | 12.80 (42) | 0.61 (1.99) | 26.51 (87) | 48 |
| C | 1.016 | 0.0028 | 17.37 (57) | 0.50 (1.65) | 26.51 (87) | 66 |
| D | 0.983 | 0.0013 | 16.15 (53) | 0.33 (1.07) | 31.38 (103) | 51 |
| E | 0.983 | 0.0011 | 13.10 (43) | 0.37 (1.22) | 31.38 (103) | 42 |

**Manning's Equation: $Q = 1.486/n * AR^{2/3}S^{1/2}$, $V = 1.486/n * R^{2/3}S^{1/2}$*
*n=roughness coefficient, 0.04 for Karnowsky Creek; A = cross-sectional area; R = hydraulic radius; S = slope*

giving the stream an opportunity to cut off meanders and develop oxbows in the floodplain over the next several decades to a century. The loss of stream length would have a negligible effect on overall gradient and sinuosity.

Once the slope and sinuosity were established, the new channel was laid out on the base map and translated to the ground using the same methods developed in the Bailey Creek restoration. The new channel was fitted to the low points in the valley as much as possible. Developing the plan view involved several iterations. Points on the new channel's centerline were translated into survey coordinates, and the new channel's location was staked on the ground with the help of a professional surveyor (Figure 6). The centerline was fine-tuned and changes were resurveyed.

After we obtained the final survey data for the channel location and existing ground elevations, we entered it into a spreadsheet and calculated the expected bank heights in the new channel, assuming a constant stream gradient through a reach. The upstream and downstream locations for pools and riffles were added to aid channel excavation on the ground. As in Bailey Creek's new channel, all of the gradient change is taken up in riffles, and the upstream and downstream ends of pools are at the same elevation in the designed pool/riffle sequence.

Constructing the new mainstem channel took place in the late summer of 2002 (Figure 7). In the lower part of the valley, where wet soil conditions persist throughout the year, the excavated material was piled in mounds on the valley floor. This eliminated the need for dump trucks to haul the material, and the soil compaction that would have resulted. These mounds also provide topography in the floodplain that could be planted with spruce and cedar, allowing some elevation advantage over reed canary grass in the tidal zone.

During the first winter after construction, willow stakes were planted in the banks, and the floodplain was planted with trees and shrubs. Water was not flowing in the main channel, which gave the willows a chance to root and become established. During the second summer (2003), ditches were strategically plugged in several locations, and water was diverted into the new channel. Lessons learned in Bailey Creek were applied here. At the point of diversion, the new channel gradually slopes up from the old ditch's bed elevation, about a 0.6 m difference in elevation. Large logs were buried at grade in the new channel just downstream of the connection to prevent downcutting. In the fall of 2003, 130 large, whole trees were added to the new channel and floodplain by helicopter to create habitat and cover for fish (Figures 8 and 9).

Work during the summers of 2003 and 2004 included recreating step-pool channels in both the upper mainstem valley and three tributaries to the main valley (Figure 6).

*Figure 7. Channel construction in lower Karnowsky Creek with a walking backhoe, summer 2002. Fill material taken from the constructed channel was shaped into floodplain hummocks that would later be planted with native trees and shrubs.*

*Figure 8. The new Karnowsky Creek channel with large wood added, winter 2003. New conifer seedlings are planted along the bank and protected by plastic tubing.*

*Figure 9: Lower Karnowsky Creek at high flow in new channel with added wood, spring 2004.*

These intermittent channels flow through 3-5% valley gradients, and buried wood and boulders to serve as grade control are critical to channel reconstruction here. These channels were also seeded with gravels of the appropriate size for the slope and channel form of constructed riffles. Filling in of the extremely incised ditches on the valley margins was much more labor intensive than ditch filling in the lower valley. This required more haul by dump truck of borrowed fill material and layer placement of this fill in ditches to prevent robbing of the much needed water table in these side valleys and the upper mainstem. Work done in these intermittent channels will be ongoing through 2006.

### Monitoring

As with Bailey Creek, annual monitoring includes low-elevation aerial photographs, 22 permanently-monumented cross sections, photo points, fall spawning surveys, and summer juvenile fish population monitoring. In addition, a network of 36 groundwater wells, set up before the project began, are being measured monthly to track changes in groundwater levels.

### Results and Lessons Learned

Although the new Karnowsky Creek channel is too young to have significant monitoring results, we are already seeing abundant coho smolts and fry in the new channel. The channel functioned well through the first winter, with frequent floodplain inundation, particularly in the tidally influenced area (Figure 9). The willows and other riparian vegetation are growing very well, especially on constructed hummocks near the main channel. Point bars are already being deposited on the inside of meander bends in the lower channel, developing a natural channel morphology. Little, if any, bank erosion is evident. Some additional lessons learned include the following:

1. A strong collaborative partnership makes a large-scale restoration much stronger. Bailey Creek was primarily a Forest Service endeavor while Karnowsky Creek has many strong partners, and the second has far exceeded the success of the first.
2. Size the channel cross section based on both flow and bankfull cross section measurements if available. Accurate flow prediction is difficult in the Oregon Coast Range.
3. Variation and complexity of meander geometry is better. In nature, radius of curvature can vary from one to seven times bankfull width (Williams 1986). Much more variation was designed into Karnowsky's new channel than Bailey's, with better results.
4. Incorporating hummocks in the floodplain from construction fill can save on haul cost, limit soil compaction and provide needed elevation so native plants can out-compete exotics.
5. Armor abrupt elevation changes where water flows. Use natural materials and check elevations with a laser level to assure that neither head cutting nor downstream cutting will occur in high flow.
6. Contracts that pay equipment by the hour should be favored over lump sum construction contracts. In our case, we incurred a third of the cost using hourly contracts on the Karnowsky project. The added flexibility to make changes is also key to successful implementation.

The Forest Service, Oregon Watershed Enhancement Board and the National Forest Foundation spent $435,000 on channel construction, native vegetation recovery and helicopter wood placement on over 4.8 km (3 miles) of new meandering stream channel. When the project is completed, the Forest Service and partners will have spent an additional $165,000 on planning, design, monitoring and implementation of the design for an estimated total cost of $600,000.

## Conclusions

The restoration of meandering channels at Bailey and Karnowsky Creeks has created more productive fish habitat, and appears to be on track to meet the other goals of restoring wetland habitat and reducing overall sediment production. Projects like these require an intensive data-gathering and planning effort by an interdisciplinary team of hydrologists, geomorphologists, fisheries biologists, and surveyors, and benefit from review by other technical experts.

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