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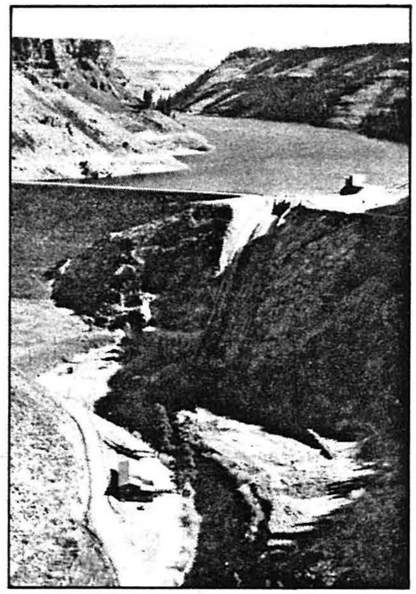

Review of FLUSHING FLOW REQUIREMENTS *in* REGULATED STREAMS

ESTES

PACIFIC GAS AND ELECTRIC COMPANY

Errata reported to ARLIS:
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Estes 1984 is incorrectly cited as Estes 1985 on the following pages:

Printed page	Online page
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26	39
27	40
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71	84
89	102

The corrected citation on page 89 is:

Estes, C.E. 1984. Evaluation of methods for recommending instream flows to support spawning by salmon. M.S. Thesis, Washington State University, Pullman, Washington. 156 pp.

REVIEW OF FLUSHING FLOW REQUIREMENTS IN REGULATED STREAMS

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NOTICE

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As evidenced by the extensive list of references, the majority of information contained in this document is the product of other investigators, and we would like to formally acknowledge their contribution toward the completion of this project. Appreciation is likewise extended to all of the questionnaire respondents for providing valuable information on flushing flows and to the people who reviewed and commented on this document.

Special appreciation is extended to the following individuals whose advice and assistance contributed significantly to the completion of this report: Thomas Wesche of the Wyoming Water Research Center, Robert Milhous of the U.S. Fish and Wildlife Service, Dave Rosgen of the U.S. Forest Service, Jim O'Brien of Colorado State University, Christopher Estes of the Alaska Department of Fish and Game, Jack Orsborn of Washington State University and Edmund Andrews of the U.S. Geological Survey.

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EXECUTIVE SUMMARY

The regulation of streamflows can alter the natural regime of a system by removing peak flows and reducing the stream sediment transport competency. The net effect can be that sediment which is inputted to the system tends to accumulate rather than being periodically removed (flushed) as during spring runoff. The deposition and aggradation of sediments ultimately becomes a problem when it affects the biotic community. In this case, a release flow (flushing flow) which simulates high runoff events may be periodically needed to remove fine sediments from the stream.

The purpose of this study was to review and summarize existing information on flushing flows and to provide a better understanding of the physical and hydraulic parameters which respond to changes in flow and how they influence the aquatic biota.

Major objectives of the study were to:

- Compile and review information pertaining to flushing flows
- Review and evaluate existing and proposed methods for recommending flushing flows
- Evaluate potential techniques useful for determining the need for, timing, magnitude and effectiveness of flushing flows
- Develop guidelines for assisting in the determination of flushing flow requirements
- Define areas for further research

Information and data on flushing flows were assembled following a comprehensive review of the literature. This review was supplemented with a detailed mail survey of various state and federal resource agencies and research institutions. The survey forms used were structured to obtain information in four principal areas: awareness and

use of methodologies, need for flushing flows, need for standardization of methods, and research activities. A total of 70 survey forms were distributed, of which 46 were completed and returned.

From the review of information, a total of fifteen methods or approaches for assessing flushing flows were identified, reviewed, and presented in summary form. A discussion of the basis for and application of each method, as well as a section on its major constraints and limitations, was included in each summary. Of the fifteen methods, seven were primarily office techniques, three were field based, and the remaining five (including one in a developmental stage) entailed a mixed office and field approach. The majority of methods described were not designed specifically for assessing flushing flows, but rather constituted approaches used for addressing sediment transport problems. The few formal methods that do exist have gone largely untested with respect to their reliability and accuracy, and have only partially addressed the overall needs of a flushing flow (i.e., magnitude, timing, duration and effectiveness).

The study further reviewed important parameters and conditions which should be monitored and evaluated when flushing flows are being considered. Emphasis was placed on defining practical techniques useful for assessing flow needs.

Fundamental in the evaluation process is an initial determination of the need for a flushing flow. Specific points which should be considered in this determination include:

- Physical location of the water development project in relation to major sediment sources
- Topography and geology of the project area
- Susceptibility of the drainage to catastrophic events
- Sensitivity of target fish species and their life history stage to sediment depositional effect
- Extent of man-induced activities within the drainage
- Operational characteristics of the project

The actual need for a flushing flow should be based on the results of sediment monitoring studies (where possible) using appropriate field techniques.

Once the need for a flushing flow has been established, it is important to determine the best time for its implementation. Important considerations include:

- o Species of fish present in the system
- o Life history functions of important species
- o Historical runoff period
- o Project flow availability
- o Water temperature

Ideally, the most effective time for implementing a flushing flow is that which provides the greatest benefits to the biotic communities. Detailed species-life history charts should be developed and consulted to assist in the determination.

The determination of the magnitude of flows is the most important and most difficult aspect of formulating a flushing flow recommendation. No single, standard approach has been developed for this purpose. Until methods are developed, evaluations today will need to utilize an approach tailored to the specific needs and characteristics of each stream and project. This may entail the use of several different office techniques to derive an initial flow estimate, followed by detailed field studies to refine and finalize the recommendation.

The most reliable method for establishing required flushing-flow rates is to observe various test flow releases. Field observations such as the sampling and tagging of bed material, should be made before and after each release to determine the actual effectiveness. Flow releases may not be feasible on all streams. However, where feasible, they provide the best results of all methods. Where test flow releases cannot be made, the use of methods based on sediment transport mechanics may be the most reliable approach for determining flushing flow rates.

An evaluation of the effectiveness of a recommended discharge for removing sediments should be a logical part of every flushing flow study. Through this process, actual, versus desired results can be compared and refinements made. This study reviewed 24 different techniques which could be used for assessing the effectiveness of the flows.

The study resulted in the development of the following guidelines for conducting flushing flow studies:

- Flushing flow studies should utilize an interdisciplinary team approach; team members should include at a minimum a hydrologic engineer and a fisheries biologist.
- An initial determination of the actual need for the flushing flow should precede detailed assessments.
- The assessment approach should be tailored to the specific needs and characteristics of each stream and project; office and field techniques both may be required.
- For comparative purposes, more than one method should be used for deriving flow recommendations.
- Flushing flow recommendations should be stated in terms of magnitude, timing and duration.
- Follow-up studies should be conducted to evaluate the effectiveness of the flow and allow for adjustments.

From the review of literature, data and results of the survey, important areas of research related to flushing flows are identified.

INTRODUCTION

Today, perhaps more than ever, the instream flow needs of aquatic resources are being considered and integrated into most water development projects. This is a real credit to the fisheries biologists of the present and past who are and have been involved in developing acceptable methodologies for determining flow needs. However, there are many facets of the instream flow problem which have not been adequately addressed. This report discusses one such aspect, that being the consideration of flushing flow requirements.

The report is divided into four major sections in addition to this INTRODUCTION. These include:

- PROBLEM DEFINITON, which reviews the process of sediment deposition and transport, and the biological consequences thereof

- REVIEW OF FLUSHING FLOW METHODOLOGIES, which lists and summarizes various methods and approaches which have been used for recommending flushing flows

- EVALUATION OF FLUSHING FLOW REQUIREMENTS, which discusses important aspects in determining the need for, and timing, magnitude and effectiveness of flushing flows

- DISCUSSION AND RECOMMENDATIONS, which summarizes the state-of-the-art in flushing flow methods, presents important guidelines in making flow assessments, and discusses important research needs.

Appended to this report are four additional sections:

- Appendix A - EFFECTS OF SEDIMENT DEPOSITION ON FISHERIES HABITAT, presents a detailed review of the problem of sediment deposition on fish spawning and rearing habitat and invertebrate production

- Appendix B - SEDIMENT TRANSPORT MECHANICS, discusses the physical processes involved in sediment transport and reviews several transport functions

- Appendix C - WESTERN UTILIZATION AND NEED FOR FLUSHING FLOW METHODOLOGIES, presents the results of a western regional survey designed to obtain information on flushing flows

- Appendix D - ADDITIONAL REFERENCES RELATIVE TO FLUSHING FLOWS AND SEDIMENT TRANSPORT

Historical Perspective

It has long been recognized that the regulation of streamflows can both positively and negatively affect existing fishery habitat and fish populations. This became most apparent in the western states where natural precipitation and runoff patterns had historically produced well-defined periods of low streamflow. It was quickly recognized that uncontrolled utilization of water for developmental purposes could result in the complete elimination of many aquatic communities. This had an alarming effect since many of the systems in jeopardy harbored significant sport and commercial fishery resources, such as the salmon fisheries of the Pacific Northwest.

Fisheries biologists began investigating the relationships between fishery habitat and streamflow with the ultimate goal of being able to prescribe flows necessary for the maintenance and/or enhancement of fish populations. To this end, a wide variety of methodologies for assessing the "instream flow" needs of aquatic life have been developed and used. Excellent descriptions of many of the methods can be found in Stalnaker and Arnette (1976), Wesche and Rechard (1980) and Orsborn and Allman (ed. 1976). The net effect is that today the regulation of most water development projects is designed with consideration for existing fishery resources.

However, many of the problems and questions associated with water developments still remain unanswered. Such is the case with flushing flow needs. Flushing flows, so named for their effect of removing ("flushing") fine sediments from gravels, have been the focus of relatively few fisheries studies in the past.

In general, the major reason for recommending flushing flows is the need to remove accumulated sediments from important fishery habitats. The need for such flows typically results from changes in the natural hydrograph of a system due to the implementation of a water development project (storage reservoir, hydroelectric development, etc.). Such projects tend to eliminate the peak flows of the stream thereby reducing its competency to transport sediment at those times. The net effect is that sediment which is input to the system tends to accumulate rather than being periodically removed, as during spring runoff. With time, continued sediment deposition can adversely affect both spawning and rearing habitat of fish.

In regulated streams, the solution to the problem is to periodically provide sufficiently high flows to remove and transport the sediments downstream out of the habitat. Unfortunately, methods or techniques for accurately determining the needed flows have not been developed to any degree of confidence or resolution (see REVIEW OF METHODOLOGIES). As such, many recommendations are being made subjectively without a rational basis. Furthermore, few follow-up studies are undertaken to verify or refute the effectiveness of the flows and suggest adjustments. This can result in either a waste of water (if flows recommended were in excess of transport needs), or in the continued degradation of habitat (if flows were insufficient). Both have economic ramifications with respect to the water and fishery resources. The importance of prescribing reliable and accurate recommendations is therefore obvious.

As noted by Wesche and Rechard (1980), if flushing flows are needed to remove fines and maintain channel integrity, reliable methods should first be developed for determining the magnitude, duration, and timing of such flows. Even more fundamental is the determination of the need itself, for under some conditions, flushing flows may be more detrimental than beneficial to the resource. In short, a decision must be made by the appropriate management agency regarding the best prescribed condition for the stream in question.

Objectives

This study was undertaken to review and summarize existing information on flushing flows. The major objectives of the study were to:

- Compile and review available information pertaining to flushing flow needs
- Review and evaluate existing and proposed methodologies for recommending flushing flows
- Evaluate potential techniques which may be useful for determining the need for and timing, magnitude and effectiveness of flushing flows
- Develop guidelines for assisting in the determination of appropriate flushing flows
- Define areas for further research

PROBLEM DEFINITION

In regulated streams, flushing flows may serve a variety of uses including channel maintenance, riparian habitat maintenance, prevention of vegetation encroachment, and the maintenance or enhancement of fishery habitat. Discussions in this report are limited to the latter, and are focused primarily on important fish spawning and rearing areas.

This section presents a summary review of the mechanics of sediment deposition and transport and its effects on the aquatic biota. Through this review, a clearer understanding of the flushing flow problem, and of the important considerations required for making valid assessments should be realized.

Deposition of Sediments in Regulated Streams

Sediment movement in streams is dependent on two factors: 1) the availability of sediment in the drainage, and 2) the sediment transporting ability ("competency") of the stream. Either factor may limit sediment transport rates, and changes in both can occur in conjunction with water development projects.

With respect to flushing flows, it is competency which is most often cited as being affected by streamflow regulation, and hence the cause of sediment depositional problems. In the western U.S. this is correct to a large degree since most developments result in the alteration of the natural hydrograph of the system, removing peak flows and decreasing the stream's sediment transport ability. Decreased competency can have direct and serious effects on the aquatic biota, including important fish populations (Figure 1). The net effect is that sediment which is inputted to the system tends to accumulate rather than being periodically removed ("flushed"), during events such as spring runoff.

The extent of sediment accumulation is dependent on the type of project, its location, as well as its operational characteristics. For example, a

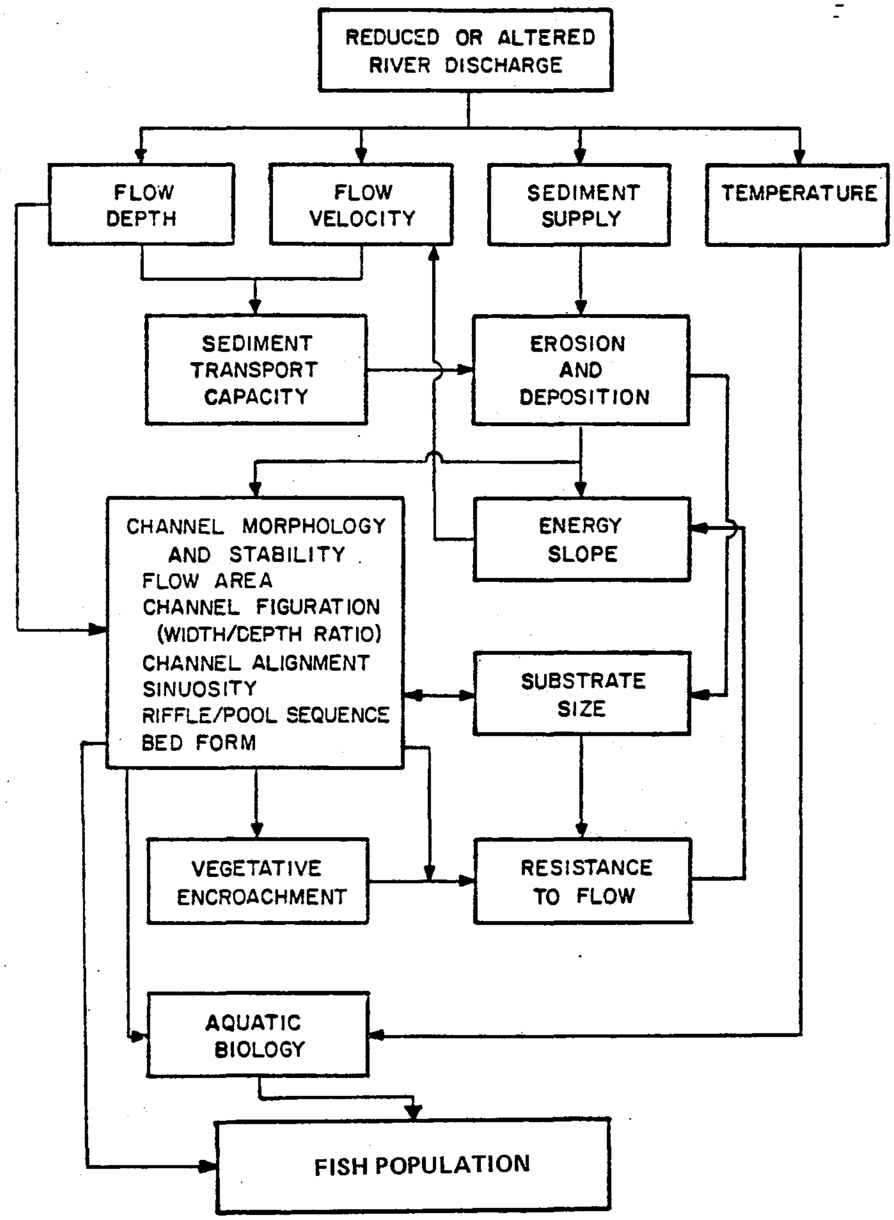


Figure 1 EFFECTS OF ALTERED FLOW REGIMES ON HYDRAULIC PARAMETERS AND ASSOCIATED BIOLOGICAL COMPONENTS. MODIFIED FROM O'BRIEN (1984)

run-of-the-river type hydroelectric project provides essentially no flow control capability. Although some "ponding" of sediments may occur immediately behind the dam, the natural hydrograph remains unaltered and normal high flows should continue to transport sediments. In comparison, large impoundments afford almost complete control of the flow regime and releases may be regulated on a demand basis.

In addition to flow control, water development projects also affect the amount of sediment input into the controlled reach of stream. A benefit often cited with large reservoirs is that sediments will settle out in the impoundment and downstream releases will be much cleaner. This results if the regulated systems are essentially closed or semi-closed with respect to upstream sources of sediment recruitment. However, the extent of the reduction in sediments in the system is dependent upon the location of the project relative to the major sediment sources in the drainage.

For projects located below major sediment sources, relatively clear, sediment-free water would likely prevail throughout the controlled reach. This same water however, now possesses a greater potential energy for sediment transport, and problems of erosional cutting and degradation may occur. Colloquially, this water is often termed "hungry" in that it readily scours and erodes the stream channel. Barring man-induced sediment recruitment to the stream, this condition can and has resulted in serious problems of gravel transport out of the system. In fact, available spawning gravels in some streams have become severely limited due to this process. In this case, it is the lack of sediment rather than its excess which creates a problem, and some extraneous inputs of gravel may actually benefit the aquatic resource (e.g., replenish spawning gravel).

In contrast, projects located above major sediment sources would have little effect on reducing sediment recruitment to downstream segments. Coupled with the regulated flow regime, sediment input rates in this situation likely exceed transport rates and sediment depositional problems are likely to occur with time. It is this circumstance which most often predicates the need for periodic flushing flow releases to remove sediments and maintain or restore natural habitat conditions.

In gravel bed streams, which are typical of western systems, deposition of sediments occurs through an upper, poorly graded, coarse pavement layer into the underlying substrate material. Fine particles traveling in suspension will deposit in the pores of this pavement layer both by gravity settling and by sieving of the intra-gravel flow entering the stream bed. Einstein (1968) found during laboratory experiments that once the fine sediment has been deposited in the gravel bed, minimal upward or horizontal movement of this material takes place. Beschta and Jackson's (1979) findings indicate that the depositional process tends to be selective in that the particle size distribution of the deposited material is finer than that of the suspended load.

The amount of material which intrudes into the gravel bed is highly dependent on the grain size distribution of the fine sediment as well as that of the gravel bed. If the size of the fine material is small relative to the receiving gravels, the gravel pores tend to fill from the bottom to the top of the pavement layer. Beschta and Jackson (1979) found that for larger suspended sediments, a filter layer can form within the gravel pavement which restricts the intrusion of additional fine material into the gravel stream bed. Einstein (1968) found that the rate at which the fine sediment accumulates in the gravel layer is dependent on the concentration of the suspended load carried by the stream, but is independent of the flow velocity or the amount of material already present within the pores of the gravel bed.

The shape of the gravel in a stream may also affect sediment deposition. Studies by Meehan and Swanston (1977) indicated that at low flow conditions, rounded gravels tend to accumulate more sediment than angular gravels, whereas the reverse is true at higher flows. Greater accumulation of sediments in the rounded gravels at low flows may be due to less turbulence levels at the gravel bed. At higher discharges a flow separation zone can develop behind angular gravels causing greater sediment deposition.

Biological Consequences of Sediment Deposition

In regulated streams, the deposition and accumulation of sediments becomes a problem when it begins to affect the biotic community. This can occur as a slow, insidious process with the continued deposition of small quantities of sediments (and no subsequent transport), or be triggered as a rapid, almost catastrophic event exemplified by a sudden slump or landslide. In either case, sediment is deposited in the stream in excess of ambient conditions.

The biological consequences of sediment deposition are well documented and have been the focus of many studies. Excellent summaries of many of these are presented in Cordone and Kelley (1964), Iwamoto et al. (1978), and Chevalier et al. (1984). In general, the studies have demonstrated inverse relationships between fine sediment accumulation in spawning and rearing areas, versus fish survival and abundance. A further discussion of the effects of sediment deposition on fisheries habitat is provided in Appendix A.

Flushing of Fine Sediments from the Gravel Bed

From the above discussion it is apparent that the periodic removal of fine sediment from gravel beds has biological significance. How this removal can be achieved forms the underlying basis for the determination of flushing flow requirements, and is the subject of this section.

The laboratory studies of Beschta and Jackson (1979) indicated that upon the elimination of a source of fine sediments, a given flow can flush fines out of the gravels to a depth of about 0.4 in. (1 cm). The gravel bed in those experiments was composed of material having a mean diameter of about 0.6 in. (1.5 cm). Such findings agree with those of O'Brien (1984) who found that fine material could be cleaned from a cobble channel bed to a depth of about 0.5 - 1.0 of the average cobble diameter. However, both investigators indicated that further flushing of fines requires mobilization of the stream bed.

Natural high flow events on unregulated streams normally provide the necessary level of stream bed mobilization to flush fine sediments. Regulated streams, however, differ in two major ways from unregulated systems. First, upstream dams can cut off the major supply of streambed gravel sediments to downstream reaches. Second, the regulation of flows may eliminate the periodic high flows which would normally set the channel bed in motion and flush the fine material from the gravels. Thus, as previously noted, the provision of a flushing flow can have both positive and negative effects on fish habitat. A positive effect would be the removal of fine sediments from important spawning and rearing habitat; the negative effects could be manifest in channel morphology changes including the downstream movement of the spawning gravels with no replacement from upstream.

It should be noted that when flushing flows are needed, the magnitude of the required discharge may vary depending upon the area of consideration, (i.e., spawning (riffles) or rearing habitat (pools)). As noted by Reiser and Bjornn (1979) streamflow changes generally influence velocities and area of riffles more than area of pools. Kraft (1972) and Wesche (1974) both demonstrated that velocity versus depth was the most dynamic parameter with respect to varying flows. The most dramatic changes in velocities are therefore likely to manifest themselves in riffle areas. Intuitively then, it would be expected that higher flows would be required to remove surface sediments from pool versus riffle areas and indeed this is the case. However, even higher flows are needed to flush fines from below an armored layer in a riffle. An armor layer forms whereby finer material is held in place by coarse material. An excellent graphical presentation of the relative magnitude of these flows is provided in Bjornn et al. (1977) and depicted in Figure 2.

As described by Bjornn et al. (1977), Figure 2A displays the critical discharges needed for transporting coarse and fine sediments across riffles, out of pools, out of riffles after dislodging the armor layer and out of the substrate after moving large boulders. The amount of coarse and fine sediments capable of being transported through a given reach of stream is a function of flow (Figure 2B). Figure 2 further

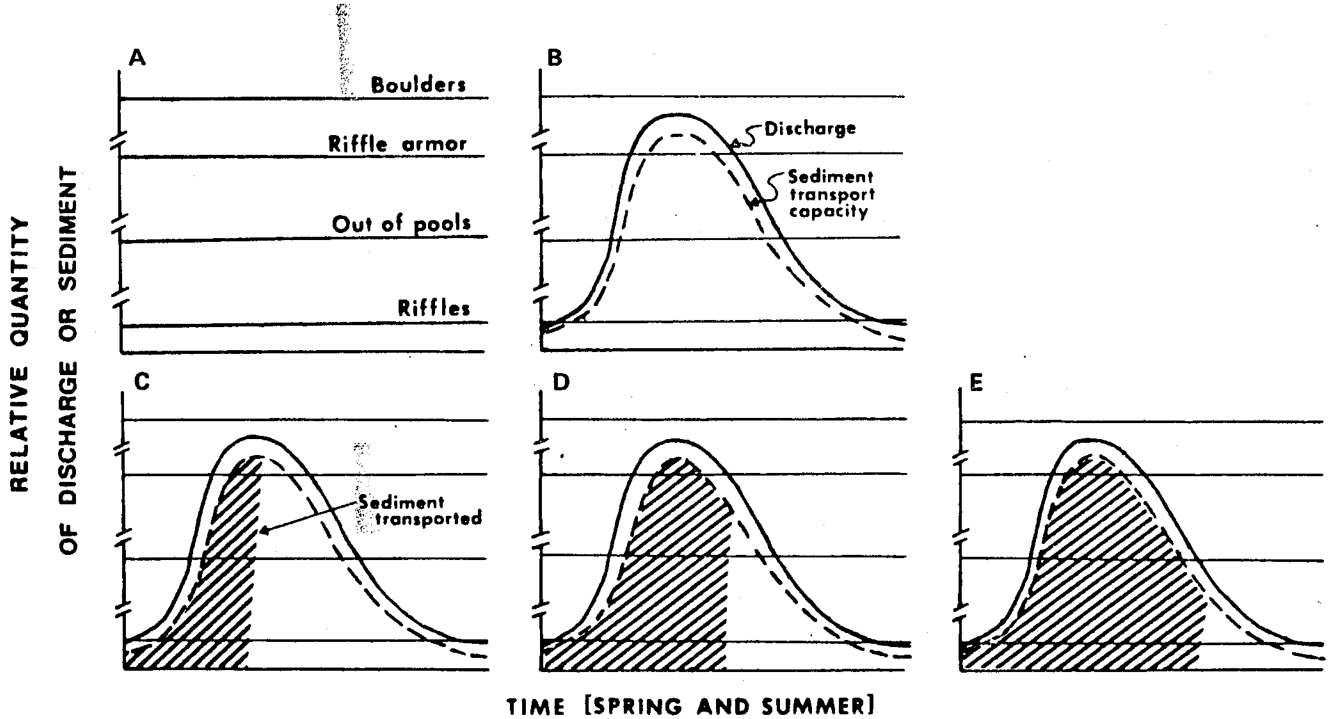


Figure 2 RELATIVE DISCHARGES WHICH TRANSPORT SEDIMENT ACROSS RIFFLES, OUT OF POOLS, OUT OF ARMORED RIFFLES, AND OUT OF SUBSTRATE ARMORED BY BOULDERS FOR A GIVEN SECTION OF STREAM. (SEE TEXT FOR EXPLANATION OF A–E.) MODIFIED FROM BJORNN et al (1977)

demonstrates three potential conditions of sediment transport in an unregulated stream.

In Figure 2C a condition of above average discharge is presented. In this condition, the flows are capable of mobilizing the armor layer on the riffles, and the fine sediment within the riffles can be transported downstream. As indicated, essentially all sediments have been transported out of the system before the flows begin to recede. Thus, very little sediment would be redeposited at the lower flows.

The condition in Figure 2D is representative of a stream which is still transporting fine sediments after the flows have declined below the level which mobilizes the armor layer on riffles. In this situation, the riffles would be refilled with sediment.

Figure 2E depicts a stream which is still transporting fine sediments after flows have fallen below levels which remove fines from pools. Thus, the pools would be refilled with sediments. It should be noted that if no armored layer is present in a stream, sediment transport from riffle areas would be occurring in all but the lowest flow conditions depicted.

The conditions displayed in Figure 2 were for an unregulated stream which exhibits characteristic runoff periods. In regulated systems, a much flatter hydrograph may result with peaks in flow being of relatively short duration. Nevertheless, the same general patterns and principles apply. That is, the magnitude and duration of the required flushing flow depend on the extent and characteristics of the sediment problem.

Under some conditions, sufficient flushing may be achieved through a relatively rapid increase - decrease in flows. Such may be the case if flushing is targeted at very fine sediments within a short unarmored riffle section located immediately below a water development project. In this case, a brief increase in flow may be sufficient to effectively transport the material. In contrast, the flushing of extensive sediment deposits within pools or within armored riffles may require bed mobilization only achieved by the sustained release of substantially higher flows.

Methodologies which have been used for assessing flow requirements are reviewed in the following section. The theoretical basis for the relationships depicted in Figure 2, including detailed discussions of sediment transport mechanics and transport functions are presented in Appendix B.

REVIEW OF EXISTING FLUSHING FLOW METHODOLOGIES

This section provides a review of direct and indirect methodologies and approaches used for determining flushing flow needs. For the most part, the methods described were not designed specifically for recommending flushing flows. Rather, they represent various approaches which investigators have used to address problems related to sediment transport. Identification of most of the methods was achieved through a comprehensive literature review, supplemented by a detailed formal survey of various state and federal resource agencies and research institutions. Results of this survey are presented in Appendix C.

Of the fifteen methods described, seven are primarily office techniques, three are field based, and the remaining five (including one in a developmental stage) require a mixed office and field approach (Table 1).

Included with each review is a discussion of the basis for and application of the methods as well as a section on the major constraints and limitations. This latter section should be useful for providing guidance in method selection. The methodologies presented include those directly related to fisheries concerns, as well as others targeted more toward channel maintenance (e.g., sediment transport models).

Tennant (Montana) Methodology (Tennant, 1975, 1976)

The Montana methodology developed by Tennant (1975) is a general instream flow methodology which addresses a wide range of flow considerations, including flushing flows. The methodology is based on over ten years of field and office research conducted on over 58 stream cross sections at 38 different flows (Wesche and Rechard, 1980). The method is founded on percentages of the average annual flow (for the period of record) as determined from USGS hydrological data provided in USGS Water Supply Papers.

Table 1

SUMMARY OF METHODOLOGIES FOR ASSESSING FLUSHING FLOW NEEDS

Methodology Author	Type	Basis	Method Considers Flow: Magnitude	Timing	Duration	Effectiveness	Comments
Tennant (Montana) Method Tennant (1975, 1976)	Office (field studies recommended but not detailed)	200% Average Annual Flow	X				Requires extensive flow records; site photographs recommended.
Northern Great Plains Resource Program Method NGPRP (1974)	Office	Average Annual Flow	X				Requires extensive flow records; method not developed primarily for flushing flows (see text).
Dominant Discharge/ Channel Morphology Method Montana Dept. Fish, Wildl. Parks (1981)	Office	Dominant Discharge (1.5 year frequency peak flow)	X	X	X 24 h		Requires extensive flow records (9 yr); suggests a gradual rising and receeding of the flushing flow.
Estes and Orsborn Method Estes (1985) Orsborn (1982)	Office	Two year average annual peak flood event - QF2P; 3 day average around QF2P 7 day average around QF2P	X		X instan. 3 day 7 day		Requires extensive flow records; flow synthesis techniques are discussed; suggests field studies for flow verification.
Hoppe Method Hoppe (1975) Hoppe and Finnel (1970)	Office	17th percentile on flow duration curve (Q_{17})	X		X 48 h		Requires extensive flow records; empirically developed for the Fryingpan River, Colorado - Q_{17} may be specific to that system.
Bed Material Transport Method Hey (1981)	Field	Threshold discharge for transport; determined using bedload tracers	X		X		Restricted to clear water systems with good visibility; several test flows required; office techniques not described.
Instream Flow Incremental Methodology (IFIM) Bovee and Milhous (1978) Bovee et al (1982)	Office/Field	Indirect approach: point at which WUA (on spawning curve) begins to decrease	X				Several assumptions must be made using this approach (see text); Presently, the IFIM does not directly address flushing flows; the CIFASG is reviewing approaches for integrating this into the IFIM.
Wesche Method (Wesche et al 1977)	Field	Bankfull discharge (empirically determined) uses drainage basin similarities for estimating unmeasured systems	X	X	X 3 day	X	Approach developed on high mountain streams in Wyoming; applicability to other systems uncertain; requires flow measurements during high flow events.

Table 1

SUMMARY OF METHODOLOGIES FOR ASSESSING FLUSHING FLOW NEEDS

Methodology Author	Type	Basis	Method Considers Flow: Magnitude	Timing	Duration	Effectiveness	Comments
Beschta and Jackson Method (Beschta and Jackson 1979)	Office	Flow/drainage area ratio (estimated at 13.7 cfs/mi^2); 5th percentile on flow duration curve Q5)	X				Developed in small coastal streams of Oregon; approach may not be applicable on other systems; flow records required.
Effective Discharge (O'Brien 1984)	Field/Office	Effective discharge/ Bankfull discharge	X	X	X 48 h	X	Developed on Yampa River in Colorado/Utah; extensive field measurements required; sediment discharge relationships based on field and laboratory studies; approach included a physical model of the system; requires extensive flow records.
U.S. Forest Service Channel Maintenance Flow Method (Rosgen, 1982)	Office	Bankfull discharge/Dominant discharge (1.5 year recurrence interval)	X	X	X 3 day	X	Developed on streams in northern Wyoming; extensive flow records rquired; method considers a wide range of flows not just peak flows.
Incipient Motion Methodology; Meyer-Peter Muller Based Water and Environment Consultants, Inc. (1980)	Field/Office	Predicting discharge which causes incipient motion of particle; employs Meyer-Peter Muller transport formula	X	X	X 3 day		Used on streams in southeastern Wyoming; Meyer-Peter Muller formula can provide widely varying results; assumptions used in this technique should be evaluated on a site specific basis; technique probably suitable for implementation type studies.
Incipient Motion Methodology; Shields Entrainment Function (this report)	Office	Predicting discharge for incipient motion of particle; based on a Shields entrainment function	X		X variable		Method based on Shields parameter of 0.03; other values can also be used which would change relationships developed; technique provides an estimate of needed flow as a function of grain size, stream width, and channel slope.

Table 1

SUMMARY OF METHODOLOGIES FOR ASSESSING FLUSHING FLOW NEEDS

Methodology Author	Type	Basis	Method Considers Flow				Comments
			Magnitude	Timing	Duration	Effectiveness	
Sediment Transport Models (see text)	Office/Field	Sediment-discharge relationships/ transport capacity	X				Model output can be highly variable; proper and careful selection and use of models is critical.
Wyoming Water Research Center Method Wesche et al (1983) (In Development)	Office/Field	Undetermined	X	X	X		This method is in a development stage at the University of Wyoming; method will consider fisheries, riparian habitat and channel maintenance concerns.

For flushing, Tennant (1975) has recommended flows of 200 percent of the average annual flow. Tennant provides the following rationale for this recommendation. The average annual flow of a stream will usually fill the active stream channel about 33 percent full, or to the line of permanent terrestrial vegetation. Three (3) times the average annual flow will often fill the active channel about to the point of overflowing onto the first bench of the flood plain. However, 200 percent of the average flow will produce effective depths and velocities within the stream channel for moving silt, sediment, and other bed load material without doing extensive damage to the banks and riparian vegetation. Thus, he suggests the 200 percent value should provide good flushing flows.

Although largely an office method, Tennant (1975) also describes field methods which serve to evaluate the suitability of the recommended flows. Of particular importance in this respect is the photographic documentation of the flows from elevated vantage points.

Tennant provides no guidelines or recommendations concerning the required duration of the flows, implying that durations will vary by drainage and depositional problems. A flushing flow period of 14 days has been recommended by resource agencies of several state, but no evaluation of the effectiveness or need for a period of this length has been undertaken.

Constraints and Limitations: Primarily an office technique. Wesche and Rechard (1980) recommend its use be restricted to planning level rather than implementation studies. The methodology was developed for streams east of and including the Rocky Mountains. Its applicability to western streams has not been thoroughly evaluated. Requires extensive flow records of pre-developmental conditions. Provides no recommendation or guidelines for determining the required duration of the flushing flow.

Northern Great Plains Resource Program Methodology (NGPRP, 1974)

Although not specifically targeted at flushing flows, the NGPRP method does reference runoff considerations. Like the Tennant methodology, the

NGPRP method is an office technique and is based on USGS flow records. The method is primarily focused on evaluating and determining the monthly instream flow requirements for aquatic resources, and detailed descriptions of procedures are provided in NGPRP (1974) and Wesche and Rechard (1980).

Flushing flows derived using this method, were assumed sufficient at flows at or near the average annual flow for the period of record; duration of the flow is not discussed. This value was selected somewhat arbitrarily, based on the supposition that such flows would generally keep channels open and clean and would maintain spawning conditions for most species. The NGPRP (1974) recommended detailed field studies for accurately determining flushing flow needs.

Constraints and Limitations: Requires extensive flow records of predevelopment conditions. Duration of the recommended flushing flow is not discussed. This methodology was not directly fomulated to derive flushing flow recommendations. It's use should be confined to planning level studies.

Dominant Discharge/Channel Morphology (DDCM) Methodology (Montana Dept. of Fish, Wildlife and Parks (MDFWP) 1981)

The Dominant Discharge/Channel Morphology methodology, an office technique, has been used by the MDFWP for making channel maintenance recommendations. As stated by the MDFWP (1981), the primary functions of high spring flow are the maintenance of channel form, bedload movement, and sediment transport. Increased discharges also result in the flushing of deposited sediments thus providing for suitable gravel conditions for fish spawning and egg incubation, and insect production.

The methodology used is based on the concept that stream channel morphology is formed by and therefore designed to accomodate a dominant discharge. The discharge, which is commonly referred to as the dominant discharge is the bankfull flow. This flow is defined as the discharge at which water just begins to overflow onto the active floodplain. The recurrence interval for a bankfull discharge tends to have a constant frequency of occurrence of about 1.5 years.

The methodology has been applied by the MDFWP (1981) by estimating the bankfull discharge for streams and rivers using the 1.5 year frequency peak flow. This flow was determined by interpolation between the 1.25 and 2 year frequency peak flow as supplied by the USGS. The MDFWP has tentatively set the duration period for these flows at 24 hours, but indicates further studies are needed to refine this value. A gradual raising and lowering of flow should be associated with the dominant discharge and the shape of the hydrograph should resemble that which occurs naturally. This suggests that the timing of flushing flows should correspond closely to historical runoff patterns. The MDFWP utilized pre-development USGS flow records to determine the time when the high flow period and peak flow normally occur. The dominant discharge is then requested for that same period.

The MDFWP (1981) suggests that the flow be increased gradually from a base flow level to the dominant discharge (24-hour duration) in two week intervals at the 80th percentile flow level, during the natural timings of the high flow period. The 80th percentile flow is that which is equalled or exceeded 80 percent of the time (i.e., 8 out of 10 years there is more water than the 80th percentile). The 80th percentile was selected by the MDFWP because it is compatible with irrigation developments.

For other water development projects, it is assumed the implementation of the dominant discharge could be tailored to specific needs, with consideration given for the timing of flows and availability of water. Thus, both the time interval and flow increment may vary.

Constraints and Limitations: As with other office based techniques, the DDCM method can only be applied to streams which have extensive pre-development USGS gage records. The MDFWP suggests a continuous 9 year period of record is the minimum for application of this technique and the USGS suggests a 10 year period. However, if a partial record is available, it should be possible to synthesize additional records using correlational techniques on a neighboring stream which has a complete flow record. The method has no field component or means for evaluating the effectiveness of the flows. Its use should probably be restricted to planning level studies unless field verification and flow adjustment components are included.

Estes and Orsborn Methodology (Estes 1985; Orsborn, 1982)

This approach for deriving flushing flow recommendations has been proposed and evaluated by Estes (1985) and was originally conceived by Orsborn (1982). Like the Tennant, Hoppe and DDCM methods, it is an office technique which requires extensive pre-development flow records (10 year period). Recognizing that many streams under consideration are ungaged, Estes (1985) also reviewed various approaches (not presented here) for generating missing data.

The methodology was based on work performed at Oregon State University which suggested that stream gravels move very little until flows approach the two year average annual peak flood event, QF2P (Orsborn 1985, pers. comm. D. Reiser). When compared with the Tennant method which recommends 200 percent of the average annual flow, the QF2P is from 600 to 1500 percent of the average annual flow (Estes 1985). This suggested that Tennant's guidelines may be too low, and the QF2P was suggested as providing a better flushing flow.

Estes (1985) noted, however, that for regulated streams, rather than relying on an instantaneous flow approximating the QF2P for flushing, a better approach is to use the three-day or seven-day average maximum flows. Such flows range from about 60-75 percent of the QF2P and should be better for sediment flushing because of their duration. Estes (1985), pers. comm. D. Reiser) further stated that under natural conditions, an instantaneous peak flow is automatically accompanied by the three and seven day flows which may be important in removing fine sediments. Therefore, in a controlled system the desired flushing flow effects would probably not be achieved with an instantaneous QF2P, if it was immediately reduced to base conditions. The three and seven day flows are determined by averaging the consecutive three-day and seven-day highest mean daily values, which includes the day the annual peak flow occurs and the days immediately following and/or preceeding the event.

Estes (1985, pers. comm. D. Reiser) considers the three and seven day averages of the QF2P to be starting points for determining required flushing flows. He further recommends conducting studies to refine such estimates.

Constraints and Limitations: Like other office techniques, this method requires extensive pre-development USGS gage records. However, techniques are discussed for synthesizing flow records should they be unavailable. The method does not include a field component or means for evaluating the effectiveness of the flows. This method should probably be restricted to planning level studies.

Hoppe Methodology (Hoppe 1975, Hoppe and Finnell 1970)

The Hoppe Method, as described by Wesche and Rechard (1980) is based on various percentile levels of a flow duration curve and various activities in the life history of the fish species present. The method is based on the results of a flow assessment study conducted on the Fryingpan River in Colorado, by Hoppe and Finnell (1970). This study indicated, through field evaluations, that suitable flushing flows corresponded to the 17th percentile on the flow duration curve (defined as the flow which is equalled or exceeded 17 percent of the time).

The Hoppe method is an office technique and can be applied as follows. Flow records for the stream in question need to be acquired from the USGS or other source, or synthetically developed. For regulated streams it is important to utilize records which predate the water development project. From the records, a flow duration curve is developed which depicts the percentage of time various flows are equalled or exceeded (see Linsley et al. 1975). As noted by Wesche and Rechard (1980), as the length of unit time increases, the range of the curve decreases. The selection of the time unit depends on the purpose of the curve. For flushing flow assessments it is probably best to utilize an interval which will give the best resolution, such as a daily time unit. Once the duration curve is developed, the flow at the 17th percentile (Q_{17}) is recommended as the flushing flow.

For the Fryingpan River study it was determined that maintenance of the Q_{17} for a period of 48 hours was sufficient to effectively remove the fines. Hence, a period of 48 hours has been recommended as the flow duration.

Constraints and Limitations: Pre-development flow records must be available and should be of sufficient length to allow for an accurate formulation of flow-duration curves. No field assessment or verification techniques are provided. The Q_{17} flushing flow may actually be specific to the Fryingpan River. Other percentiles are likely more appropriate for other drainages which would require field verification. Wesche and Rechard (1980) classify the Hoppe Method as a planning level methodology useful in providing rough approximations of the required flows.

Bed Material Transport Methodology (Hey 1981)

This technique, as described by Hey (1981) offers an empirical means for determining threshold discharges for sediment transport in gravel-bed rivers. The procedure is field based, and includes the use of bed material tracers.

At each site under consideration, the size distribution of the bed material is defined by sampling and measuring the intermediate axis of a hundred pebbles obtained from the bed of the channel using a grid sampling procedure. The sample is divided, and half of the pebbles are painted (fluorescent paint) and replaced in a line across the channel perpendicular to the banks. Because of its small size, material less than 10 mm is not used for tracing purposes. In addition, as tracers are unlikely to be replaced in a natural position, some movement is expected at flows below the actual transport threshold until the marked pebbles become re-established on the bed of the channel. Movement less than 1.64 ft (0.5m) is considered to be due to this process and is disregarded in the analysis.

The tracers are then observed during and after several predetermined flow events which enables the determination of both the minimum flow which causes movement and the maximum flow which doesn't cause movement. Given a favorable range of flow conditions, the values will converge and the threshold discharge for bed materials can be defined. If the flows do not range around the threshold discharge during the experimental period, it will be necessary to estimate its probable value given the two limiting flows.

Constraints and Limitations: Because this technique requires visual observation of materials during flow releases, its use is limited to clear water systems. It may require a number of large test flows in determining threshold discharges. Use is limited to gravel-bed streams and rivers.

Instream Flow Incremental Methodology (IFIM) (Bovee and Milhous 1978; Bovee 1982)

The Instream Flow Incremental Methodology (IFIM) developed by the U.S. Fish and Wildlife Service, has been used extensively in the western states for assessing impacts of water development projects and recommending instream flow regimes for maintenance of aquatic biota. Detailed descriptions of the theory and application of the method are provided in Bovee and Milhous (1978), Trihey and Wegner (1981), and Bovee (1982).

In its present form, the IFIM and its associated Physical Habitat Simulation system model (PHABSIM) do not directly address flushing flow needs (B. Milhous, 1984; pers. comm. D. Reiser). The Cooperative Instream Flow and Aquatic Systems Group (CIFASG) at Fort Collins, Colorado is beginning to evaluate existing approaches, models etc. which look encouraging for determining suitable flushing flows.

However, the IFIM has been used by the USFWS to indirectly assess flushing flows in two systems in New Mexico; San Juan River below the Navajo Dam, and Rio Chama River below the El Vado Dam. As described by Couret (1984, pers. comm. D. Reiser), the approach used assumes that adequate flushing flows are somewhat less than that which would transport spawning material. This was estimated by determining the flow at which the weighted usable area (WUA) as calculated by the IFIM, begins to decrease with increasing flows. Couret noted, that this assumes the spawning gravels are not heavily embedded by sediments, in which case, significantly higher flushing flows would be needed. This approach also assumes that velocity is the primary parameter which causes the WUA to decrease. Furthermore, it assumes that when the WUA begins to decrease, the stream velocities are sufficient for sediment transport. These assumptions may or may not be true depending upon the species of fish under consideration (i.e., the shape of individual velocity and depth curves) and the nature of the material to be transported. Couret (1984) encouraged the "fine-tuning" of recommended flushing flows by directly observing the effects of a given flow.

The U.S. Forest Service (USFS) in Idaho (Payette National Forest) has modified the output obtained from the PHABSIM to indirectly address sediment deposition and flushing flows. As described by Burns (1984, pers. comm. D. Reiser), this was accomplished by incorporating the parameters of substrate embeddedness into the analysis (substituting for the IFG substrate codes). Burns suggests integrating the IFIM with the USFS Channel Maintenance Methodology, which includes a hydraulic simulation model for flushing.

Clearly, with the ever increasing acceptance and use of the IFIM, it would be extremely useful if the method could be modified and expanded to directly address flushing flow needs. Pragmatically, this should be possible given the dynamic and flexible nature of the PHABSIM system, vis a vis the integration of the instream temperature model. Indeed, this appears to be one item receiving attention at the CIFASG.

Constraints and Limitations: In its present form, the IFIM does not directly address flushing flow needs. The method can be used to obtain indirect estimates of these flows provided certain assumptions are made and proven valid.

Wesche Methodology (Wesche et al. 1977)

Wesche et al. (1977) utilized a methodology for recommending flushing flows which included visual observations and field measurements. The technique is useful for streams in which flow records are few or non-existent. Based on McLaughlin (1977) who recommended bankfull flow as a maximum flushing discharge, Wesche et al. (1977) assessed such flows in six headwater streams of the Little Snake River drainage in Wyoming. Such streams were being proposed for water diversion, and a quantification of flushing flow needs was conducted.

The estimation of bankfull flows for three of the streams was determined directly through field measurements by quantifying flow conditions during runoff. On one of the streams however, bankfull conditions never occurred. In this case, the bankfull flow was estimated from cross-sectional data using Manning's equation (see Appendix A, Sediment Transport Mechanics)

Flushing flows for the remaining three streams were based on their similarities in mean basin elevation, forest ratio and channel maintenance constant (defined as the amount of drainage area required to maintain a given length of stream channel) with the three measured streams. The first two factors directly influence the quantity, timing and duration of runoff (Wesche et al. 1977). A flushing flow of an unmeasured stream was determined from the measured stream with the greatest similarity of factors as follows:

$$\frac{\text{Flushing Q (measured)}}{\text{Drainage Area (measured)}} = \frac{\text{Flushing Q (unmeasured)}}{\text{Drainage Area (unmeasured)}}$$

Wesche et al. (1977) recommended a 3 day duration for each of the estimated flushing flows. This was based on the work of previous investigators (McLaughlin 1975; Eustis and Hillen 1954) but was also substantiated through field observation.

The timing of the flushing flow releases was assessed with consideration for the following:

- o Life history functions of important fish species - flows were recommended to occur prior to any spawning activity of salmonids in the stream; this would prevent both the subsequent dewatering of redds (if flows released during spawning), or the dislodgement of eggs and alevins (if flows released after spawning).
- o Historical runoff period - recommended timing of release flows corresponded to historical peak flows.
- o Water temperature - to the extent possible, the timing of the flows should occur when water temperatures are low. This will take advantage of the higher viscosity of the colder water with the effect that particles will remain in suspension longer.

Constraints and Limitations: This approach was utilized on high elevation, headwater streams in Wyoming; applicability to larger drainages is uncertain. This method assumes bankfull discharge will provide suitable flushing flows; this may or may not be true. Method requires flow determinations during high flow events which can prove difficult. However, bankfull flow can also be estimated using slope area calculations or a rating curve extension. Bankfull discharge determined empirically with no support documentation or flow records. This method is one of few which addresses the magnitude, timing and duration of flows.

Beschta and Jackson Methodology (Beschta and Jackson 1979)

Beschta and Jackson (1979), in evaluating the process of fine sediment intrusion into gravels, also assessed the mechanism and timing of flushing flows in small streams. They concluded that flushing of fines can only occur during periods of relatively high flows that disrupt the channel bed and cause bedload transport.

From field measurements made in Oregon Coast Range streams, it was determined that the general transport of bed material (< sand size) occurs after flows exceed about 13.7 cfs/mi^2 drainage area (0.15 m^3/S/km^2). They determined from a frequency analysis of daily flows, that this level was exceeded on a mean basis about 20 days each year. This would represent the Q_5 on a flow duration curve or the flow which is equalled or exceeded 5 percent of the time. Based on the above, it can be estimated that a stream with a drainage area of 100 mi^2 would need a flow of about 1370 cfs to flush fines from the stream bed.

Although Beschta and Jackson (1979 do not formally suggest using this approach for determining flushing flow requirements, its potential value should not be dismissed. It may be that similar relationships exist for drainage basins having similar characteristics to the ones originally measured during the investigation (i.e., small coastal headwater streams). Wesche et al. (1977) utilized the assumption of drainage basin similarity in making flushing flow recommendations for two different systems in Wyoming.

Constraints and Limitations: To ensure applicability of this approach, detailed information of the respective drainage basin characteristics is required. Flow records are needed to determine exceedence levels. Primarily an office technique, this approach should probably be reserved for planning level studies. This technique offers no consideration of the timing or duration of flows. No description of field techniques is provided.

Effective Discharge Methodology (O'Brien 1984)

O'Brien (1984) conducted a study in the Yampa River in the Dinosaur National Monument, designed to assess the minimum streamflow regime for preserving the processes and natural conditions vital to the channel morphology and aquatic life systems of the river. The particular concern was the maintenance of channel conditions conducive to the maintenance of the endangered Colorado River squawfish. The study included both field and laboratory tests designed to investigate sediment transport - streamflow relationships.

Field studies included the establishment of more than 21 cross channel transects and the measurement of suspended sediments, bed load and various physical and hydraulic parameters (velocity, depth, slope, substrate particle size). A physical model of one study reach was constructed in an experimental flume to aid in the evaluation of sediment transport dynamics. The study resulted in the development of a synthetic hydrograph for the maintenance of channel morphology and existing aquatic systems.

Flushing flows, defined in terms of effective discharge and bankfull discharge were integrated into the hydrograph. As noted by O'Brien (1984), the effective discharge is the flow that transports the most sediment over a long period of time. It is the product of the magnitude of the sediment transported by a given discharge and the frequency of occurrence of that discharge. In the Yampa River, the effective discharge was computed as 11500 cfs with a return period of about 1.5-2 years.

The bankfull discharge, which is often equated with the dominant discharge is usually considered the flow event which controls channel morphology. Indeed, the dominant discharge has been recommended and used as a flushing flow by other investigators (MDFWF, 1981; Wesche et al. 1977; McLaughlin, 1977). However, these have generally been associated with alluvial streams where, as noted by Rosgen (1982), the bankfull discharge has an average return period of 1.5 to 2.0 years. This frequency makes the discharge an effective channel forming event. For the Yampa River however, O'Brien (1984) determined the bankfull discharge to be about 21,500 cfs which had a recurrence interval of 20 years. He noted that the Yampa River was not an alluvial stream but an incised river. Thus, channel adjustment flows are limited to infrequent events.

O'Brien (1984) utilized both flow events (effective and bankfull discharge) in recommending flushing flows for the Yampa River. This he defined as the 48-hour discharge that equals or exceeds 11500 cfs (effective discharge) but is less than 21000 cfs (bankfull discharge). The effective discharge was recommended as a flushing flow for retarding vegetation encroachment, replenishing beach and bar areas with sand, and scouring areas of sand deposition in the cobble reach. Flow up to the bankfull discharge would serve to rework and maintain cobble bars and prevent changes in channel morphology.

The approach utilized by O'Brien is perhaps the most thorough method reviewed for deriving flushing flow recommendations. The technique included both office and field studies, and the actual physical modeling of one stream reach.

Constraints and Limitations: Perhaps the greatest constraints associated with this method are in its time and cost requirements. These are apt to be high considering the field data collection and analysis needs (e.g., determination of sediment loadings). This approach should be applicable to implementation studies, especially where the economic value of release flows is at a premium.

U.S. Forest Service Channel Maintenance Flow Methodology (Rosgen 1982)

In 1982, a procedure for recommending channel maintenance flows in north central Wyoming was developed by the U.S. Forest Service (Rosgen 1982). The procedures are targeted for flows which will maintain the channel stability of a system, and include a bankfull discharge, a range of flows representing the rising and receding limbs of a hydrograph, and a baseflow discharge. Such flows, according to Rosgen (1982) are needed annually for transporting the bulk of the water and sediment in an orderly fashion.

The quantities and durations of the above flows are determined by hydraulic geometry measurements, drainage basin characteristics, and regionalized demensionless flow-duration curves developed from longterm stream gage records. Specific techniques for determining these values are presented in Rosgen (1982).

For the drainage systems studied in Wyoming, the recommended maintenance flow regime approximated the rising and receding limbs of the natural snowmelt hydrograph. This included a series of flows distributed over a 69-day period commencing with the mean annual discharge, increasing to bankful discharge for 3 days, and decreasing back to mean annual discharge. A baseflow condition is required during the remainder of the year, which corresponds to about 11 percent of the mean annual discharge or 1.7 percent of bankful discharge. This regime includes flows representing about 78 percent of the total average annual water yield. Rosgen (1982) suggests that a range of flows are important in channel maintenance since both high and low flows have the potential for sediment deposition.

However, about 80-90% of total sediment yield is normally transported during snowmelt runoff. In this regard, Rosgen recommends a stepped increase in flow to the bankfull discharge, maintenance of the bankfull discharge for 3 days, followed by a stepped reduction to mean annual discharge. The stepped reduction is recommended by Rosgen (1982) since a rapid increase and/or decrease in flows can result in accelerated bank erosion. In this procedure, bankfull discharge (recurrence interval 1.5 years) is synonymous with dominant discharge, which for the streams studied equalled the effective discharge. This contrasts with the work of O'Brien (1984) on the Yampa River which indicated an effective discharge of about half of the dominant discharge (see Appendix B, Channel Morphology). In general, this facet of the regime could serve as a flushing flow recommendation since it is primarily concerned with sediment transport and channel shaping.

Overall, the USFS channel maintenance flow methodology is the most comprehensive with respect to defining and tailoring a flow regime to a particular stream. Rosgen (1985, pers. comm. D. Reiser) indicates that the USFS has adopted this approach on a national basis and is presently finalizing a procedure manual which provides step-by-step instructions for formulating recommendations. The manual should be available in early 1985.

Constraints and Limitations: The method requires the development of regionalized flow duration curves and therefore extensive flow records (pre-development) are required. The procedures were developed on relatively small streams in northern Wyoming and their applicability to larger streams and streams in other regions (e.g., Pacific Northwest) has not been evaluated. Methods are based on sound theoretical principles. However, little field verification of the suitability of the recommended flows has been done to date. Rosgen did note that the USFS is beginning work in the area of long-term monitoring. This method is primarily an office technique which should prove useful in the planning process.

Incipient Motion Methodology Based on Meyer-Peter Muller Formula (Water and Environment Consultants (WEC) Inc., (1980)

In 1980, WEC used an adaptation of the Meyer-Peter transport formula and Manning equation for assessing flushing flows on 18 headwater streams in southeast Wyoming. The methodology was focused on predicting the incipient motion of a specific size sediment, rather than on the entire channel bed.

Field data collected at each site included; bed material samples, stream bed and water surface slopes, water velocities, and general watershed and river characteristics. Measurements were made at three cross sections located about 150 ft (46 m) apart, with the study reach encompassing about 300 ft (91 m) in total length.

Data analysis was performed using the Meyer-Peter Muller transport formula and tractive force theory (see Appendix B, Meyer-Peter Muller formula). Because of the steep slopes and armored nature of the channels studied, WEC (1980) assumed that a hydraulically rough boundary existed. Thus, a flushing flow was defined as the discharge which produces critical shear stress (via a shear velocity V_c) on a given sized particle on a rigid boundary. This approach is applicable for removing surficial fines but would not result in the mobilization of the bed, which some investigators indicate is required to flush interstitial fines.

Analyses included the computation of several hydraulic parameters (including average velocity) for each cross section for several increments of flow. This was done until the slowest cross sectional velocity was equal to the desired V_c. As noted by WEC (1980), it was assumed that if the velocity in the slowest cross sections was sufficient to move a given particle size, then the velocities in the other cross section would be sufficient. In this manner, the representative reach should be in a condition of incipient motion for the specified sediment size. Flushing flows were based on discharges for incipient motion of 2 mm and 3 mm diameter particles.

The flows determined were recommended for a 72 hour duration and were to coincide with the natural spring run off period.

Constraints and Limitation: This methodology employs the Meyer-Peter Muller transport formula which has been shown to give widely varying results. As used, several assumptions were made which would need to be evaluated closely if used in other streams or drainages. Approach used is comprehensive and probably suitable for implementation level studies.

Incipient Motion Methodology Based on a Shields' Entrainment Function

Another approach for assessing flushing flow needs was derived during this study. Also defined as an incipient motion method, it was derived from a Shields' entrainment function (Shields' parameter estimated at 0.03), and provides a means for estimating needed flows for bed mobilization given different grain sizes and channel slopes. The required discharges are expressed as a discharge per unit stream width (Figure 3). The derivation of this approach and an example of its use are provided in Appendix B.

The duration of the estimated flows can be approximated using the travel time - median bed grain size relationships shown in Figure 4. Details on its derivation and use are presented in Appendix B, under Duration of Flushing Flows.

Constraints and Limitations: The method is based on a Shields' parameter value of 0.03. Other values have been used which would significantly change the relationship presented. No consideration is given to channel embeddedness effects. See Subsection in Appendix B on Sediment Transport Mechanics and Duration of Flows for other limitations.

Sediment Transport Models

Various sediment transport models have or could be used in the process of estimating flushing flow needs. Their utility stems from their ability to estimate bedload sediment transport capacity. Such information can then be factored into discharge relationships and flushing flow estimates derived based on the quantity and extent of the sedimentation problem. Unfortunately, the derivation and reliability of the models can be difficult and highly variable depending upon the type of stream and its physical and hydraulic characteristics (see Appendix B, Sediment Transport Functions).

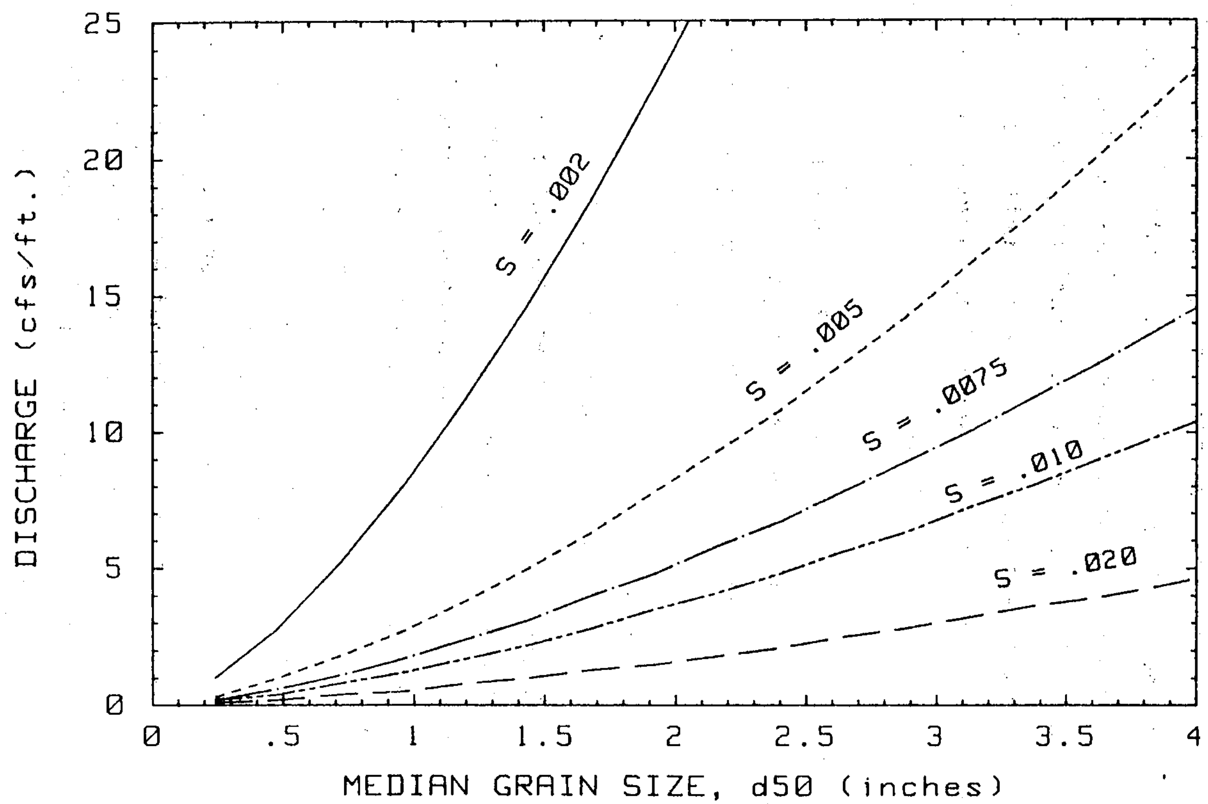


Figure 3 CRITICAL UNIT DISCHARGE FOR BED MOBILIZATION AS A FUNCTION OF GRAIN SIZE AND CHANNEL SLOPE. RELATIONSHIPS DERIVED FROM A SHIELDS' ENTRAINMENT FUNCTION.

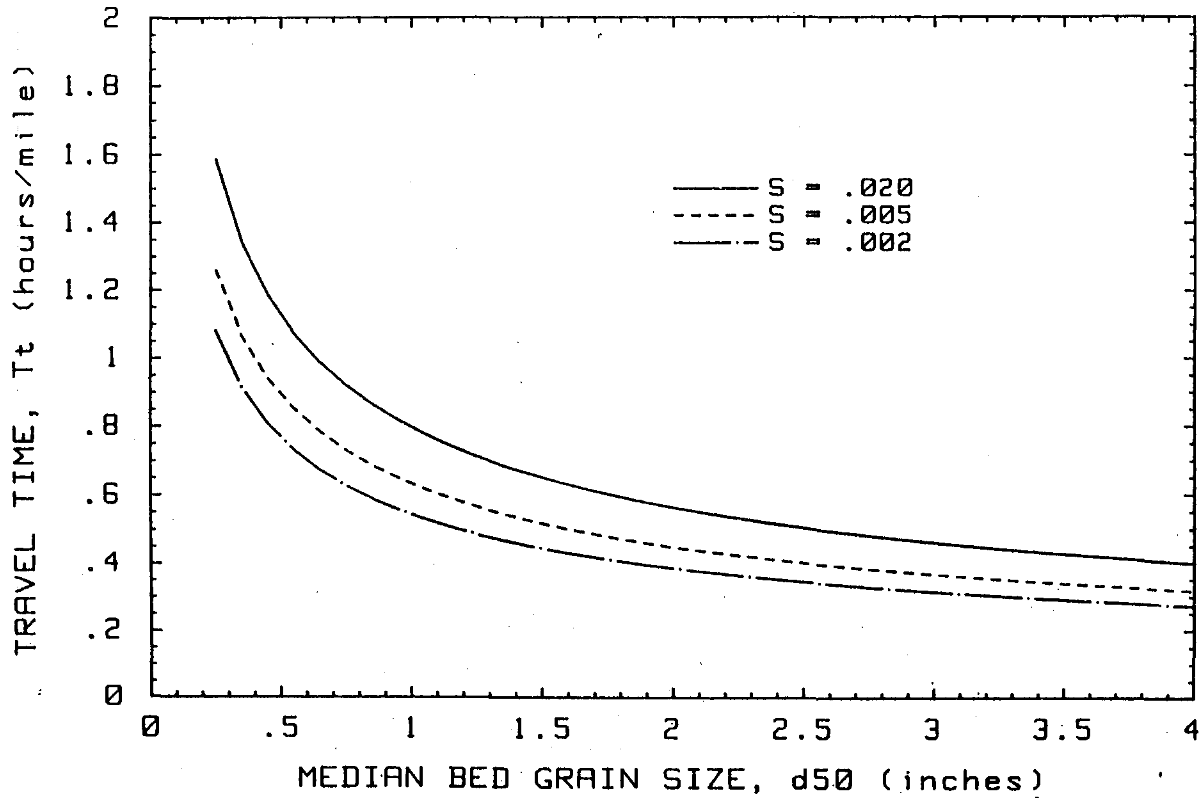


Figure 4 TIME REQUIRED TO FLUSH FINE SEDIMENTS AS A FUNCTION OF MEDIAN BED GRAIN SIZE AND CHANNEL SLOPE. SEE TEXT FOR LIMITATIONS.

Two commonly applied techniques for estimating bed material discharge include the Meyer-Peter and Muller, and Einstein (1950) methods. According to Richardson et al. (1975), the Meyer-Peter and Muller equation is applicable to streams with little or no suspended-sediment discharge and has been used extensively for gravel and cobble bed streams. The Einstein method is generally used for sandbed streams. A third technique developed by Parker et al. (1982) also shows promise for use in gravel streams.

Of the three methods, the Meyer - Peter Muller equation has perhaps received the widest application in salmonid stream systems, the majority of which are gravel-cobble streams. Neilson (1974) and Bjornn et al. (1977) utilized this equation for evaluating sediment transport in Idaho Batholith streams. Wesche et al. (1983) are currently evaluating the applicability of both the Meyer-Peter and Muller, and Einstein equations for predicting sediment transport in small Wyoming streams. See Appendix B on Sediment Transport Functions for specific information on these models.

Constraints and Limitations: Results obtained from the different models can be highly variable. Richardson et al. (1975) state that for the same discharge, the predicted sediment discharges can have a 100 fold difference between the different models applied. Results should therefore be used with caution. This variation can partially be explained given the number of variables, their interrelatedness, and the difficulty in measurments. The models do not address the timing or duration of needed flows.

Wyoming Water Research Center (WWRC) Methodology (In Progress, Wesche et al. 1983)

Although incomplete as of this writing, formal studies are underway at the University of Wyoming's Water Research Center which are focused on the development of a formalized flushing flow methodology. The research project, entitled Development of a Methodology to Determine Flushing Flow

Requirements for Channel Maintenance Purposes was initiated in early 1984 and incorporates both laboratory and field tests. The project is somewhat unique in that it addresses flushing flows from three perspectives: channel maintenance, aquatic habitat, and riparian vegetation. Specific objectives of this project are to:

- Document and begin to quantify the rate of change of channel morphologic features, riparian community structure and aquatic habitat quality resultant from channel aggradation/degradation processes under altered flow regimes

- Identify important variables and begin to quantify the physical and hydraulic properties causing the entrainment and transport of sediments

- Test the predictive capabilities of several existing sediment transport models (i.e., Meyer-Peter and Muller, and Einstein equations) against the results of quantitative field measurements

- Develop a methodology to predict the hydrologic and hydraulic conditions which must be met for flushing deposited fine sediments from stream channel bed and banks, in order to maintain a given stream in a prescribed hydraulic, physical and biological condition

Laboratory tests are being conducted in an 80 ft (24.4m) long x 4 ft (1.2m) wide experimental flume in which flows can be regulated up to 5 cfs. Field studies are being conducted in drainages which include streams that have received large deposits of fine and coarse sediments.

The above research is perhaps the most promising with respect to the development of a formalized flushing flow methodology. If successful, it would be the first to consider a variety of flushing flow needs (e.g., channel maintenance, vegetation encroachment), and should be applicable for implementation type studies.

Constraints and Limitations: Presently in a developmental stage.

EVALUATION OF FLUSHING FLOW REQUIREMENTS

From the above review and discussion it is apparent that the evaluation of flushing flows should be made with proper consideration for various physical, hydraulic and biological parameters. It is the interaction of these parameters which, in part, determines the need for, and timing and magnitude of flushing flows. This section reviews the important factors and conditions which should be monitored and evaluated when flushing flows are being considered. Emphasis is placed on defining practical techniques and approaches useful in assessing flow needs.

Determining the Need for Flushing Flows

Fundamental in the evaluation process is an initial determination of the need for a flushing flow. An unsubstantiated "blind" recommendation and implementation of a flushing flow may actually be detrimental to the aquatic resource.

In regulated stream systems, the evaluation process should commence even before a real problem is recognized. The assessment should focus on the geomorphic, and hydrologic characteristics of the drainage and how they can influence the biotic environment. Through this evaluation, it should become evident whether sedimentation problems are likely to occur in the drainage below the water development project. Specific points for consideration include:

- Physical location of the water development project
  - Is the project above or below the major sediment sources in the drainage?
  - What is the sediment contribution of major tributaries below the project?
- Topography and geology of the project area
  - Steep and open (susceptible to erosion)
  - Flat and stable

- o Susceptibility of the drainage to catastrophic events (e.g., landslides, storms, etc.)
    - Relates to climatic and topographic factors
- o Sensitivity of important fish species and their life history stages to sediment depositional effects (salmonids vs. centrarchids vs. catostomids etc.)
- o Extent of man-induced activities within the drainage which may increase sediment recruitment
    - Road construction
    - Mining
    - Logging
    - Other
- o Operational characteristics of the project
    - Large, multipurpose storage reservoir
    - Large scale hydroelectric project
    - Small scale hydroelectric project
    - Low head hydroelectric; run-of-the-river

The operating characteristics are important in determining whether the systems will likely be open or closed to upstream sediment recruitment.

The next step then is to establish or demonstrate the actual need for a flushing flow. From a biological perspective, it can be stated that flushing flows are needed when sediment levels within the stream exceed historic levels and begin to affect important aquatic habitats and life history functions.

To the extent possible this determination of need should be based on an objective, rather than subjective evaluation. Perhaps the best approach would be to establish several preproject test sections within the river reach which could be used to monitor sediment levels. The sections should include habitats (e.g., spawning areas, riffles, and pools) known to be used by resident fish species, and which are representative of other sections. The intent of this procedure is to initially define baseline sediment conditions within important habitats, which reflect unperturbed conditions. Continued monitoring of the same habitats will permit temporal and spatial comparisons, and should delineate any major changes in sediment concentration. A variety of techniques can be used for this purpose including:

- Substrate core sampling and analysis
- Intergravel sediment sampling
- Visual substrate characterization and ratings
- Cross-sectional profiling of bed elevations
- Photographic documentation
- Scour and deposition indicators
- Groundwater standpipes
- Bedload samplers

Details on these and several other methods are described in the section on Assessing the Effectiveness of Flushing Flows. Any changes in sediment levels observed need to be carefully evaluated with respect to potential impacts on the aquatic biota. Designated standards or limits of sediment deposition should be established above which a flushing flow would be required. These standards could be based on values derived from the literature, but ideally would be developed on an individual stream or drainage basis. The relationships presented in APPENDIX A of this report should be useful in this regard.

Certainly there will be circumstances when a determination of flushing flow is warranted but the above approach is not applicable. This would be the case when a landslide or debris flow introduces a catastrophic input of sediment. In these instances, "spot" measurements using the above techniques should be taken, coupled with a review and discussion of the potential problem by hydrologists, and fisheries biologists to ensure that all alternatives are considered. This should result in a mutually agreed-to solution that is in the best interests of the aquatic resource.

Determining the Timing of Flushing Flows

When the need for a flushing flow has been established, it is equally important to determine the best time for its implementation. Important considerations in this regard include:

- Species of fish present in the system
- Life history requirements of important species
- Historical runoff period and flow availability
- Water temperature

In this report the primary concern is the maintenance of the aquatic biota. Hence, flow timing should be based on the life history requirements of important fishes in a system. Depending on the magnitude and duration, flushing flows may simulate a short term peaking regime with a rapid increase and decrease in discharge. Peaking flows can have deleterious effects on the aquatic resource including the dislodgement and transport of eggs (Wade and White 1978), dewatering of redds constructed during high flow periods (Reiser and White 1983, Becker et al. 1982), stranding of fish which have entered side pools that become unbridged as flows recede (Witty and Thompson 1974), and large increases in catastrophic invertebrate drift (Wade and White 1978).

Ideally, then, the most effective time is that which provides the greatest benefits, or imparts the least harm to the biotic communities. This would certainly not be the case if flows were released during or after salmonid spawning. Released then, such flows could dislodge eggs and alevins and dramatically reduce recruitment potential. In contrast, flushing flows released prior to spawning should effectively remove and clean fine sediments from the substrates, and serve to enhance egg and alevin survival. Scheduled correctly, it may be possible for flushing flows to serve a dual purpose (i.e., flushing fine sediments from spawning gravels, and transporting smolts downstream). Maximization of benefits for the given water released should be a guiding principal when assessing the timing of flows.

Development of a detailed life history-periodicity chart for species in the system will help determine the best timing of the flows (Figure 5). This figure provides a means for reviewing the timing of all life history functions including those most sensitive to flow augmentation. This type of presentation can be valuable in stream systems managed for both cold and warmwater species.

A review of historical flow records will also be beneficial in determining the timing of releases. In many cases, the fishes present in the stream (assuming no introductions by man) have evolved around and adapted to the normal hydrograph of the system, including runoff and baseflow conditions. In these cases, flow releases scheduled during normal peak flow periods may provide the most benefits. This of course, should be reviewed in conjunction with the periodicity chart.

As noted by Wesche et al. (1977), another consideration in the timing of releases pertains to water temperature. In theory, the colder the water, the higher its viscosity, the longer entrained particles will remain in suspension. However, the actual value of using colder water for flushing is probably insignificant. This is especially true in light of the potential problems which may be imparted to the aquatic resource resulting from sudden changes in water temperature (e.g., thermal shock, migrational delays etc.).

All of the above considerations assume that flows from a project can be delivered at any time. Unfortunately, this is not always the case and releases may need to be made based on water availability. In general, the determination of the timing of flushing flows should be geared to maximize benefits for the given water released.

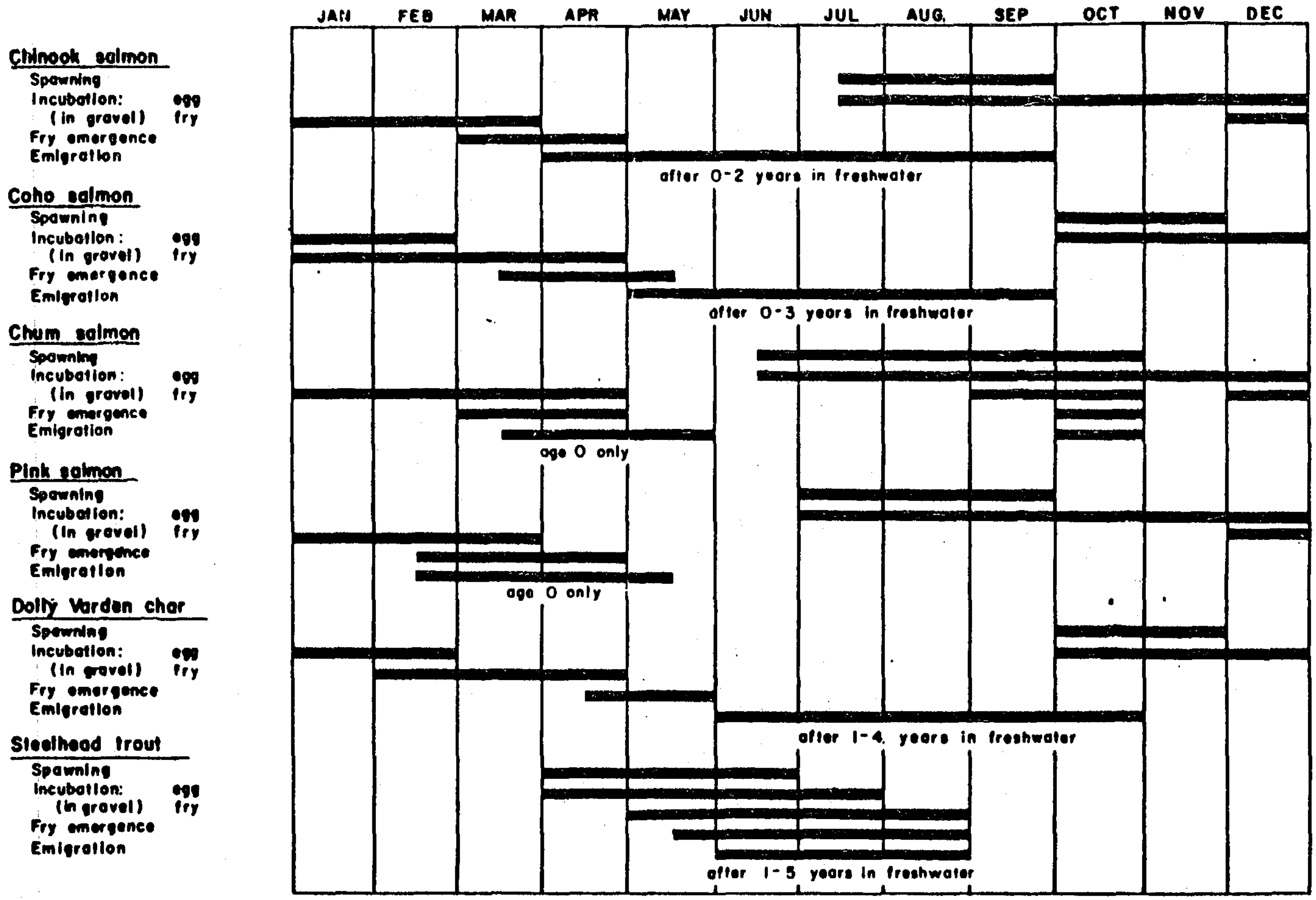


Figure 5 EXAMPLE OF SPECIES LIFE HISTORY – PERIODICITY TABLE USEFUL IN EVALUATING THE TIMING OF FLUSHING FLOWS. MODIFIED FROM VTN, 1982.

Determining the Magnitude of Flows

The determination of the magnitude of flows is the most important, yet most difficult and least understood aspect of formulating a flushing flow recommendation. No standard method or approach has been developed for this purpose (see Review of Existing Methodologies). With this in mind, what then can be done for determining the magnitude of a flushing flow?

Certainly, the methods presented and reviewed in this report should provide some guidance in formulating recommendations. A careful review of the techniques, including those derived in this document may result in the development or adaptation of an approach which lends itself to a given problem. However, this report is not a user guide for selecting flushing flow methods. Thus, the selection of one approach over another does not guarantee any better resolution in the final recommendation.

It is of interest to note the disparity in flow recommendations which can result using two different methods. Wesche et al. (1983) noted an average difference of 60 percent in the flushing flows recommended on two independent studies for the same stream systems in Wyoming. The approach of Estes (1985) and Orsborn (1982) can result in as much as a 600-900 percent difference in flows, when compared with recommendations derived using the Tennant methodology (Tennant, 1975). The methods which employ the derivation of bankfull discharge and dominant discharge via office versus field techniques would also likely vary.

In general, for studies in the planning stage, the safest approach may be to use the technique providing the highest flow estimate. This should be easy to determine since most of the office techniques have the same general data requirements (see Table 1). Using this conservative approach, water budgets and operating rules for proposed hydroelectric or water development projects can be formulated around these needs. If refinements are later warranted to reduce anticipated biological impacts or minimize economic losses they would likely result in a reduction rather than an increase in flows recommended.

For implementation studies which would include the development of final recommendations for new or existing facilities, both office and field techniques should be used. Office methods can provide an initial estimate of needed flows, which can then be refined through field evaluations. Depending upon the project and its physical setting, field techniques can range from the use of sediment transport mechanics to empirical assessments of bed transport under different flow releases. The purpose of the field component would be to verify or refine the initial recommendation as dictated by the specific characteristics of each drainage system. Flushing flow recommendations should be developed on a site-specific basis, when feasible.

The variability of results generated from the different methods, amplifies the importance of follow-up evaluation studies. Indeed, today, such studies remain as the only way to verify the sufficiency of a recommendation, and furthermore provide a means to evaluate the effectiveness of the methods themselves.

Assessing the Effectiveness of Flushing Flows

An evaluation of the effectiveness of a given discharge should be a logical part of every flushing flow study. Only through this process can the actual versus desired results be compared and necessary refinements made. Unfortunately, as the results of the survey indicate (Appendix C) few studies that have recommended flushing flows have been followed by an assessment of their effectiveness.

This section presents various methods and techniques which could be used to evaluate the effectiveness of flushing flows. The methods presented have been grouped by common analytical approach, and are summarized in Table 2. The utility of essentially every technique is contingent upon its application both before, and after a given flushing flow. In most instances however, the pre-flow assessment should already be part of the process for determining flow need. Many of the methods reviewed were developed to assess the quality of salmonid spawning grounds, and therefore lend themselves to this type of analysis.

Table 2

POTENTIAL METHODS FOR USE IN EVALUATING THE NEED FOR AND EFFECTIVENESS OF FLUSHING FLOWS

Method	Reference	Description	Before and After Approach[a]
Substrate Core Sampling (Grab sample)	McNeil and Ahnell (1964) Tagart (1976) Reiser and Wesche (1977)	6-12 inch diameter tube (generally stainless steel); (See Figure 6)	Sampler inserted into substrate within test area; sediments removed from encased area; particle size analysis (sieving) performed on sample; quantification of fine sediments in sample.
Substrate Core Sample (Freeze Core)	Ryan (1970) Walkotten (1976) Lotspeich and Reid (1980) Platts and Penton (1980) Everest et al. (1980) Everest et al. (1981) Platts et al. (1983)	Single or multiprobe (tri-core) standpipes; dimensions about 4 ft long x 1.5 in (O.D.); (see Figure 7)	Sampler driven into substrate within test area; injection of liquid nitrogen or carbon dioxide (preferable) into tubes; remove frozen core; thaw and perform particle size analysis; quantification of fine sediments in sample. Approach allows for evaluation of sediment deposition in different strata.
Sediment traps	Mahoney and Erman (1983)	Small plastic devices (open on top) containing artifical medium (marbles, glass beads)	Sediment traps installed in gravels at set intervals from target areas (at bed surface); upstream gravels are "disturbed" for a standard time interval; sediment is deposited in traps which is then quantified on site; sediment accumulated in traps is related back to sediments in target riffles. (device selects for fine sediments).
Intergravel sediment samplers	Reiser (1981; 1983) Wesche et al (1983) Whitlock (1978)	Modified Whitlock-Vibert boxes @ 5.5 in long x 3.5 in. deep x 2.4 in wide, containing artificial or natural medium (see Figure 9)	Sediment samplers installed intergravelly in target riffles for set time interval; samplers removed and fine sediments quantified on site (device selects for fine sediments). Could be used continuously as monitoring device.
Sediment deposition cans	Meehan and Swanston (1977)	Open ended (top) no. 10 cans containing clean gravel medium	Cans containing gravels are weighed, then boring flush with substrate surface; cans removed after set time period, oven dried and weighed to determine sediment addition. Could be used as monitor device
Mesh cylinders	Meehan and Swanston (1977)	Stainless steel mesh cylinder (18 inch deep x 12 in diameter) filled with gravel medium	Cylinders with gravel installed flush with substrate surface; cylinders removed after set time period; gravel and sediment fraction quantified by particle size analysis (sieving). Could be used as monitoring device.

(a) Unless specified, all techniques would require a pre-and past flow assessment.

Table 2 (continued)

POTENTIAL METHODS FOR USE IN EVALUATING THE NEED FOR AND EFFECTIVENESS OF FLUSHING FLOWS

Method	Reference	Description	Before and After Approach[a]
Ocular analysis of fines	Platts et al. (1983) Williams (1975) O'Brien (1984) Iwamoto et al. (1978)	Documentation of surface fines based on ocular assessment of size classifications	Composition of substrate evaluated at specified intervals along permanent transect line. Individual classifications are totaled to obtain amounts representative of different size categories. *This could be used with the PHABSIM model to reflect sediment change as a function of WUA.
Embeddeness	Bjornn et al. (1977) Platts et al. (1983) USFS (1977) Stowell et al. (1983)	Ocular rating of degree that larger particles are surrounded or covered by fine sediments (see Figure 6)	Embeddedness ratings taken at specified intervals along permanent transect line.
Substrate Score	Crouse et al. (1981)	Ocular rating of substrate characteristics	Substrate scores evaluated at specified intervals along permanent transect lines.
Photo transects	Corley and Burmeister (1980) Chapman et al. (1979)	Photographic documentation of substrate characteristics and sediment deposits	Photographs taken at specified intervals along permanent transect lines; general photos also taken from permanent photo marks.
Sediment mapping	Stuehrenberg (1975) Bjornn et al. (1977) Collings (1972)	Physical mapping of sediment deposits (see Figure 6)	Physical mapping of sediment deposits using surveying techniques and planimetric analysis; preparation of map overlays which depict sediments.
IFIM - Weighted Usable Area (WUA)	Bovee and Milhous (1978) Bovee (1982)	Determination of WUA based on substrate characteristics	Quantification of WUA within test reach before and after release flows (as a function of substrate change).
Cross channel transects	Wesche et al. (1983) Platts et al. (1983) Bovee and Milhous (1978) Corley and Newberry (1982)	Permanent headpins (1/2 in. rebar stakes) positioned across important pool or riffle areas	Bed elevations and visual substrates measured across channel transects at specified intervals.
Scour cords	Foley (1976) Iwamoto et al. (1978) Platts et al. (1983)	Chain links buried in substrate	Chains driven vertically into test areas noting length of chain (or # of links) exposed; comparisons made after flow releases (chain locations should be surveyed in to ensure relocation.
Tethered floats		Tethered floats (e.g., ping pong balls, plastic balls) buried in substrate	Same as for scour cords except floats are buried manually (not driven); comparisons of the number of floats exposed are made before and after flow releases.
Deposition pins	Wesche et al. (1983)	30 in. sections of 1/2 in. rebar buried in substrate	Deposition pins driven vertically into the gravel at specified intervals along permanent cross channel transects; bed elevations from top of pin to substrate surface noted as well as ocular substrate analysis adjacent to pin.

(a) Unless specified, all techniques would require a pre-and post flow assessment.

Table 2 (continued)

POTENTIAL METHODS FOR USE IN EVALUATING THE NEED FOR AND EFFECTIVENESS OF FLUSHING FLOWS

Method	Reference	Description	Before and After Approach[a]
Bed material tracers	Hey (1981) Platts et al. (1983)	Brightly colored (painted) substrate or artificial medium	Position known numbers of different sized colored substrate in pool or riffle areas and compare locations pre and post flows; initial locations should be surveyed or marked to allow an accurate estimate of replacement.
Intergravel dye tracers	--	Rhodamine B dye tablets	Place dye tablets in plastic vials and bury to desired depths within test areas (vials are inverted when buried so water does not come in contact with tablets). When bed material begins to move around the vial it will shift allowing dye tablet to contact water; dye plume should be evident downstream.
Radioactive spikes		Injection of low level radiation spikes into gravel sediments	Injection of spikes into gravel sediments and subsequent monitoring downstream during and after flow augmentation.
Gravel permeability	Wickett (1954) Terhune (1958) Reiser and Wesche (1977) Chapman et al. (1979) Reiser and White (1981) Tagart (1976)	Steel, aluminum or PVC 1.25 inch diameter standpipes with perforations at bottom	Fixed standpipes installed along cross channel transect at specified intervals; permeabilities measured pre- and post flushing flows (permeabilities related to sediment deposition).
Intragravel (apparent) velocity measurements	Wickett (1954) Shelton (1955) Terhune (1958) Pinchak (1973)	Dye dilution Salt bridge (conductivity) Thermistor	In conjunction with standpipes, measure intragravel velocity (apparent velocity related to sediment deposition).
Intragravel dissolved oxygen	Terhune (1958) Sheridan (1962) McNeil (1962) Reiser and Wesche (1977) Shelton (1955) Chapman et al. (1979) Tagart (1976) Reiser and White (1981)	Dissolved oxygen meter Winkler technique	In conjunction with standpipes, measure intragravel dissolved oxygens (D.O. indirectly related to permeability and apparent velocity).
Bedload samplers	Helley and Smith (1971) Neilson (1974)	Measurement of bedload sediments using standard sampling equipment	Bedload quantification made at specified intervals along a permanent cross channel transect at specified flows; comparisons made pre-and post flows.
Sediment - biological response model	Stowell et al. (1983)	Method for predicting effects of sediment yield on stream habitat and fisheries	This method will be useful in determining the initial biological need of the flushing flows.

(a) Unless specified, all techniques would require a pre-and post flow assessment.

The selection and implementation of any of the methods should of course be preceded by a review of its data collection and analysis techniques, and its applicability to a given stream system. Where practical, special emphasis should be made to design sampling programs to ensure the collection of meaningful, statistically valid data which can be factored into the evaluation process. The following discussions of the sampling techniques assume that valid study designs would be used.

Substrate - Sediment Analysis (Core Sampling)

Perhaps the oldest and yet most often used approach for assessing sediment deposition in spawning gravel is the complete removal of a small portion of steambed for size distribution analysis and determination of percentage of fines. The approach has been used extensivly to document the impacts of fine sediment accumulation in gravels resulting from a variety of land use activities (e.g., channelization, logging road construction, mining, water development projects).

The collection of substrate samples is generally accomplished using one of two techniques: grab (or manual) sampling techniques described by McNeil and Ahnell (1964), Tagart (1976), Reiser and Wesche (1977), Moring and Lantz (1974) and Corley and Burmeister (1980); and freeze core sampling techniques developed by Ryan (1970) and Walkotten (1976). The efficiency of the latter sampling method has subsequently been improved by Platts and Penton (1980) and Everest et al. (1980).

Grab sampling techniques generally employ a metal tube open at both ends which is manually forced into the gravel to a specified depth. The material encased in the tube is removed by hand and analyzed for particle size distribution. Although a variety of sample designs have been used, most have been patterned after the McNeil type sampler (Figure 6) which was originally designed by McNeil (1964) and McNeil and Ahnell (1964). Tube diameters which have been used have ranged from 6 to 12 in (15 - 30.5 cm). Platts et al. (1983) recommend a minimum diameter of 12 in (30.5 cm); Shirazi and Seim (1979) suggest the diameter should be two to three times the diameter of the largest particle sampled.

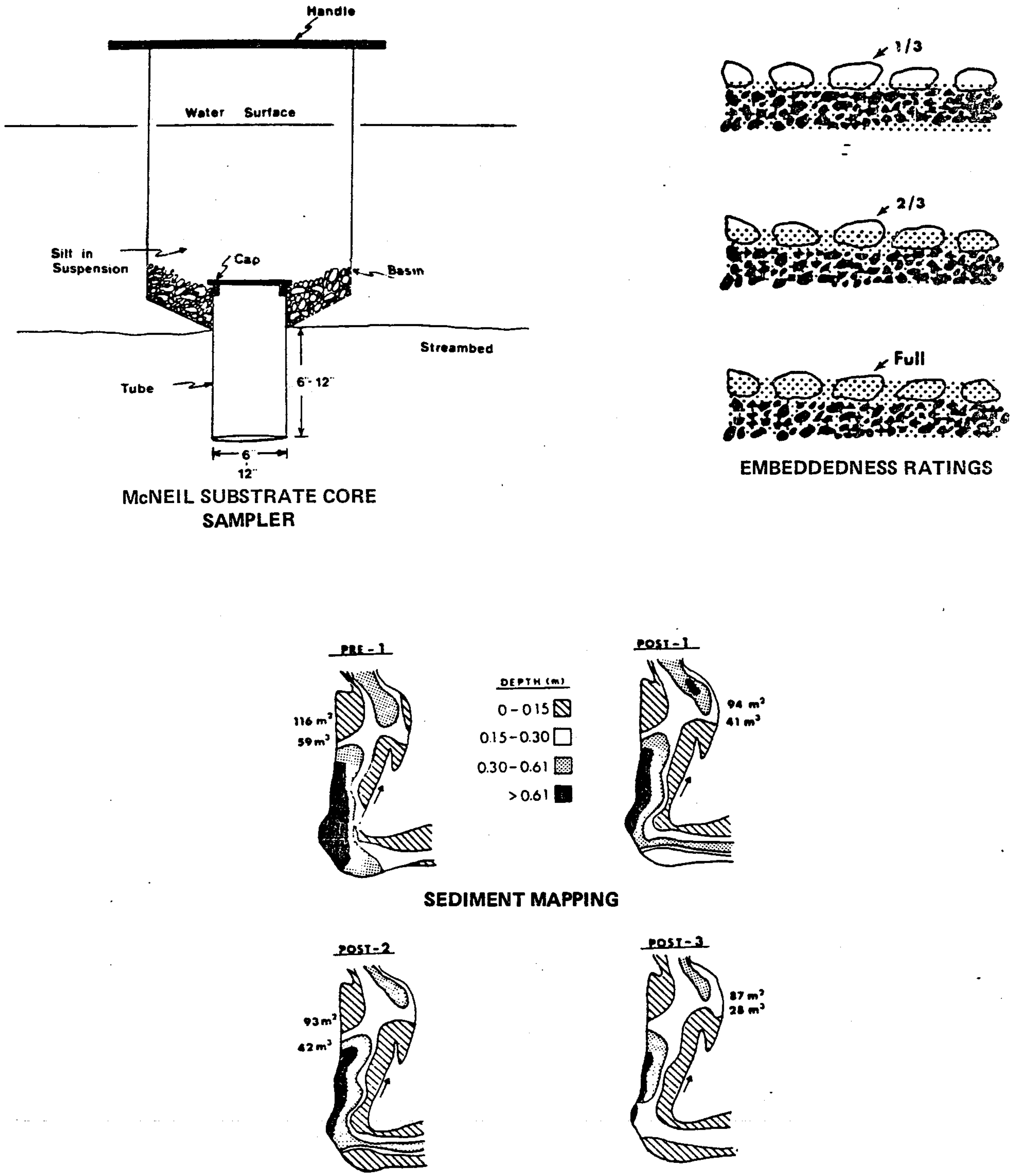


Figure 6 POTENTIAL TECHNIQUES (CORE SAMPLING, EMBEDDEDNESS, MAPPING) FOR EVALUATING THE NEED FOR AND EFFECTIVENESS OF FLUSHING FLOWS. (SEE TEXT FOR DETAILS.) MODIFIED FROM PLATTS et al (1983), AND BJORNN et al (1977)

Freeze core sampling techniques entail the driving of a hollow probe(s) into the substrate, injecting the probe with a cryogenic medium, and after a set time, removing the probe and frozen core of sediment adhering to it. The core sample is then thawed for particle size analysis. The core sample collected in this manner can be analyzed by strata and thus, sediment deposition over time can be assessed. To date, the most effective and economical freezing medium is liquid CO_2 (Everest et al 1981, Walkotten 1976). Both single probe (Platts and Penton 1980) and multiple (tritube) probe (Lotspeich and Reid (1980); Everest et al. (1980) core samplers have been utilized (Figure 7). Everest et al. (1981) and Platts et al. (1983) suggest the use of the tri-tube sampler when numerous cores are collected, and the single tube when only a few large cores are required.

Shirazi and Seim (1979) evaluated the two methods and concluded that both techniques provide comparable results when properly used. However, both techniques have shortcomings which should be kept in mind when designing a sampling program. These include, as reported by Everest et al. (1981) and Platts et al. (1983):

- Grab sampling disadvantage
  - The core tube often pushes larger particle sizes out of the collecting area.
  - Core materials are completely mixed so no interpretation can be made of vertical or horizontal differences in particle size distribution.
  - Suspended sediments in the core are lost.
  - Particle sizes larger than the core tube cannot be collected.
  - The sampler may not be able to be inserted to a specified depth if sediment particles are large and the substrate is compacted.

FREEZE CORE SAMPLERS

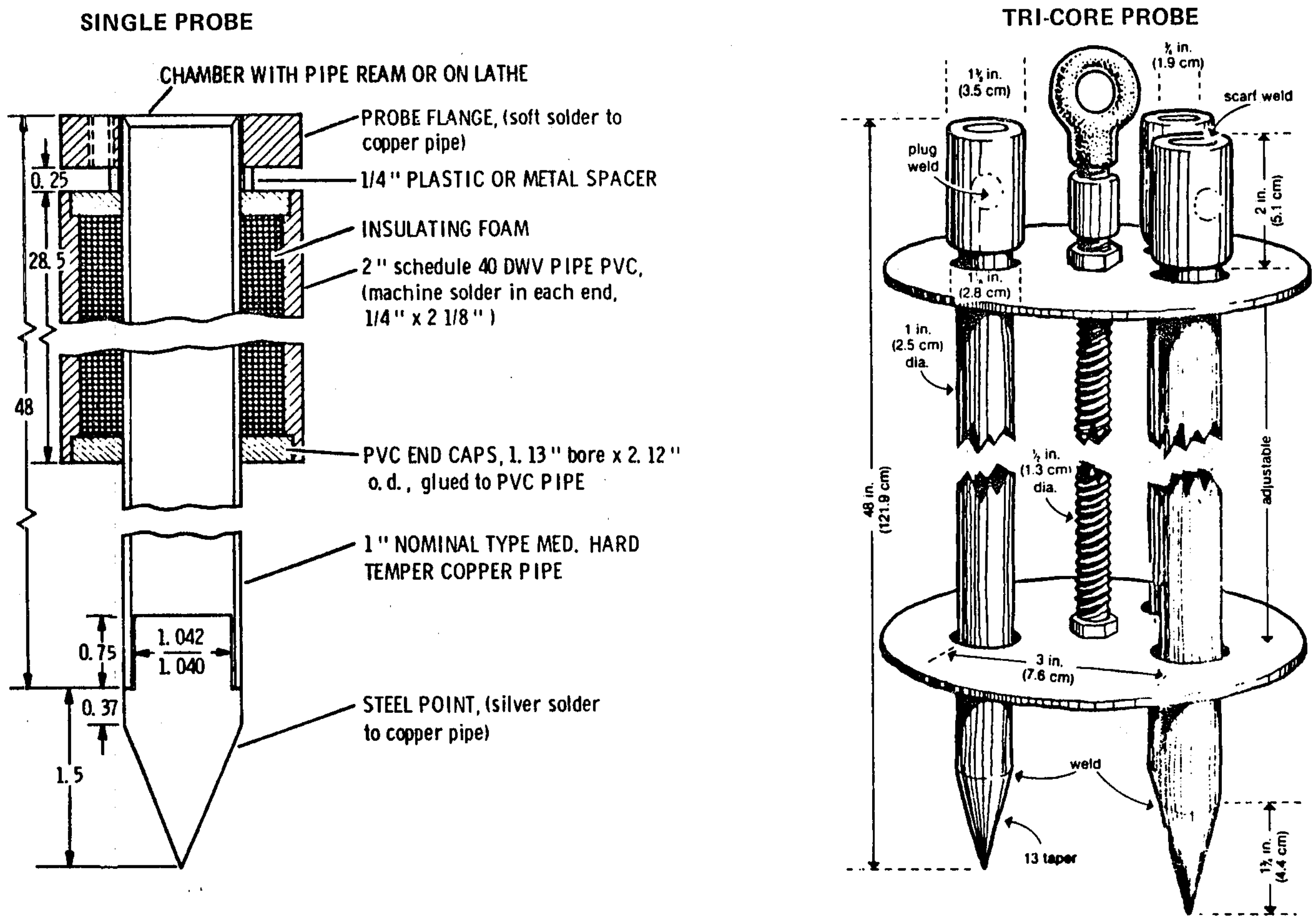


Figure 7 SINGLE (LEFT) AND MULTIPLE (RIGHT) PROBE FREEZE CORE SAMPLERS USED FOR COLLECTING SUBSTRATE SAMPLES IN STREAMS. SUCH SAMPLERS MAY BE USEFUL FOR EVALUATING THE EFFECTIVENESS OF FLUSHING FLOWS. MODIFIED FROM PLATTS AND PELTON (1980) AND EVEREST et al (1981)

- Freeze core disadvantages

  - The freeze core probes are difficult to drive into substrate containing many particles over 4.0 inch (10 cm) in diameter.

  - The freeze core technique is equipment-intensive requiring CO_2 bottles, hoses, manifolds, probes and a sample extractor. Because of this, freeze core sampling is generally limited to readily accessible areas.

  - The size (volume) and weight of the samples obtained using this technique makes them difficult to handle and analyze (subsampling may be required).

Substrate samples collected using either method are analyzed using a series (12-16) of sieves with recommended sizes ranging from 4 inches to 0.002 inch (100-0.06mm) in diameter. Tappel and Bjornn (1983) developed a promising analytical technique which suggested two sieve sizes (0.37 and 0.03 in., or 9.5 and 0.85 mm), should be sufficient for characterizing fine sediment; and could greatly reduce laboratory analysis time. Two sieving techniques are presently used, wet sieving which is based on volumetric displacement, and dry sieving based on gravimetric analysis.

Data obtained from sediment samples can be reported in a variety of ways. The original manner was in terms of the percentage of fines less than a given size class of sediment thought to be most harmful to egg incubation (0.25, 0.19, and 0.03 in., or 6.4, 4.7, and 0.85 mm were commonly cited). Investigators have since demonstrated that this did not accurately characterize the entire sample and now recommend the use of the geometric mean diameter (Shirazi and Seim 1979; Platts et al. 1979) and fredle index (Lotspeich and Everest 1981; Platts et al. 1983).

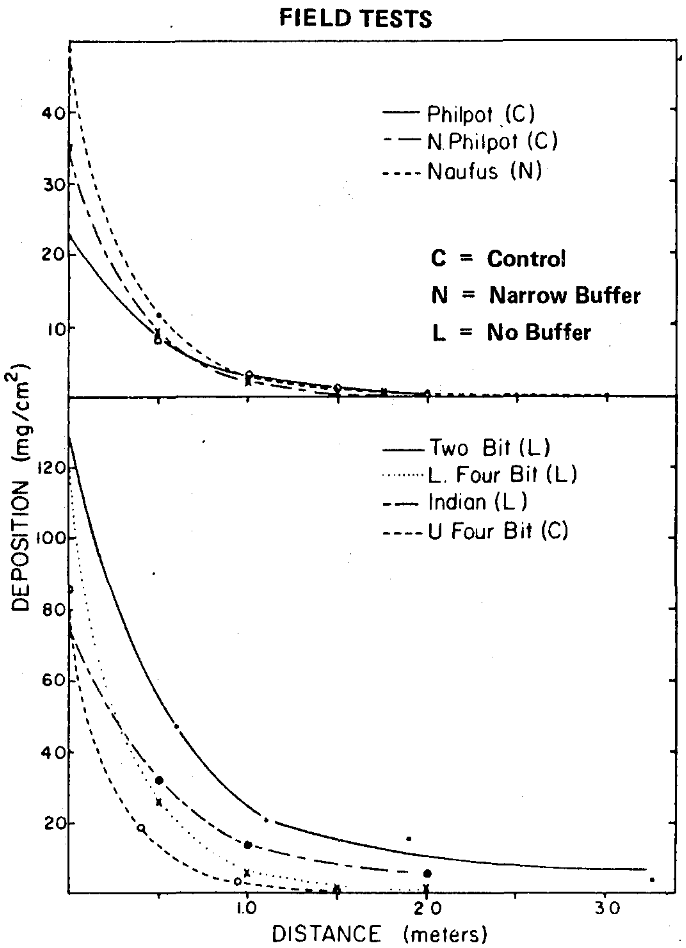
Regardless of the technique employed, the general approach for evaluating the effectivness of flushing flows is to collect and analyze a series of samples before and after the flow release. Effectiveness can be measured in terms of the change in sediment content within the test reach expressed as the percentage difference between actual versus estimated (or targeted) sediment levels.

Intergravel Sediment Sampling

Another approach for assessing the effectiveness of flushing flows is through the quantification of fine sediments within the intergravel environment using sediment "trapping" devices. Depending upon the technique used, both instantaneous and continuous measurements can be made, the latter especially useful in monitoring studies. The basic approach would utilize a before and after assessment of sediments. Mahoney and Erman (1984), Carling, (1984), Meehan and Swanston, (1977) and Reiser (1983) have all described methods potentially useful for measuring intergravel sediment accumulation.

The technique developed by Mahony and Erman (1984) involves the burial of sediment traps (containing marbles) within the gravel in several equidistantly spaced rows within a riffle area; tops of the traps are flush with the substrate surface. A site upstream from the first row is disturbed with a trowel for a specified time interval (2 min). Lids are placed on the traps, the traps are removed and the sediments vacuum filtered on site; samples are later oven dried in the laboratory. The quantity of sediment is estimated by back extrapolating to zero distance the sediment concentration in the different rows (Figure 8). The total sediment deposition (expressed as mg/cm^3 0.3 mm diameter) is determined as a function of the deposition occurring between the different rows as influenced by changing settling velocities. As noted by Mahoney and Erman (1983), this technique has several advantages over coring methods, including ability to index the quantity of fines in stream beds which are too rocky for coring devices, and the sampling of a greater expanse of the riffle area providing a more reliable estimate.

Meehan and Swanston (1977) utilized buried cans ("deposition cans") and stainless steel mesh cylinders for evaluating the effects of sediment deposition on salmonid egg survival. The deposition cans (size 10) are filled with clean gravel, weighed and buried just below the gravel pavement layer in the stream. Following a specified time interval, the cans are recovered, oven-dried and weighed to determine the amount of sediment which accumulated during the duration of flow. The mesh



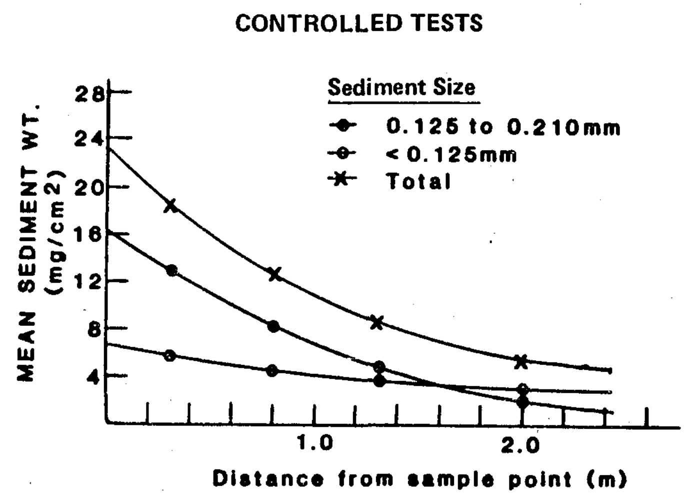


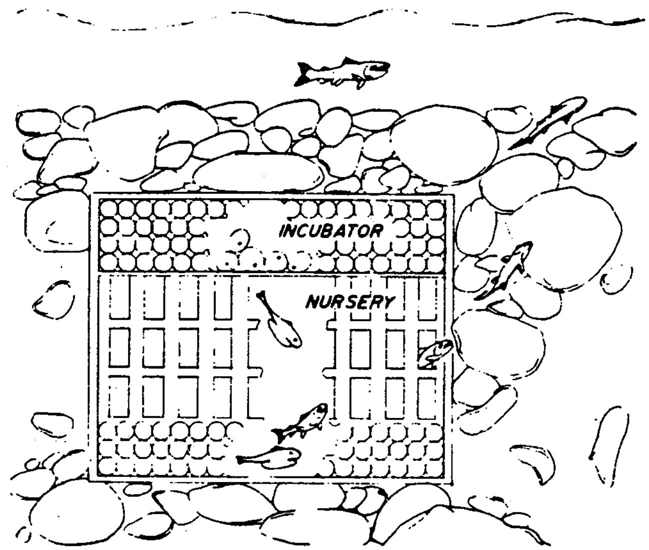
Figure 8 BACK CALCULATION OF TOTAL SEDIMENTS BASED ON DEPOSITION IN DOWNSTREAM SEDIMENT TRAPS IN FIELD (LEFT) AND CONTROLLED (RIGHT) TESTS. THIS TECHNIQUE MAY PROVE USEFUL FOR EVALUATING THE EFFECTIVENESS OF FLUSHING FLOWS. MODIFIED FROM MAHONEY AND ERMAN (1984)

cylinders measure 18 in (46 cm) deep x 12.5 in (32 cm) diameter and are filled with clean gravel. The cylinders are buried in the gravel flush with the surface of the substrate. The cylinders are left in the gravel a specified time and subsequently removed for particle size analysis and determination of fine sediment accumulation.

Reiser (1983) has proposed the use of modified Whitlock - Vibert (W-V) boxes (Whitlock 1978) for assessing intergravel sediment accumulation. W-V boxes are made of polypropylene and measure 5.5 in. (14 cm) long x 3.5 in (8.9 cm) deep x 2.5 in (6.4 cm) wide. The sides, top and bottom of the W-V box are perforated, with various sized and shaped rectangular slots to allow water circulation (Figure 9). The utility of the W-V box for assessing fines accumulation was noted by Reiser and White (1981) during salmonid egg survival studies; W-V boxes were used as egg containers which were planted in artificial redds. In these studies, substrate core samples (McNeil sampler) were collected from each redd to quantify percentage fine sediments. When recovered, the percentage of material contained in the W-V box was evaluated and subsequently correlated with fines from the core sample analysis (Figure 9). A definite relationship between the amount of sediment in the W-V boxes and the sediments in the surrounding gravel was indicated. This method is being tested further at the University of Wyoming, Water Research Center (Wesche et al. 1983) and as part of a PGandE stream sediment monitoring study. The W-V box has the advantage of being small and inexpensive. This permits a more extensive sampling effort and perhaps a more accurate characterization of accumulated sediment.

For flushing flow studies, two study approaches could be followed using these techniques. The first would involve positioning a number of samplers in the test reach for a sufficient time for sediments to equilibrate with the ambient concentrations. Sediment levels in the samplers removed at that time would represent "before" conditions. Flushing flows would then be released, the remaining samplers recovered, and the changes in sediment concentrations noted. The major drawback in this approach is the length of time needed to define the ambient sediment content and, the uncertainty when ambient conditions have been attained.

Figure A



Whitlock-Vibert Box

Figure B

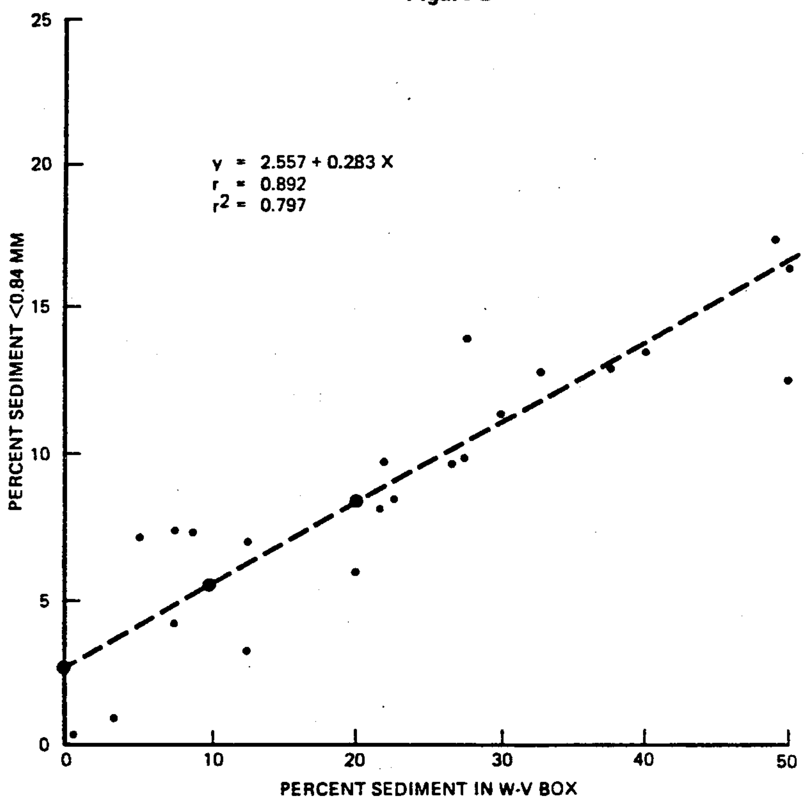


Figure 9 FIGURE A – SCHEMATIC DIAGRAM OF A WHITLOCK VIBERT BOX USED FOR INCUBATING SALMONID EGGS (FROM STREAM ENHANCEMENT RESEARCH COMMITTEE, 1980); FIGURE B – RELATIONSHIP BETWEEN PERCENT SEDIMENT IN W-V BOXES AND PERCENT SEDIMENT $<$ 0.84 mm COLLECTED IN A McNEIL CORE SAMPLER (UNPUBLISHED DATA FROM REISER, 1981)

The second approach involves the complete filling of the samplers with fine sediments and clean gravel and then placing them within the test riffle. Pre-and post-flow comparisons would thus be based on the amount of sediments removed (flushed) from the samplers. This procedure is more direct and would require less time, but may be less representative of actual conditions.

Ocular Assessment Techniques

Several ocular (visual) assessment techniques or indices exist which can help evaluate the effectiveness of flushing flows. Although these methods are subjective, the use of specific rating criteria reduces the inherent variability.

Three techniques lend themselves to before and after type studies: visual analysis of substrate composition, embeddedness ratings, and substrate score. Each of the assessment methods would use permanently established transects positioned across test areas (riffles, pools, etc.). Individual ratings (before and after flow releases) are recorded at specified intervals across the transect and comparisons made.

Visual Analysis of Substrate Composition. The objective of this method is to quantify, by major size class, the amount of substrate materials along a transect line. The procedure would include the stretching of a measuring tape between the end points of each transect, and characterizing the stream bottom at one foot increments. For each transect, the individual 1 ft (0.3 m) classfications are totaled to obtain the amount of bottom representative of each size class. Bovee (1982) suggests several approaches for coding substrate sizes which may also be applicable for this type of analysis.

Embeddedness. Embeddedness is another visual technique useful in flushing flow studies. As defined by Stowell et al. (1983), embeddedness is a rating of the degree the larger particle sizes such as gravel, rubble etc., are covered with finer sediments (Figure 6). Presently, two systems for evaluating embeddedness are practiced, one using a rating system, the other based on percentages. Platts et al. (1983) utilize the first, and recommend the use of the following ratings for assessing embeddedness:

Rating	Description
1	75% of surface substrate covered by sediments
2	50-75% of surface substrate covered by sediments
3	25-50% of surface substrate covered by sediments
4	5-25% of surface substrates covered by sediments
5	0-5% of surface substrates covered by sediments

Stowell et al. (1983) use a direct percentage basis ranging from 0 to 100 percent; a 100 percent rating would occur when the surface substrates are completly covered by fine sediments.

Embeddedness ratings taken at specified intervals across a transect, both before and after a given flushing flow, can be useful for documenting sediment transport and the overall effectiveness of the flow. The ratings can be taken in concert with the visual substrate characterizations to provide a dual means of assessment.

Substrate Score. An approach which integrates both substrate size and embeddedness ratings has been evaluated and proposed by Crouse et al. (1981). Termed, "substrate score", the method is an adaptation of a technique originally developed by Sandine (1974). As described by Crouse et al. (1981) the substrate score is a summation of four ranks, three concerning the size of the substrate, the fourth a level of embeddedness. The predominant and subdominant particles are ranked based on substrate size. A third rank corresponds to the size of the material surrounding the predominate substrate particles. The fourth rank is the level of embeddedness. The values of the rankings are summed for a single value defined as the "substrate score". The lower the value, the poorer the habitat. Crouse et al. (1981) used the same embeddedness rankings as noted above; substrate size rankings were as follows:

Rank	Particle Type or Size
1	Organic cover (over 50%)
2	0.04 - 0.08 inch
3	0.08 - 0.2 inch

4	0.2 - 1.0 inch
5	1.0 - 2.0 inch
6	2.0 - 4.0 inch
7	4.0 -10.0 inch
8	10.0 inch

Results of studies by Crouse et al. (1981) suggest that visual "substrate scores" are highly correlated with geometric mean diameters determined from detailed particle size analysis (Figure 10). They also found significant correlations between "substrate score" and fish production. Use of this approach then, in addition to providing an index of physical change, may also be useful for evaluating the change on a biological basis. This may be useful both in determining the need for and sufficiency of a given flushing flow.

Survey and Photographic Techniques

Methods which utilize standard survey techniques would also be useful in flushing flow effectiveness assessments. Such methods include cross-sectional profiling, sediment mapping, photo transects and the use of the IFIM (based on substrate characteristics).

Cross-sectional profiling. According to Platts et al. (1983) the best method for quantifying channel aggradation and/or degradation is with cross sectional profiling. Both Corley and Newberry (1982) and Wesche et al. (1983) have used this approach for assessing temporal changes in substrate composition in streams. In this technique, bed elevations are measured at specified intervals across a permanent transect (Figure 11) as referenced to headstakes and an established bench mark (BM). Several transects should be used to define the characteristics of each test feature (e.g. pool, riffle). Bed elevations taken at the same locations along each transect, as well as elevational differences among the transects can be compared between pre-and post flushing flows. Such comparisons should illustrate the amount and location of bed elevation change.

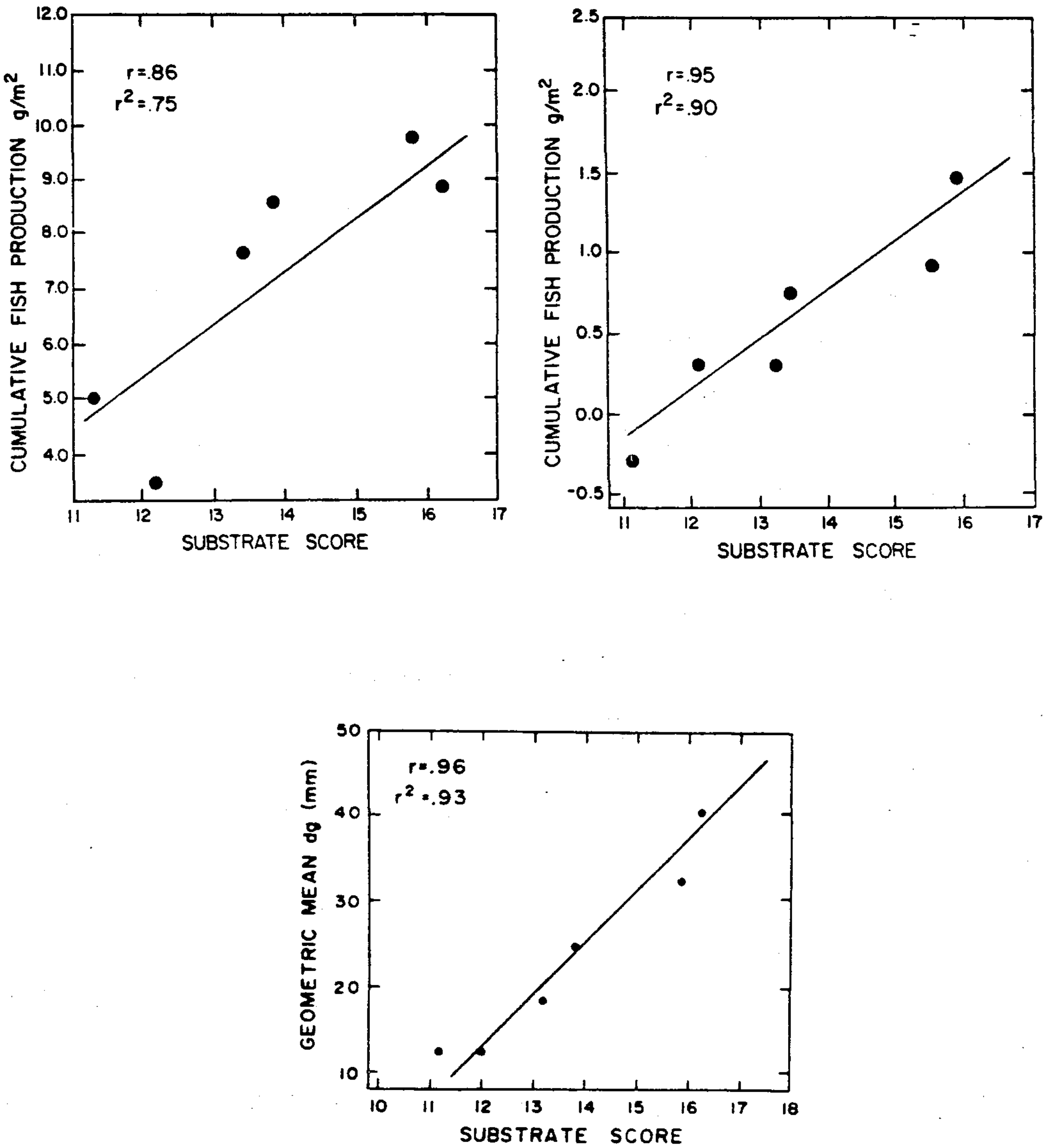


Figure 10 RELATIONSHIPS OF SUBSTRATE SCORE TO FISH PRODUCTION (UPPER) AND GEOMETRIC MEANS AS DETERMINED BY CROUSE et al 1981. (SEE TEXT FOR EXPLANATION OF SUBSTRATE SCORE.)

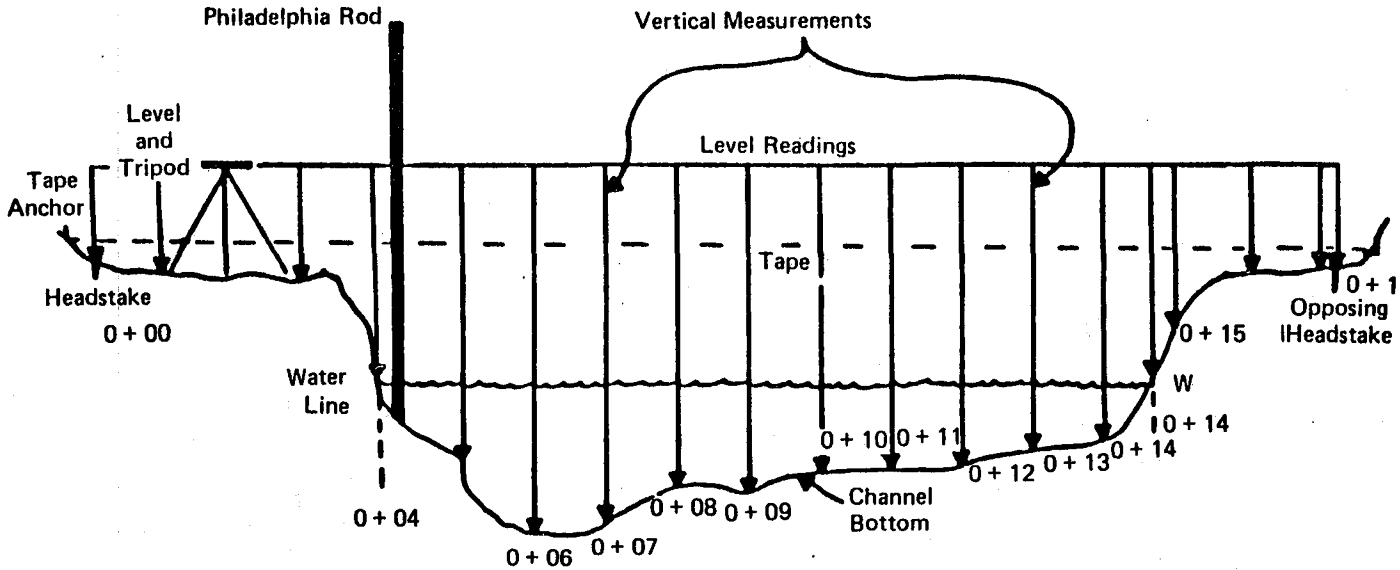


Figure 11 CROSS-SECTIONAL PROFILE OF A HYPOTHETICAL TRANSECT 0+00 SHOWING LOCATION OF HEADSTAKES AND VERTICAL MEASUREMENTS FOR DETERMINING BED ELEVATIONS. PROFILING BEFORE AND AFTER A GIVEN FLUSHING FLOW WILL DOCUMENT CHANGES IN BED ELEVATION.

Sediment - Mapping. Sediment mapping is an extension of cross-sectional profiling. The procedures would closely follow the techniques described by Collings (1972) for the mapping of salmonid spawning habitat. The mapping could be based on two parameters, depth (bed elevation) or visual substrate characterization. A simple approach for mapping would include the following:

- Establishment of a surveyed baseline along the periphery of the test reach; baseline to include equidistantly spaced stakes (transect locations) between major headstakes

- Depth (or bed elevation) profiling along each of the transects at specified intervals (alternatively, or in combination, a visual characterization of substrates could also be made); measurements would be made before and after each flushing flow

- For each set of data, development of schematic overlay maps which depict depth isopleths within the reach; or a substrate characterization map which depicts major sediment deposits

- Comparison of data and map overlays to determine areal extent of change; this method lends itself to planimetric evaluations

Stuehrenberg (1975) and Bjornn et al. (1977) used this technique to evaluate the reduction in salmonid rearing habitat resulting from the addition of fine sediments (Figure 6).

Photo Transects. Photographic documentation of pre-versus post-flow sediment conditions can also be an effective evaluation technique. This can be accomplished on either a generalized or detailed basis. A general approach would be to establish permanent photo points which afford views of specific sediment deposits in the stream. Photographs taken from these points before and after each flushing flow could be compared for changes in the quantity and location of sediments. Corley and Burmeister (1980), used this technique in their evaluation of the South Fork of the Salmon River in Idaho.

A more detailed approach might be to integrate photographic documentations of substrate conditions into standard transect analysis. Thus, each cell visually characterized across a transect could have a corresponding pre-vs. post-photograph.

IFIM - Weighted Usable Area (WUA). A slight modification in the use of the IFIM may also prove useful for assessing flushing flows (as a function of habitat) especially for streams which have recently undergone a detailed IFIM analysis. The approach involves the re-characterization of substrate types along each transect following a given flushing flow, and the subsequent re-running of the HABTAT model to generate new habitat vs. flow relationships. The difference in the curves (before and after) are expressed as gains (or losses) in habitat (WUA) resulting from the flushing flow (Figure 12). Milhous (1982) used a similar approach for assessing the effects of sediment transport on fisheries habitat. Likewise, Estes (1985) used this approach in evaluating the sensitivity of the HABTAT model to changes in parameter values.

For example, through an IFIM study it may be determined that an area which provides excellent depths and velocities for spawning, but which is heavily sedimented may only provide 1000^2ft/1000 ft of stream (for a given flow) of WUA for spawning. The re-evaluation of substrate after a flushing flow and the re-running of the HABTAT model may then indicate that 2000 ft^2/1000 ft of stream are now available for the same flow. Thus, habitat has been increased by 100 percent following the flow. It is unreasonable to assume that bed elevations will remain the same after a flushing flow and for this reason it is probably best to use the IFG-4 model for hydraulic simulation.

Assuming that the same hydraulic model would be applicable for both pre- and post-flow assessments, this approach offers a unique way of presenting potential benefits of a given flushing flow on a habitat (WUA) basis.

Scour and Deposition Indicators

Two techniques are offered which have proven useful in evaluating scour and deposition in streams. Conceptually, all of the methods provide a reference point from which changes can be assessed. Scour cords, as described by Foley, (1976) and noted in Iwamoto et al. (1978) and Platts et al. (1983) consist of chain links which are driven vertically into the

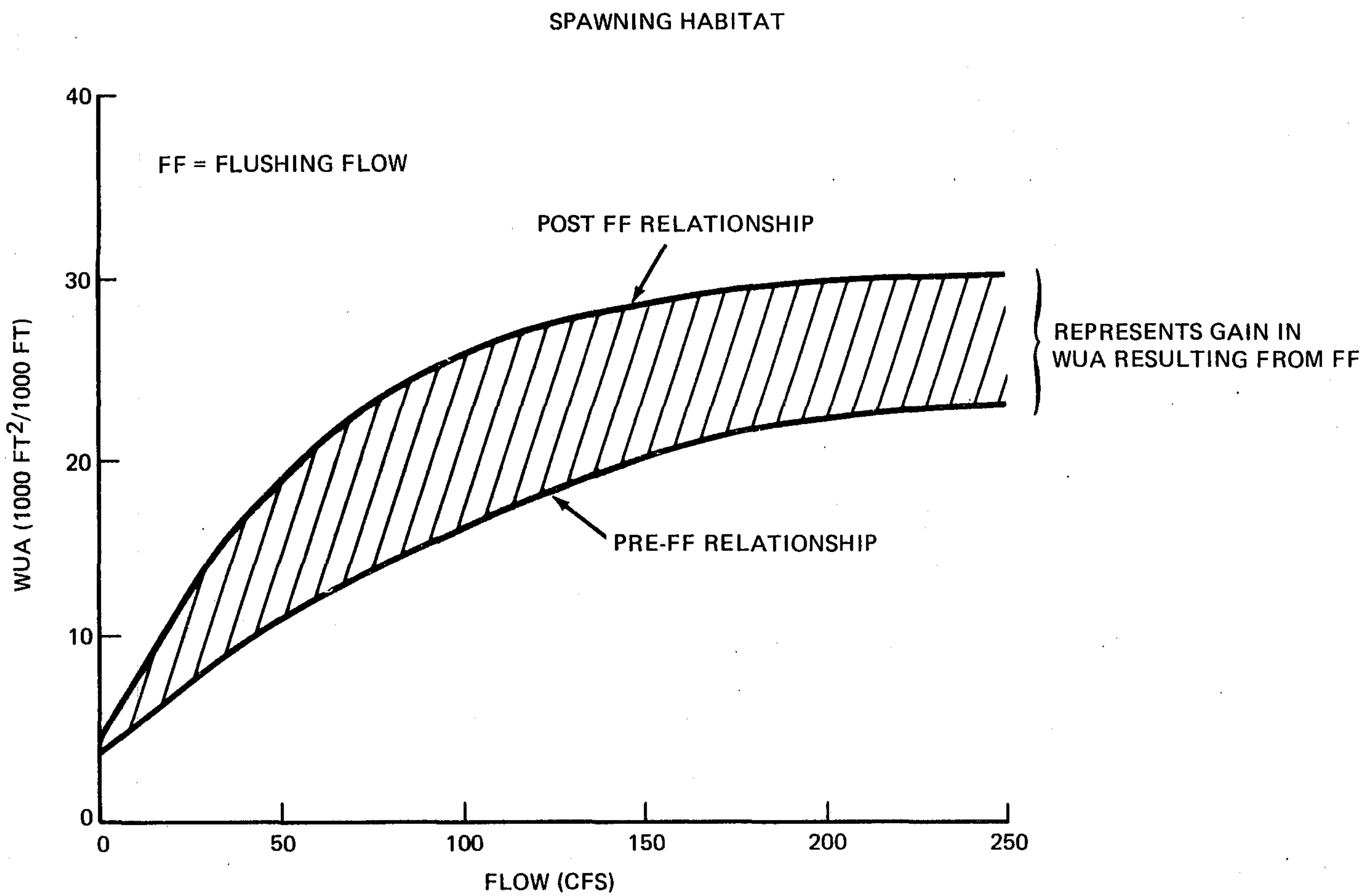


Figure 12 HYPOTHETICAL RELATIONSHIP BETWEEN WUA AND STREAMFLOW BEFORE AND AFTER IMPLEMENTATION OF A FLUSHING FLOW. AREA BETWEEN THE CURVES REPRESENTS GAIN IN HABITAT. (SEE TEXT FOR DETAILS.)

test area. A pre- and post-flow measurement of the length of chain exposed (or number of links exposed) is made for comparative purposes. Tethered floats using ping pong balls (Kelly and Dettman 1980) could be similarly used.

Deposition pins (Wesche et al. 1983) consist of 30 in. (76 cm) sections of 0.5 in (1.3 cm) rebar which is driven vertically into the streambed. The pins can be installed randomly within specified areas, or positioned at specified intervals across a given transect. Every effort should be made to get the pins flush with the streambed, if possible. Bed elevation measurements are made at the top of the pin and at its intercept point with the substrate; visual substrate analysis is also made. As with other techniques, comparisons are made before and after each flushing flow.

Tracers

Tracer materials can also be used in conjunction with flushing flow assessments. These may include bed material tracers, dye tracers or radioactive spikes. Of these, bed material tracers are the most promising. In concept, this technique described by Hey (1981) and Platts et al. (1983) entails the marking of various sized substrate particles, placing known numbers within pools or riffles areas, and subsequently monitoring their displacement after a given flow. The marking of the materials can be done with fluorescent paint or other waterproof medium. Platts et al. (1983) noted that placement of the painted materials must be done carefully so they are fitted into the streambed surface in a manner similar to the undisturbed bed particles. The failure to recover the materials, or the recovery of materials downstream from the original location would provide an indication of the size of material transported by a given flow.

Dye tracers (Rhodamine B) and radioactive spikes offer two other assessment techniques, although the applicability of the latter may be limited by regulatory constraints. Dye tracers (tablet form) placed in vials and buried in the gravel to set depths may be useful for documenting gravel disturbance (mobilization) in conjunction with flushing flows. As flows increase and the bed becomes mobilized, the vials should shift allowing the dye to mix with water. Assuming a high enough concentration of dye, a dye plume should be evident downstream. This technique would require continuous observation during the rising and early stabilization of the flushing flows.

Intergravel Standpipes

Intergravel (groundwater) standpipes can be used to measure several different parameters which are related to sediment deposition, and which should be influenced by a flushing flow. The parameters include gravel permeability, intragravel velocity (apparent velocity) and intragravel dissolved oxygen. The relationship of these parameters and their importance for salmonid egg incubation are discussed in Appendix A.

Standpipes are open at both ends and are generally made of steel or PVC pipe which is then driven or buried within the stream bed to a specified depth (Figure 13). The standpipe affords an access portal for measuring various parameters in the intergravel environment (Gangmark and Bakkala 1978). Although a variety of designs have been developed, the standpipes originally conceived by Pollard (1955) and modified by Terhune (1958) remain the most frequently used.

Standpipes have been used in a variety of studies including those attempting to locate sources of groundwater flow (McNeil 1962), spawning gravel characterization studies (Terhune 1958, Wickett 1954, Shelton 1955, Sheriden 1962, Tagart 1976, Reiser and Wesche 1977, Chapman et al. 1979), and studies evaluating the effects of flow alterations on the incubation environment (Reiser and White 1981, Parametrix, et al. 1979, Chapman et al. 1980).

For flushing flow studies fixed standpipes can be installed at specified intervals along a cross channel transect, or positioned in important spawning areas. Selected measurements can then be made before and after the flushing flow and comparisons made. Gravel permeability measurements

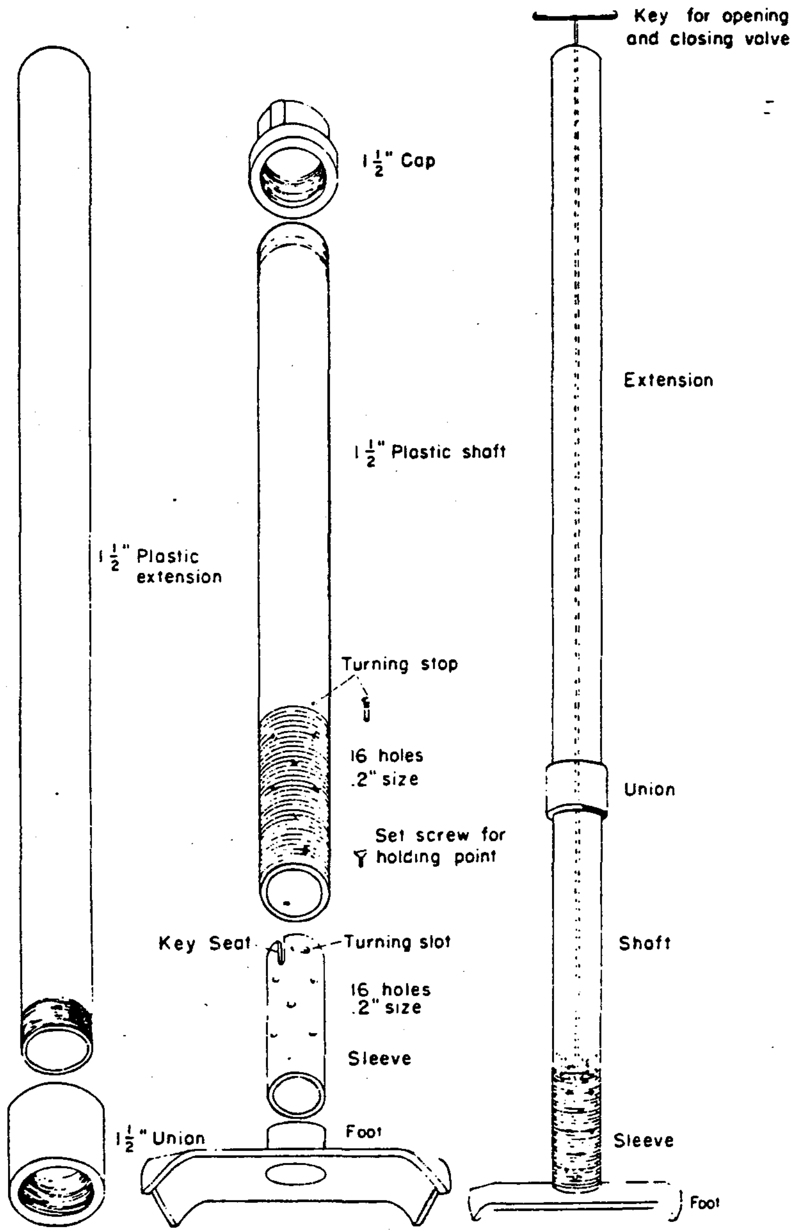


Figure 13 TYPE OF GROUNDWATER STANDPIPE WHICH COULD BE USED FOR DETERMINING GRAVEL PERMEABILITIES, INTRAGRAVEL VELOCITIES, AND DISSOLVED OXYGEN CONCENTRATIONS. MODIFIED FROM SHELTON (1955)

would follow the techniques of Terhune (1958); apparent velocity measurements can be made using colorimetric (Terhune, 1958), conductive (Shelton, 1955) or thermistor (Pinchak 1973) methods; dissolved oxygen measurements can be made directly within the pipes via an oxygen probe, or water samples can be removed and standard Winkler techniques used.

Bedload Samplers

Bedload samplers can also be used to document flow effectiveness by comparing quantities transported by specific flows, before and after the flushing flow. Such measurements could be made at selected intervals along a cross channel transect, using one of a number of bedload samplers (Neilson, 1974). Today, the sampler designed by Helle and Smith (1971) is becoming the recognized standard.

Sediment - Biological Response Model

A method which may prove useful in determining the need for and effectiveness of flushing flows from a biological perspective has recently been developed (Stowell et al. 1983). The method includes a procedure for relating sediment yields to factors limiting fish abundance including fish habitat and population responses. A flow diagram depicting the various procedures and considerations is presented in Figure 14 (Stowell et al. 1983). The reader should refer directly to Stowell et al. (1983) for details of this procedure.

Data requirements for use of the method include:

- Estimates of sediment yield under natural conditions
- Substrate core data (or visual characterizations) from critical reaches to determine existing conditions
- Embeddedness measurements in critical reaches
- Stratification of the stream by channel type
- Fish population information sufficient to determine if sediment could be a limiting factor

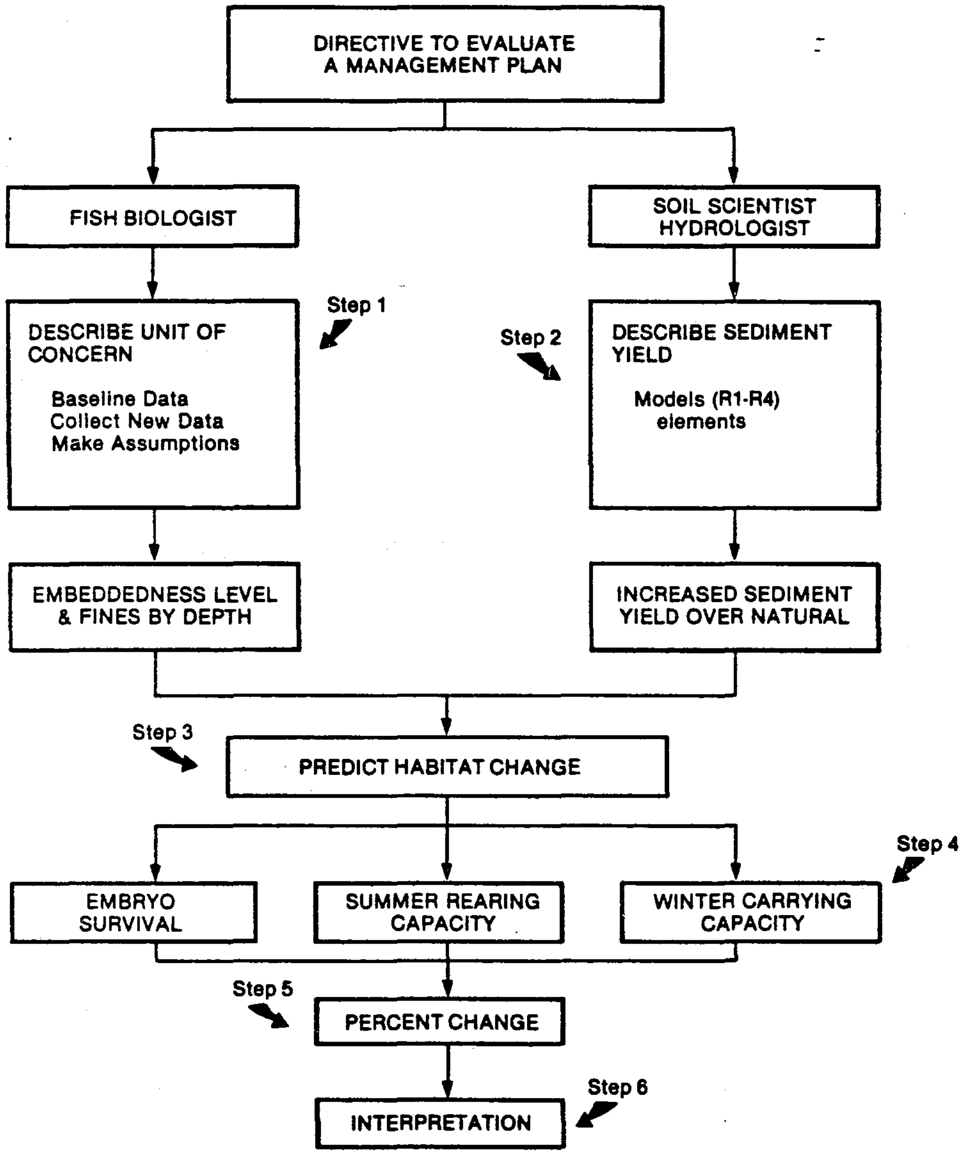


Figure 14 PROCEDURAL APPROACH FOR EVALUATING EFFECTS OF SEDIMENT YIELD ON FISH HABITAT AND POPULATIONS USING THE SEDIMENT – BIOLOGICAL RESPONSE MODEL AS DEVELOPED BY STOWELL et al (1983)

Development of the method was based on several assumptions, including:

- Sediment delivery to and deposition in stream channels is an important source of mortality to salmonids.
- The Region 1 and Region 4 (R1-R4) sediment guides (Cline et al. 1981) will be used for predicting sediment yields in the target watershed.
- As long as sediment inputs to the channels exceed transport capacities, impacts to fish habitat are cumulative.
- Degraded fish habitats and populations usually recover at slower rates than their watersheds.
- Critical reaches within each watershed can be used to estimate effects on the entire stream.

In practice, this method can be particularly useful on systems in which sediment recruitment (yield) can be accurately predicted. The authors caution that the model was developed for streams in the Idaho Batholith and that its application on other systems should be carefully reviewed.

DISCUSSION AND RECOMMENDATIONS

The regulation of streamflows can alter the natural flow regime of a system by removing peak flows and reducing the streams' sediment transport competency. As a result sediment which is input to the system tends to accumulate rather than being periodically removed (flushed) as during spring runoff. The deposition and aggradation of sediments can eventually become a problem when it begins to affect the biotic community. This can occur slowly, following a continued deposition of small quantities of sediment, or rapidly, resulting from a debris flow or landslide. In either case, a release flow (flushing flow) may be needed to remove fine sediments from the stream before the aquatic biota are adversely affected.

Although a variety of approaches and techniques have been used for assessing sediment transport, remarkably few formal methods have been developed for prescribing flushing flow needs in streams. Those that have are inadequately tested with respect to their reliability and accuracy, and only partially respond to the overall needs of a flushing flow (i.e., magnitude, timing, duration and effectiveness).

The majority of methods identified in this report are office techniques requiring extensive flow records (Table 1). Of these, the Tennant Methodology, based on 200 percent of the average annual discharge, appears to be the most widely recognized and used technique in the western states. Most other office methods are founded on the principle that a bankfull flow or dominant discharge is the channel forming flow, and therefore should be used for effectively transporting fine sediments. Of the fifteen methods reviewed, only five address the question of timing of flows, of which three include considerations for evaluating its effectiveness. The duration of the prescribed flows as addressed by 10 of the methods, ranges from a period of hours to 7 days; one survey respondent noted a 14-day duration was typically recommended.

Overall, it can be concluded that there is no present state-of-the-art methodology or approach for prescribing flushing flow needs. Moreover, the few methods which are in use today are largely untested, and may be providing unrealistic recommendations.

Many of the proposed methods are predicated on what is generally called regime methods. These methods assume that some flow rate such as the bank-full flow, is the dominant channel forming flow. However, a river "in regime" in general, scours in some places and deposits in others. Thus, flushing flow magnitudes based on these methods will be of uncertain accuracy at best.

The most certain methods for establishing required flushing-flow rates would be to observe various test flow releases. Field observations such as the sampling and tagging of bed material, should be made before and after each release at each point of interest on the stream to determine the actual effectiveness. Flow releases may not be feasible on all streams. However, where feasible, it provides the most certainty of all methods.

Where test flow releases cannot be made, the use of methods based on sediment transport mechanics provides the most reliable approach for the determination of required flushing flow rates. Proper application of these methods also requires the collection of field data such as sediment gradation, channel geometry, and channel slope.

It is encouraging that research relevant to the question of assessing flushing flows is progressing at a number of research institutions including the Wyoming Water Research Center (Laramie, Wyoming), and the USFWS Cooperative Instream Flow and Aquatic Systems Group (Fort Collins, Colorado). The interest in the subject of flushing flows expressed by the respondents to the survey suggests that the formulation and development of specific approaches for assessing flushing flow needs may be forthcoming.

Guidelines for Assessing Flushing Flows

Until standard methods are developed for assessing flushing flows, evaluations need to use an approach tailored to the specific needs and characteristics of each stream and project. This may dictate the use of several different office techniques to derive an initial flow estimate, followed by detailed field studies to refine the recommendations. For projects in the planning stage, an office approach may be all that is needed; implementation studies should include detailed field investigations.

Recommended guidelines for conducting flushing flow studies include:

- The utilization of an interdisciplinary team approach. Study team members should include at a minimum a hydrologic engineer, and a fisheries biologist.
- An initial determination of the actual need for the flushing flow should precede detailed assessments.
- The assessment approach used should be tailored to the specific needs and characteristics of each stream and project; office and field techniques may both be required.
- For comparative purposes, more than one method should be used for deriving flow recommendations.
- A determination of the timing and required duration of the flow should be included as part of the assessment process.
- Flushing flow recommendations should be stated in terms of magnitude, timing and duration.
- Follow-up studies should be conducted to evaluate the effectiveness of the flows and allow for necessary adjustments.

A summary of guidelines including considerations and techniques for assessing the need, timing, magnitude and duration of flushing flows is presented in Table 3.

Table 3

GUIDELINES FOR ASSESSING THE NEED FOR, AND TIMING, MAGNITUDE, AND EFFECTIVENESS OF FLUSHING FLOWS

	FLUSHING FLOWS			
	NEED FOR	TIMING OF	MAGNITUDE OF	EFFECTIVENESS OF
CONSIDERATIONS WHEN ASSESSING:	o Physical location of project - above or below major sediment sources o Topography of project area - susceptibility to erosion o Extent of man-induced perturbations in the drainage o Susceptibility of drainage to catastrophic events o Operational characteristics of the project o Sensitivity of target fish species to effects of sediment deposition	o Species of fish present in the systems (native, introduced) o Timing of the history functions of important species o Historical runoff period o Availability of project flows o Water temperature (colder water is more viscous)	o Level of investigation required - planning level studies - implementation level studies o Availability of flow records o Availability of test flows	o Availability and reliability of background data for defining pre-flushing flow conditions o Time interval between end of flushing flow and field assessment o Potential influence of extraneous activities on the effectiveness of a flushing flows (e.g., sediment input from tributaries, road construction)
TECHNIQUES FOR ASSESSING:	o Establish and monitor test reaches by: - subtstrate analysis - cross sectional profiling - photographic documentation - scour and deposition indicators - groundwater standpipes - bedload samplers - etc. o Comparison of data with standards - literature based - site specific based (preferred) o Spot assessments made (as needed)	o Prepare and review species life history - periodicity charts and note preferred timing release periods o Review historical flow records and note timing of peak flows o Review water budgets of project and note availability of flows o Adjust timing recommendations accordingly, (Timing of flows should be based on maximizing benefits for the given water released)	o For planning level studies use appropriate office techniques for initial estimate o Implementation studies - refine estimates through field/laboratory investigation - sediment transport models - empirical assessments of bed transport - physical modeling of stream reach o No standard approach or method presently available o Recommendations should be based on site specific information and include estimates of flow-duration	o Pre- and post flow comparisons of substrate-sediment deposition and composition by: - substrate analysis - cross sectional profiling - photographic documentation - etc. o Post-flow analysis of data should be factored into necessary adjustments in recommendations

Research Needs

From the review of literature, data and results of the survey, several important research areas related to flushing flows have been identified.

Development and Testing of New Flushing Flow Assessment Methods and Techniques

Although many studies related to sediment deposition and transport are underway, relatively few are directly linked to flushing flows, and more specifically to the development of standard methods or procedures for its assessment. Clearly, more research is needed to develop applicable and reliable methods for making accurate recommendations. This was stated as a definite need by the majority of survey respondents (See Appendix C).

The development of regional methodologies based on either sediment transport mechanics or regime theory may be feasible. These relationships would probably take the form of either the flushing flows being a function of the channel geometry and slope, or a function of a flood event or flow duration relationship.

Compare and Evaluate Existing Methods

The present study reviewed fifteen different methods and techniques which have been or could be used for making flushing flow recommendations. Studies are now needed to compare their reliability and effectiveness for prescribing suitable flows. Such studies should be conducted on regulated stream systems which could provide controlled flow releases for evaluating flushing efficiencies. The comparisons would entail the independent formulation of recommendations using the different methods, and follow-up field verification studies to assess the suitability of the recommended flows.

To optimize water usage, the possibility of integrating studies of this type into proposed instream flow studies (IFIM studies) should be explored.

Expansion of IFIM and PHABSIM to Include Sediment Transport Considerations

If the IFIM continues to be used as one of the standard methodologies for instream flow assessments, its versatility should be expanded to address flushing flow needs. Two indirect assessment approaches using the IFIM were noted in this report. In addition, a potential evaluation technique was described. However, further studies are needed to establish sediment transport and flushing flow assessment capabilities directly within PHABSIM. Such research is apparently underway at the CIFASG in Fort Collins, Colorado, and this linkage may soon be realized.

Development of New Sediment Sampling Techniques

Research should be continued into the development and testing of new methods for assessing stream sedimentation problems. Emphasis should be placed on developing new, reliable techniques which are inexpensive, easy to use, provide wide sampling coverage and lend themselves to monitoring type studies useful for evaluating the effectiveness of flushing flows.

Studies to Evaluate the Biological Effects of Flushing Flows

Depending on its magnitude and duration, flushing flows may directly impact the biotic community in much the same manner as peaking flows or runoff events. Studies are therefore needed to evaluate potential impacts and formulate alternative approaches for implementing flushing flows.

An Evaluation of Other Uses of Flushing Flows

This report has focused on the utilization of flushing flows for enhancing fisheries habitat. Other potential uses, as identified in the survey include riparian habitat maintenance, channel maintenance, limiting introduced fish and recreational pursuits. These and other uses should be evaluated and, to the extent possible, appropriate methodologies developed for their consideration.

Summary

This report has presented a technical review of many of the biological and engineering considerations needed for assessing flushing flow requirements in regulated streams. Emphasis was placed on defining a set of guidelines and presenting specific considerations and techniques for assessing the need for, and magnitude, timing and effectiveness of flushing flows. The report further described fifteen methods and approaches currently being used for estimating flushing flows. It is intended that this review of information and identification of research needs will promote a better understanding of the complexity of flushing flows.

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Appendix A

EFFECTS OF SEDIMENT DEPOSITION ON FISHERIES HABITAT

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Many investigators in the past have studied and noted the adverse impacts of sediment deposition on important fisheries habitat. Recent studies have continued in this area, but have also focused on the prediction of the effects of a given sediment yield on existing fish populations.

In this respect, Stowell et al. (1983) developed an overall generalized sediment-fish habitat relationship (Figure A-1). As displayed in the figure, increases in sediment yield to a stream results in a degradation of fish habitat; as sediment yield decreases, habitat degradation decreases. Stowell, et al. (1983) noted that with additional land disturbance activities, increases and decreases in sediment yields would continue with yields tending to stabilize at higher rates until activities cease. The quality of fish habitat would follow a parallel, although delayed pattern of decline and recovery in response to the increase or decrease in sediment yield. The delay in fish habitat recovery response is of course related to the natural hydrologic characteristics of the stream, notably the variability in the timing and magnitude of peak flows.

It can be reasoned then, that on regulated stream systems where flushing flows can be controlled and delivered, it should be possible to reduce the period of habitat recovery. The feasibility of this is, of course, contingent on accurately providing the flow needed at the right time to achieve the desired result.

Spawning and Incubation

The effects of sediment deposition are well documented for salmonid spawning, egg incubation, and fry emergence. Many investigators including Stuart (1953), Koski (1966), Peters (1962), McCuddin (1977), Hall and Lantz (1969), Bjornn (1969), Tappel and Bjornn (1983), Phillips, et al. (1975), McNeil and Ahnell (1964), Lotspeich and Everest

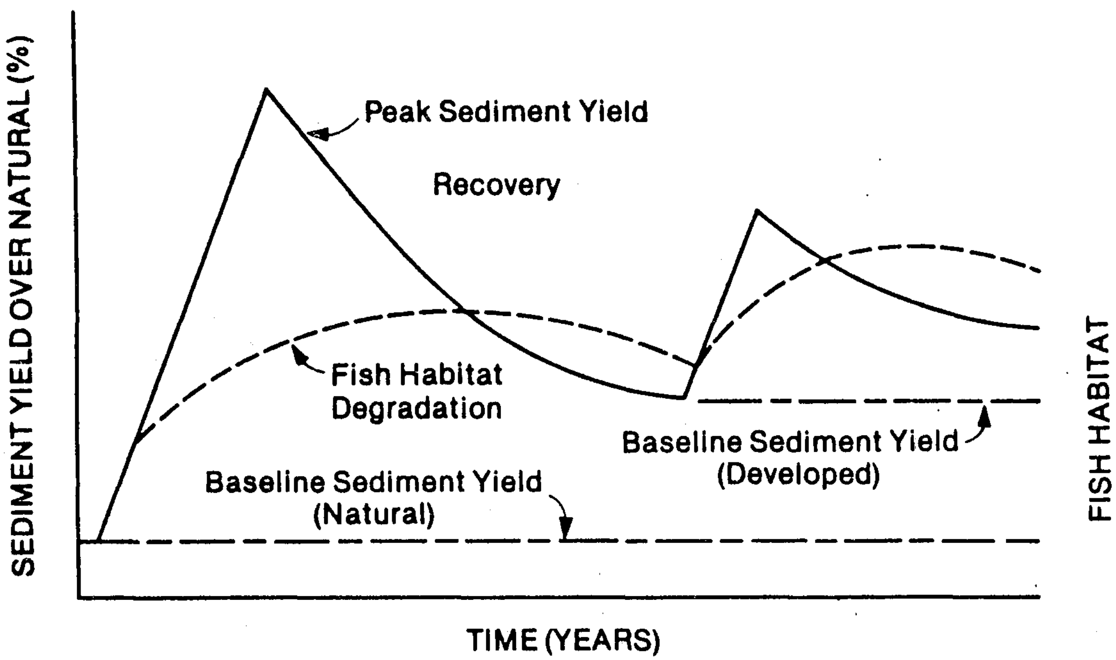


Figure A-1 ILLUSTRATION OF SEDIMENT YIELDS AND FISH HABITAT RESPONSE TO SEDIMENT PRODUCING ACTIVITIES OVER A SHORT TIME FRAME. MODIFIED FROM STOWELL et al (1983)

(1981), Cooper (1965), Reiser and White (1981) and Meehan and Swanston (1977) have found inverse relationships between quantity of fines, egg survival and fry emergence.

Intragravel conditions precipitated by sediment accumulation include reductions in intragravel water velocity (apparent velocity) which supplies the developing embryos with oxygen and removes metabolic wastes, and reductions in gravel permeability which determines the range of intragravel velocities which can occur (Wickett 1960). The concentrations of intragravel dissolved oxygen have also been directly related to sediment levels and gravel permeabilities as depicted in Figure A-2 (Tagart 1976; Reiser and White 1981). Each of these parameters in turn has been directly related to embryo survival (Figures A-3, and A-4). In addition, sediment deposition can smother incubating eggs as well as entomb alevins and fry thereby precluding emergence (Bjornn 1969, McCuddin 1977, Tappel 1981). Such results confirm that excessive deposition of fine sediments into streams can adversely affect the success of salmonid reproduction.

The timing of sediment deposition may also influence the overall survival of developing eggs. Studies by Reiser and White (1980 unpublished) suggest that sediment accumulations during early embryonic development (precirculatory stage) may result in higher egg mortalities than if deposition occurred after the circulatory system was functional. This, as was noted by Wickett (1954), may be due to the greater efficiency in oxygen uptake by the embryo once the circulatory system is functional. Similar findings were reported by Shaw and Maga (1942) with respect to coho salmon (Oncorhynchus kisutch) egg survival. In their studies, silt and sediment which were deposited during the initial incubation period resulted in higher mortality of coho egg and fry than silt added in the later stages.

It has been shown that the nest building activity of a female salmonid does, to some degree, clean or "flush" fine sediments from the substrate (Figure A-5). Thus, in a natural redd, initial egg development occurs in

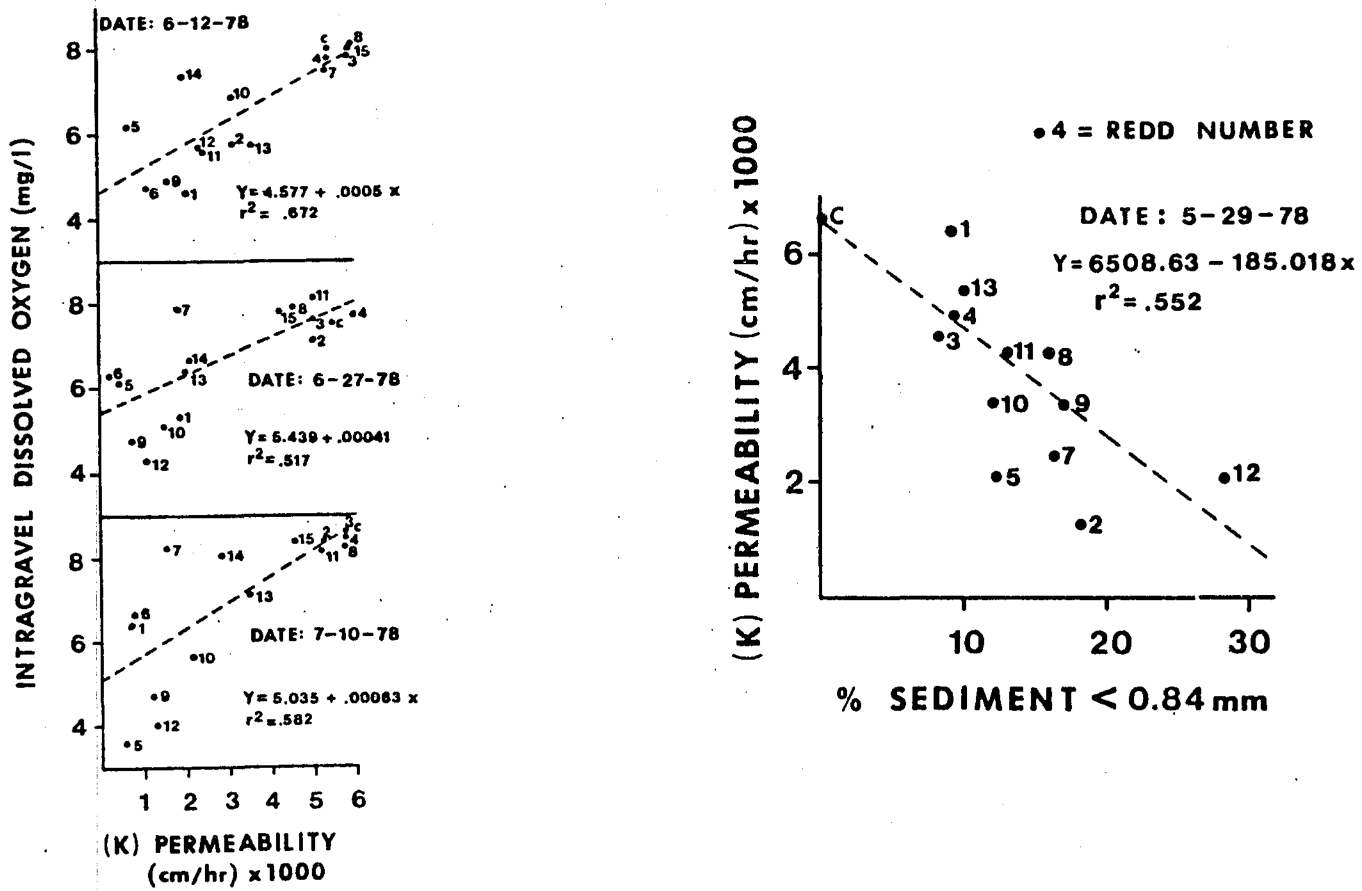
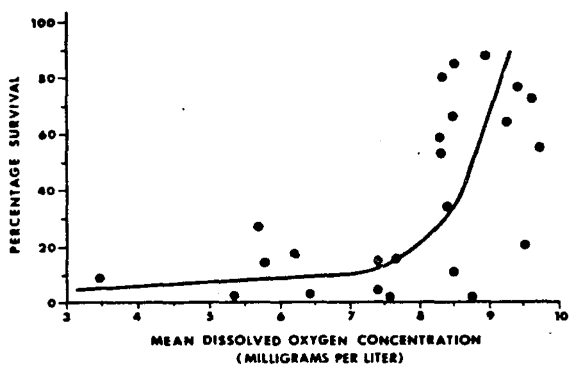


Figure A-2 RELATIONSHIP BETWEEN GRAVEL PERMEABILITY AND INTRAGRAVEL DISSOLVED OXYGEN (LEFT), AND FINE SEDIMENT (< 0.84 mm) AND GRAVEL PERMEABILITY (RIGHT) IN BIG SPRINGS CREEK, IDAHO. MODIFIED FROM REISER AND WHITE (1981)

STEELHEAD TROUT



COHO SALMON

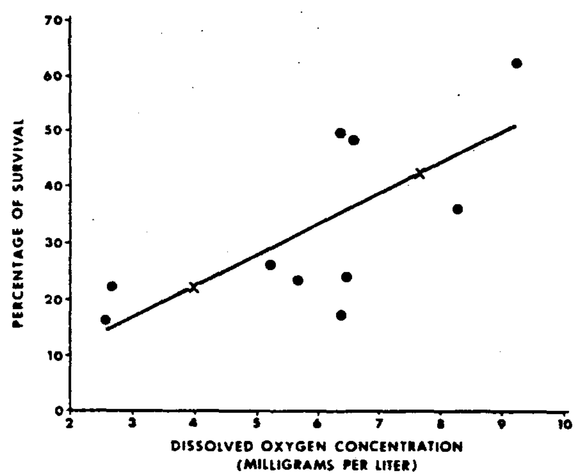


Figure A-3 RELATIONSHIP OF DISSOLVED OXYGEN CONSTRATION TO EMBRYO SURVIVAL OF STEELHEAD TROUT (UPPER) AND COHO SALMON (LOWER). UPPER FIGURE FROM COBLE (1961); LOWER FIGURE FROM PHILLIPS AND CAMPBELL (1961); MODIFIED FROM REISER AND BJORNN (1979)

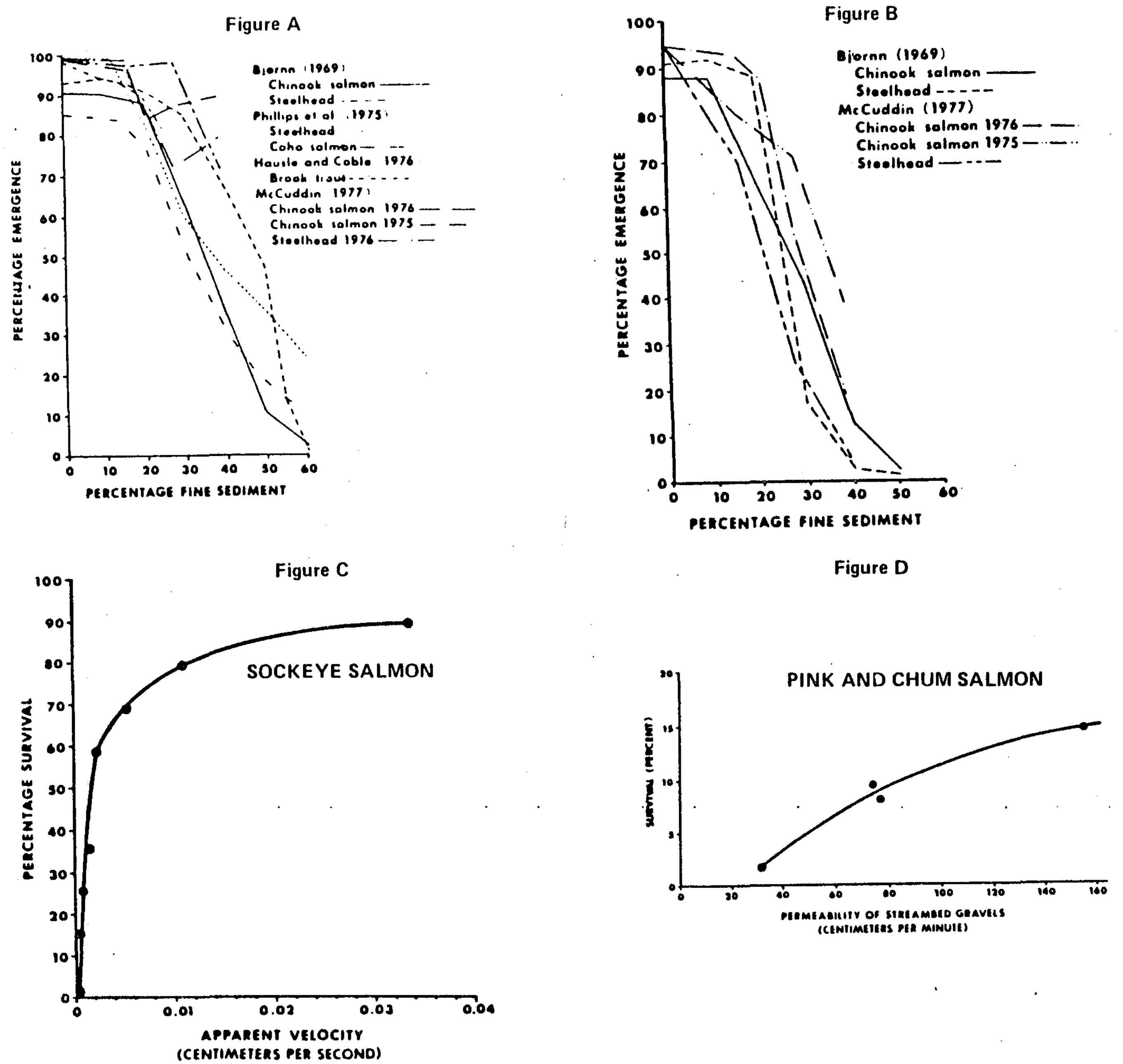
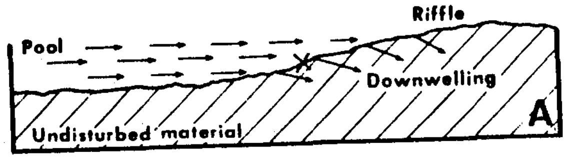
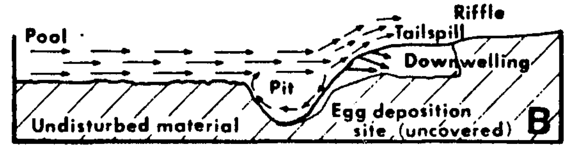


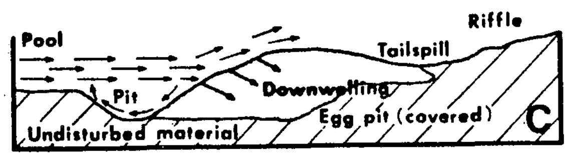
Figure A-4 RELATIONSHIP OF VARIOUS INTRAGRAVEL PARAMETERS TO SALMONID EMBRYO SURVIVAL – FIGURE A AND B MODIFIED FROM REISER AND BJORNN (1979); FIGURE C FROM COOPER (1965); FIGURE D FROM McNEIL AND AHNELL (1964)



A) CONVEXITY OF SUBSTRATE AT POOL-RIFFLE INTERCHANGE INDUCES DOWNWELLING OF WATER INTO THE GRAVEL. AREA LIKELY TO BE USED FOR SPAWNING IS MARKED WITH AN X

B) REDD CONSTRUCTION RESULTS IN THE CLEANING OF GRAVELS AND INCREASED CURRENTS OVER AND THROUGH (DOWNWELLING) THE TAILSPILL





C) EGG COVERING ACTIVITY RESULTS IN THE FORMATION OF A SECOND PIT, AND THE COVERING OF EGGS IN THE FIRST PIT. INCREASED PERMEABILITY OF THE GRAVEL AND THE CONVEXITY OF THE SUBSTRATE INDUCES DOWNWELLING OF WATER CREATING A CURRENT PAST THE EGGS

Figure A-5 **LONGITUDINAL SECTIONS OF SALMONID SPAWNING AREAS BEFORE (A), DURING (B) AND AFTER (C) REDD CONSTRUCTION. MODIFIED FROM REISER AND WESCHE (1977)**

relatively clean gravel. However, as demonstrated by Wickett (1954, 1960) and McNeil and Ahnell (1964), with time the sediment conditions within the redd gradually return to ambient levels. Under normal conditions, this may pose no problem since the later developing stages may be better able to cope with the return to higher sediment levels. However, streamflow regulation coupled with improperly conducted land use practices can result in the accumulation of large amounts of fine sediment in streams, thereby reducing the time in which the redd is clean, or rendering the initial cleaning activity ineffective.

The size of sediment most damaging to egg and fry survival has been the subject of numerous investigations. Depending on the study, salmonid embryo survival has been related to sediment sizes including less than (<) 6.4 mm (Bjornn 1969, McCuddin 1977, Tappel 1981); <4.6 mm (Platts pers. comm. D. Reiser 1980); <3.3 mm (Koski 1966), <2.0 mm (Hausle and Coble 1976) and <0.84 mm (McNeil and Ahnell 1964, Hall and Lantz 1969, Tagart 1976, Cloern 1976, Reiser and White 1981). Stowell, et al. (1983) used two size classes in their definition of fines, described as sediment <6.4 mm of which at least 20 percent are <0.84 mm in diameter.

Recognizing this problem, several recent studies have focused on standardizing the characterization of spawning gravels. In this regard, Platts et al. (1979) and Shirazi and Seim (1979) recommended the use of the geometric mean diameter (d_g) for characterization studies. By refining this approach, Lotspeich and Everest (1981) developed a new index for determining gravel quality. Termed the fredle index, f_i, it provides for comparisons of gravel quality within and between streams, as well as a means for monitoring temporal changes in texture and permeability.

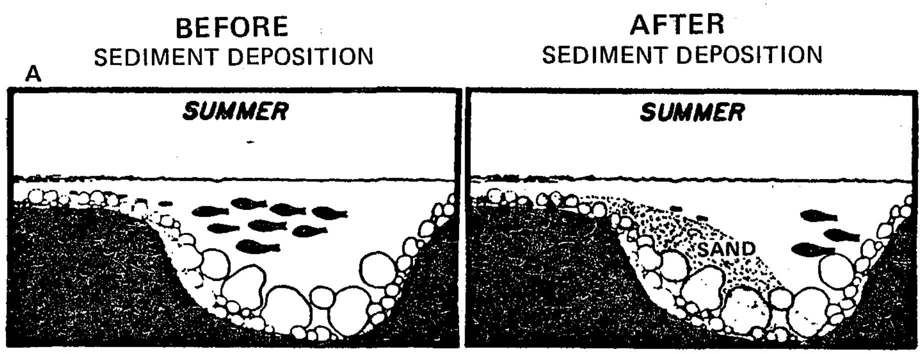
Bjornn et al. (1977), Stowell et al. (1983) and Kelley and Dettman (1980) have used the rating of embeddedness as another measure of fine sediment accumulation and gravel quality. Defined as the degree larger particles are covered with fine sediments, embeddedness ratings have been inversely related to invertebrate production (Bjornn et al. 1977, Brusven and Prather 1974), egg survival (Parametrix et al. 1979; Chapman et al. 1979) and rearing capacity (Bjornn et al. 1977, Stowell et al. 1983; Kelley and Dettman 1980).

From a flushing flow standpoint, the size of the fine sediment to be removed may influence both the magnitude and more significantly the duration of the needed flow. As such, an onsite characterization of the sediment composition in important areas is needed to define target sizes. The geometric mean diameter, fredle index and embeddedness ratings may all be useful in this regard. Embeddedness may prove to be especially useful in evaluating the effectiveness of flushing flows (see Assessing the Effectiveness of Flushing Flows).

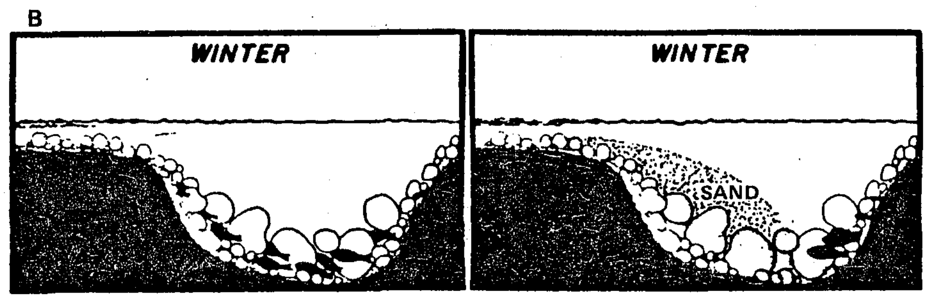
Rearing

The deposition of sediments in streams may also reduce available summer rearing and winter holding habitat by filling in pool areas (Figure A-6). Both can result in reductions in fish numbers since less space is available for occupancy. The conditions imposed in the winter can be especially taxing since many juvenile salmonid species reside in the intergravel spaces of the substrate during winter conditions (Chapman and Bjornn 1969; Morrill and Bjornn 1972). Without these areas, the fish may be forced out of the stream system or into less desirable areas where increased mortality may occur. Bjornn et al. (1977) and Stuehrenberg (1975) added fine sediment (6.4 mm) to natural stream channels and found juvenile salmon abundance decreased in almost direct proportion to the amount of pool volume lost to fine sediments (Figure A-7). Indirect support for this type of relationship was provided in studies by Nickelson and Hafele (1978) and Nickelson and Reisenbichler (1977) who demonstrated a direct relationship between pool volume and juvenile coho salmon standing crops (Figure A-7).

The question of the size of fine sediments in pools has not been a concern as it has in spawning riffles. However, the sizes of material to



A) IN SUMMER, FISH REAR WITHIN THE WATER COLUMN. SEDIMENT DEPOSITION DECREASES POOL VOLUME AND AVAILABLE REARING SPACE



B) IN WINTER, FISH HOLD IN GRAVEL INTERSTITIAL SPACES WITHIN POOLS. SEDIMENT DEPOSITION "FILLS-IN" THE SPACES REDUCING HOLDING AREA

Figure A-6 SUMMER REARING (TOP) AND WINTER HOLDING (BOTTOM) HABITAT BEFORE (LEFT) AND AFTER (RIGHT) SEDIMENT DEPOSITION. MODIFIED FROM BJORNN et al (1977)

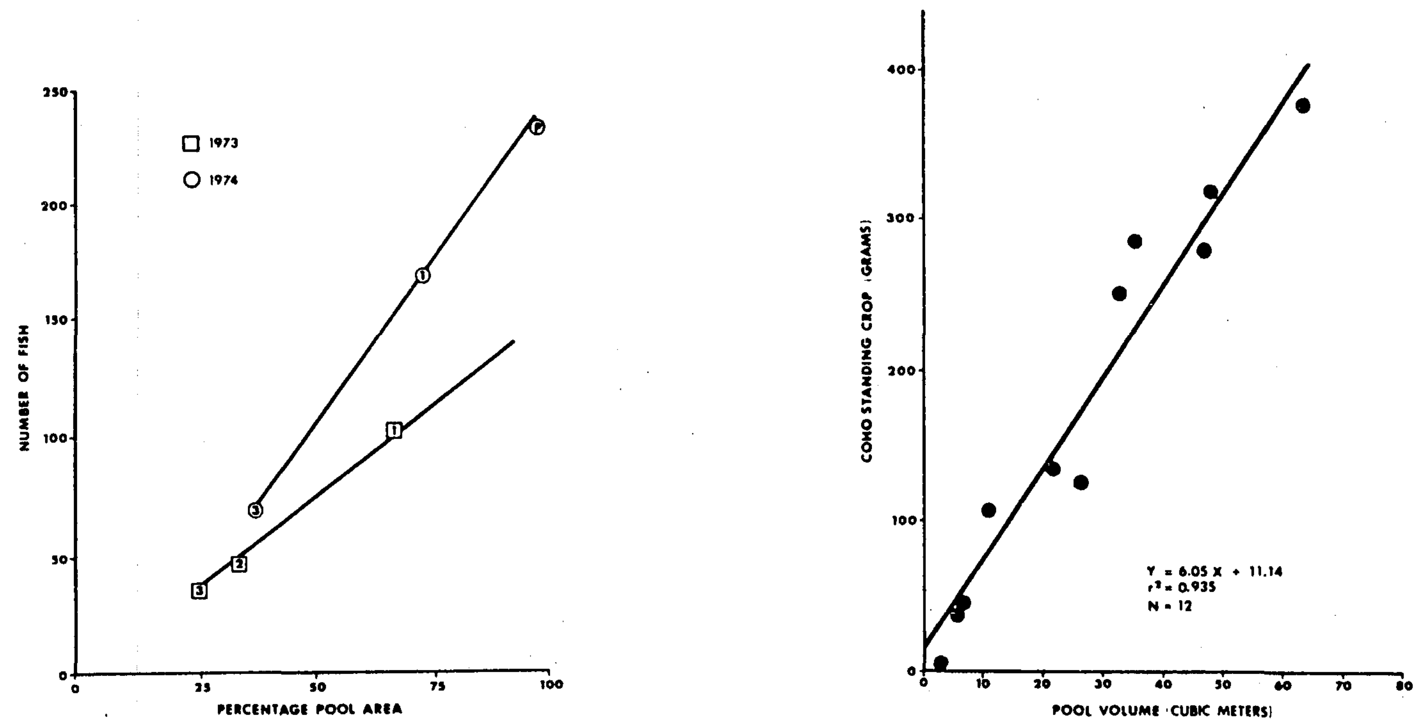


Figure A-7 RELATIONSHIP OF SALMONID NUMBER (LEFT) AND STANDING CROP (RIGHT) TO POOL AREA AND VOLUME RESPECTIVELY. REDUCTION IN POOL AREA ON THE LEFT DUE TO ADDITIONS OF SEDIMENT. FIGURES MODIFIED FROM BJORNN et al (1977) AND NICKELSEN AND HAFELE (1978) be transported may be influencing factors in determining the magnitude and duration of required flushing flows.

The point at which the quantity of fines in a pool becomes a problem has not been determined. Bjornn et al. (1977) recommended using the percentage of fine materials in riffle areas as a general index of the "sediment health" of the stream. Their assumption was that if riffle areas contained negligible amounts of fine sediment then the pool areas should have negligible amounts of sediment. This assumption may not be valid for regulated streams where riffle velocities may be sufficient to transport surficial fines from gravels, but pool velocities may not. The net result may be that riffle areas are relatively sediment free, while the pools are essentially trapping and filling up with sediments.

Stowell et al. (1983) and Kelley and Dettman (1980) have used embeddedness ratings for assessing rearing habitat, in much the same manner as for spawning habitat. Such recommendations are founded on empirically developed relationships between embeddedness and fish densities (Figure A-8 and A-9).

Invertebrate Production

Mention should also be given to the detrimental effects of sediment deposition on aquatic invertebrates since they constitute a major food source to the fishery resource . Many investigators including Hynes, (1970), Cummins (1966) and Cummins et al. (1966) have reported that the highest production of invertebrates occurs in clean gravel-rubble size materials. Pennak and Van Gerpen (1947) noted a decrease in the number of benthic invertebrates in the progression rubble - bedrock - gravel - sand. Kimble and Wesche (1975) noted a similar decrease in the series rubble - coarse gravel - sand and fine silt. As noted by Reiser and Bjornn (1979), rubble seems to be the most productive substrate, providing insects with a surface to cling to and protection from the current.

SUMMER REARING CAPACITY "RUN"

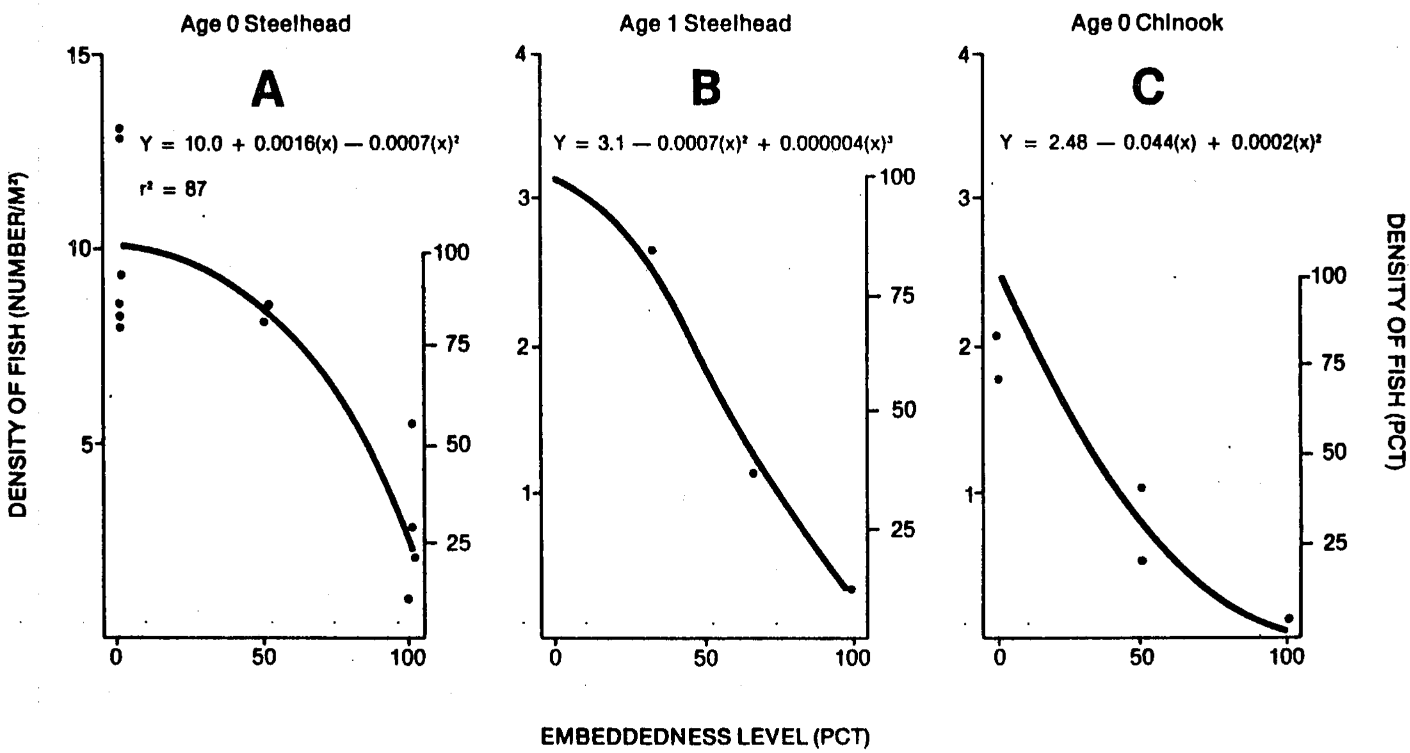


Figure A-8 RELATIONSHIP OF SUMMER REARING CAPACITY (FISH DENSITY) AND SUBSTRATE EMBEDDEDNESS FOR STEELHEAD TROUT AND CHINOOK SALMON; DATA FROM BJORNN et al 1977; MODIFIED FROM STOWELL et al (1983)

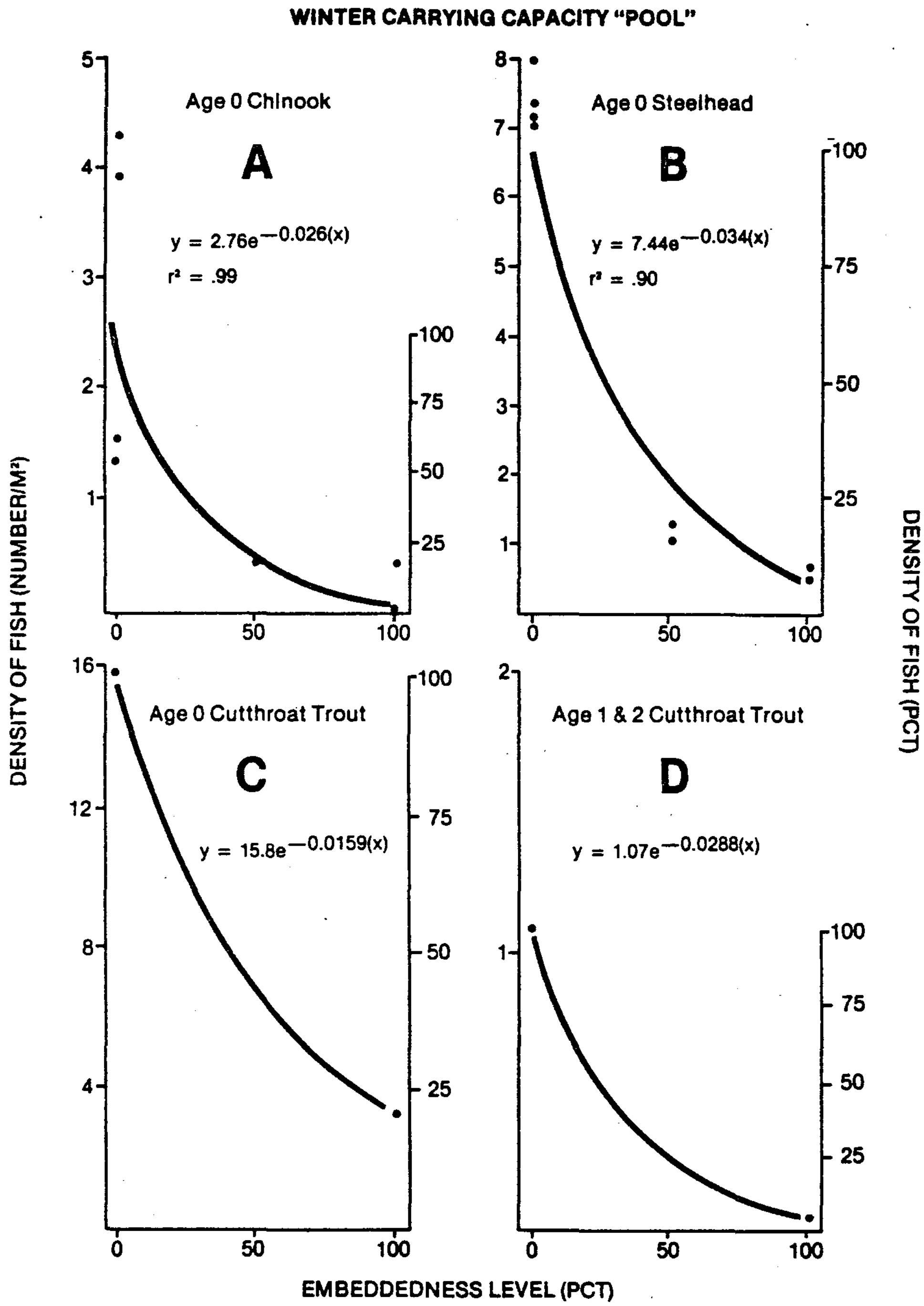


Figure A-9 RELATIONSHIP BETWEEN WINTER CARRYING CAPACITY OF POOLS AND SUBSTRATE EMBEDDEDNESS FOR VARIOUS SALMONID SPECIES. MODIFIED FROM STOWELL et al (1983)

Appendix B

SEDIMENT TRANSPORT MECHANICS

SEDIMENT TRANSPORT MECHANICS

Initiation of Motion

The physical processes involved at the beginning of sediment motion have been studied by many investigators since the 18th century. The most significant modern work in this area was carried out by Shields in 1936 as reported by Vanoni (1975).

The general form of the governing equations can be derived by evaluating the forces acting on a particle of non-cohesive sediment resting in a bed of similar material. These forces include the gravitational force of the submerged weight of the particle, and the hydrodynamic forces of lift normal to the bed, and drag parallel to the bed. This is depicted schematically in Figure B-1 with ϕ = the slope angle of the bed, Θ = the angle of repose of the submerged sediment, τ_c = the critical shear stress when incipient motion begins. The gravitational force is $c_1(\gamma_s - \gamma)d_s^3$,

where: $c_1 d_s^3$ = the volume of the particle,

d_s = the particle size (often taken as the median particle size, d_{50}), and

γ_s, γ = specific weights of the fluid and sediment

The critical drag force is $c_2 \tau_c d_s^2$ in which $c_2 d_s^2$ is the effective area of the particle exposed to the critical shear stress τ_c.

Since the lift and drag forces are both functions of the same variables, and the constants in the theoretical equations are experimentally determined, the lift term is often not separated out in the formulation. If the moments of the governing forces about a point are equated and the resulting equation is rearranged, the analysis yields:

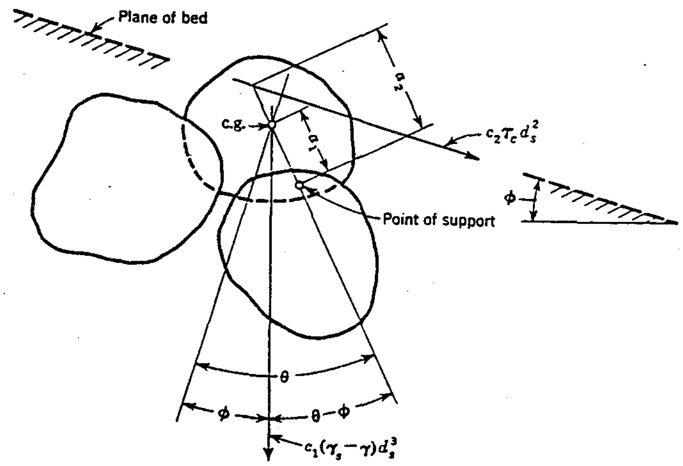


Figure B-1 FORCES ON A SEDIMENT GRAIN IN A BED OF A SLOPING STREAM (MODIFIED FROM VANONI, 1975)

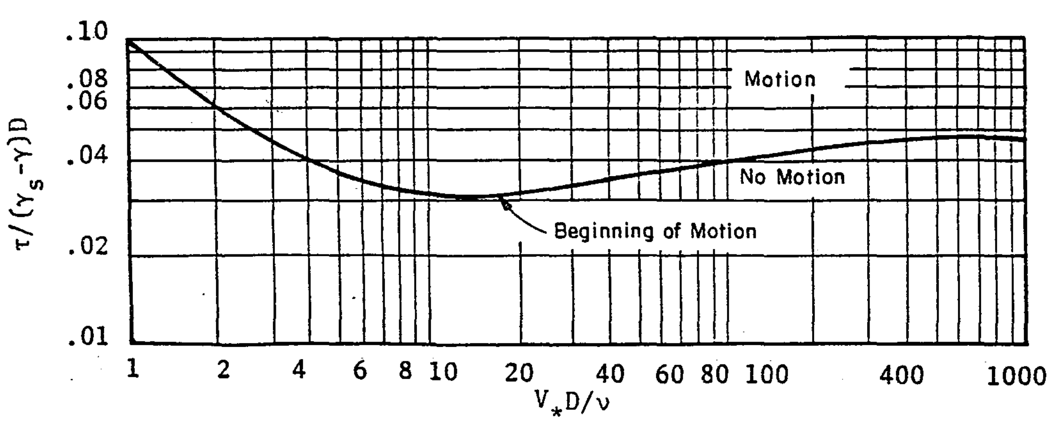


Figure B-2 SHIELDS' RELATIONSHIP FOR BEGINNING OF MOTION (MODIFIED FROM GESSLER, 1971)

$$= \frac{c_1 a_1}{C_2 a_2} (\tan \Theta - \tan \phi) (\cos \Theta) (\gamma_s - \gamma) d_s \qquad (1)$$

For the relatively small bed angles associated with natural streams, the equation takes the form;

$$= K(\gamma_s - \gamma) d_s \qquad (2)$$

where K = a constant

The constant, K is commonly referred to as the Shields parameter. The above analysis, however assumes that the inertial forces are large relative to the viscous forces (fully turbulent flow). For relatively large viscous forces (small Reynolds numbers), the Shields parameter will not be constant. The Shields diagram depicted in Figure B-2, shows the variation of this parameter with the boundary Reynolds number.

Shields obtained his results by measuring the bed load at various values of $\tau/(\gamma_s - \gamma)d$, with all values of τ being at least twice the critical value (τ_c). He then extrapolated his findings down to the point of zero bed load. With this technique, he avoided the problem of defining the exact point where motion of the bed begins. Gessler (1971) points out, however, that Shields did not differentiate between losses due to bed form and those due to grain roughness. Consequently, he overestimated the Shields parameter at incipient motion by as much as 10 percent. The diagram shown in Figure B-2 has been adjusted to reflect this correction.

Shields results are in a dimensionless form that is difficult to interpret in physical terms. If the density of the bed material is assumed to be constant and the fluid is assumed to be fresh water, the Shields diagram can be transformed into a diagram of critical shear stress versus grain size as depicted in Figure B-3.

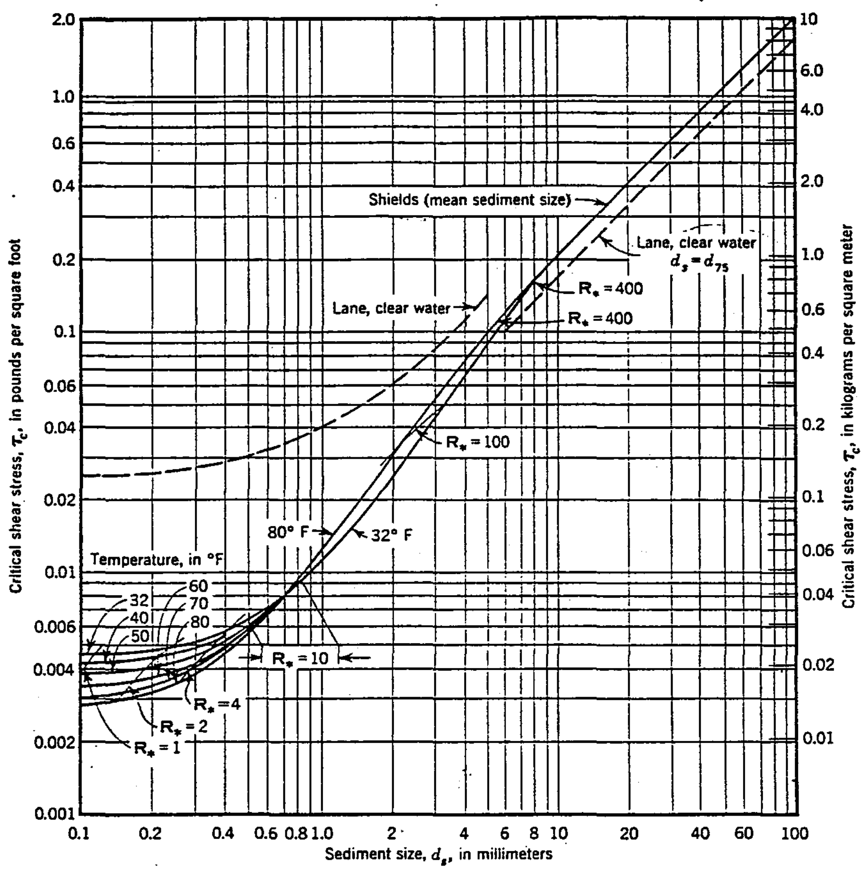


Figure B-3 CRITICAL SHEAR STRESS FOR QUARTZ SEDIMENT IN WATER AS A FUNCTION OF GRAIN SIZE (MODIFIED FROM VANONI, 1975)

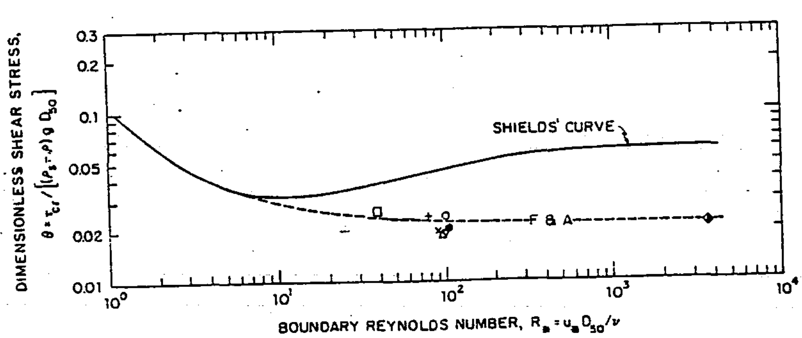


Figure B-4 SHIELDS' FACTOR FOR NONUNIFORM BED SEDIMENT (MODIFIED FROM ODGAARD, 1984)

The investigations that led to the development of the Shields diagram were based on the use of uniform grain materials. The pavement layer of a gravel bed stream or river is composed of non-uniform material. The grain size distribution of this pavement layer has been studied by several investigators including Gessler (1971), Little and Mayer (1972), Kellerhals and Church (1977), Shen and Lu (1983), and Odgaard (1984).

Recent investigations suggest that, for the same median grain size, the turbulence intensity at the bed increases with increases in the largest particles in the bed. As a result, the effective Shields parameter is reduced. Rakoczi (1975) concluded that the d_{10} of the material (material for which 10 percent is finer by weight) is appropriate in the Shields relationship for gravel-sized particles, while Shen and Lu (1983) recommend the use of d_{30} of the material along with a modification of the Shields diagram. Odgaard (1984) has proposed a modification to the Shields diagram which he has termed the "armor layer Shields curve" for non-uniform bed materials using the d_{50} of the material (Figure B-4). This figure indicates that the Shields parameter could be as low as .02 for gravel sized material. However, this curve is based on very little data. Parker (1979) developed a bed-load transport function using extensive data from gravel-bed streams. Included in his transport function is a threshold shear stress parameter (Shields parameter) of .03. Andrews (1983) found from investigations of 24 self-formed, gravel-bed rivers in Colorado that the mean critical dimensionless shear stress relative to the median particle diameter (d_{50}) was .033. Consequently, a Shields parameter of about 0.03 appears to be appropriate for the mobilization of gravel bed streams.

Therefore, for particles larger than about 0.2 in. (6 mm) in water, the Shields relationship becomes;

$$_{c} = .030\ (\gamma_s - \gamma) d_{50} \tag{3}$$

where:

d_{50} = the median particle size

τ_c = the critical shear stress

The channel-bottom shear stress that is required to mobilize the bed can be expressed in terms of mean channel flow properties. A commonly used form is;

$$\tau_o = \gamma RS \tag{4}$$

where:

γ = the specific weight of the fluid

R = the hydraulic radius (flow area/wetted perimeter)

S = the friction slope; equivalent to the channel bottom slope for uniform flow

τ_o = the cross-sectional average shear stress

Care must be taken when using this relationship since the slope term (S) refers to the energy losses associated with the bed roughness, and not the bed form (ripples or dunes) or channel allignment. Generally, however, neither ripples nor dunes form in gravel bed streams. If the stream is relatively wide (width/depth >10), the hydraulic radius may be approximated by the flow depth, and the bottom shear in equation (4) can be expressed as;

$$\tau_o = \gamma y S \tag{5}$$

where:

τ_o = bottom shear

y = the flow depth

Manning's equation for a wide channel can be expressed as:

$$q = 1.486/n \; S^{1/2} \; y^{5/3} \tag{6}$$

where q = the unit discharge (cfs/ft)

S = the friction slope (ft/ft)

y = the flow depth (ft)

n = Manning's coefficient

If Manning's equation is solved for y and substituted into equation (5), the bed shear can be expressed as;

$$\tau_o = \gamma S \left[\frac{nq}{1.486\ S^{1/2}}\right]^{3/5} \qquad (7)$$

Analysis of data from many rivers, canals, and flumes (Anderson et al. 1968) indicates that Manning's coefficient can be predicted by the equation;

$$n = .04\ d_{50}^{1/6} \qquad (8)$$

where:

d_{50} is the median particle size in ft

If equation (8) is substituted into equation (7) and the bed shear in equation (7) is equated to the critical shear in equation (3), the required discharge for mobilizing the bed can be expressed as a function of the particle size and the friction slope:

$$q = 0.25\ \frac{d_{50}^{1.5}}{S^{1.17}} \qquad (9)$$

where:

q = the unit discharge at incipient motion (cfs/ft); flow needed for bed mobilization

d_{50} = the median particle size of the pavement layer (ft)

S = the friction slope (ft/ft); equivalent to the bed slope for uniform flow

The relationship in equation (9) is shown in Figure B-5 as a set of curves of unit discharge versus grain size for various channel bed slopes.

This figure provides a means to estimate the discharge in a stream that is required to mobilize the bed and initiate motion. For example, for a stream in which the d_{50} is 2.0 in (5 cm) and the channel slope is 0.005, a flow of about 8 cfs/ft of stream width would be required. If the average channel width is 25ft (7.6 m), this equates to a required

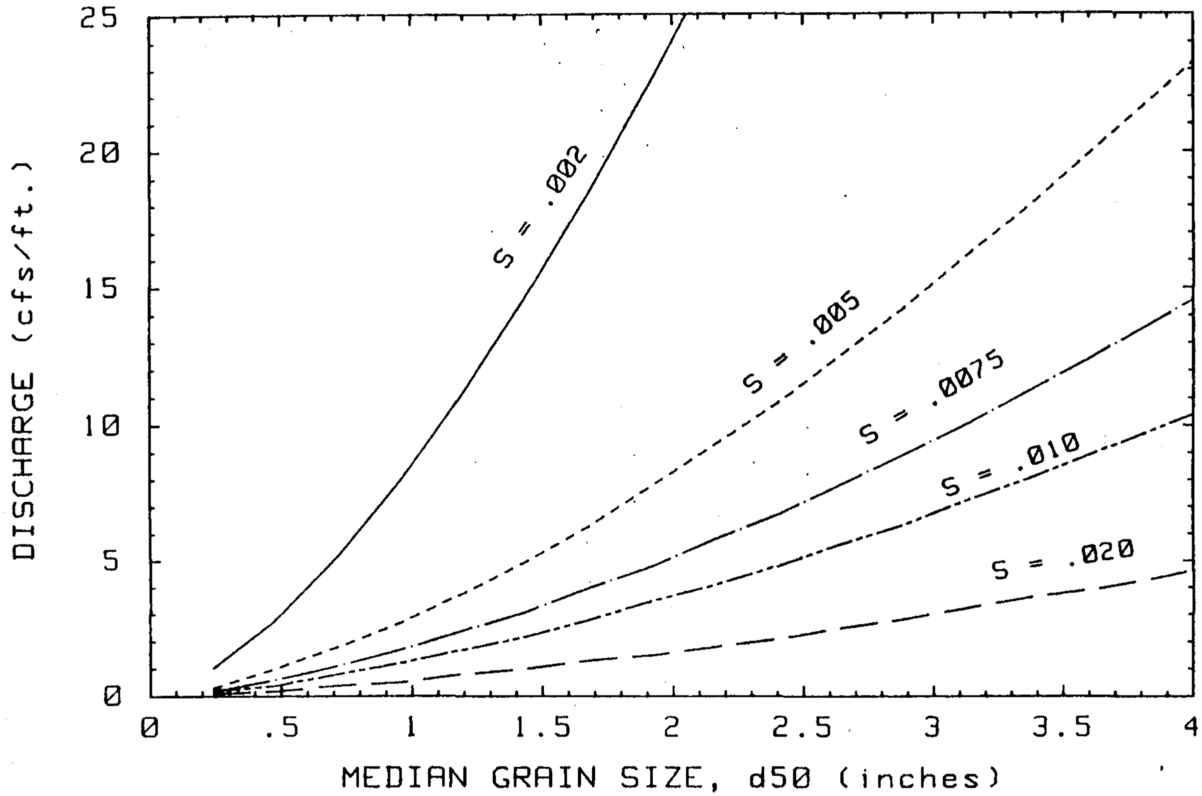


Figure B-5 CRITICAL UNIT DISCHARGE FOR BED MOBILIZATION AS A FUNCTION OF GRAIN SIZE AND CHANNEL SLOPE. RELATIONSHIPS DERIVED FROM A SHIELDS' ENTRAINMENT FUNCTION.

flow of 200 cfs. However, the analysis leading to the development of these curves is an over-simplification of the incipient motion process in a natural stream. Either embedding of the steam gravels in fine material or imbrication of the gravels can greatly increase the flow required for mobilizaion. The estimated discharge is also sensitive to the Shields parameter. For instance, a commonly used value for the Shields parameter is .047 suggested by Gessler (1971) and Meyer-Peter and Muller (1948). An increase in this parameter for the relationships presented from .03 to .047 would more than double the required discharge. Additional complications are associated with the selection of an appropriate d_{50} and an appropriate frictional slope for the stream or rivers. Nonlinear channel allignment or a non-planar bed make this latter parameter difficult to assess.

Sediment Transport Functions

The quantity of sediment transported in a stream is dependent upon the interactions between the factors determining the supply of sediment (drainage basin vegetation, soil conditions, bank stability, and rainfall distribution and intensity) and the factors determining the carrying capacity of the stream (slope, discharge, sediment size and gradation). Einstein (1964) describes this interaction as:

> "Every sediment particle which passes a particular cross section of the stream must satisfy the following two conditions: (1) It must have been eroded somewhere in the watershed above the cross section; (2) it must be transported by the flow from the place of erosion to the cross section.
>
> Each of these two conditions may limit the sediment rate at the cross section, depending on the relative magnitude of two controls: the availability of the material in the watershed and the transporting ability of the stream. In most streams the finer part of the load, i.e., the part which the flow can easily carry in large quantities, is limited by its availability in the watershed. The coarser part of the load, i.e., the part which is more difficult to move by flowing water, is limited in its rate by the transporting ability of the flow between the source and the section."

The transport of bed material is therefore controlled by the transport capacity of the stream, while the transport of fine sediments is controlled by the supply delivered to the stream. Many equations have been developed to estimate bed load transport rates. These equations often predict widely varied sediment discharges for the same set of hydraulic conditions. A factor of 100 between predictions by different methods is not uncommon. Therefore, in order to obtain useful information, the limitations of each method must be recognized. For gravel bed streams, the bed material is transported mostly as bed load and not as suspended load. Consequently, three bed load transport functions which have been applied to gravel bed streams are briefly discussed below. These are the Meyer-Peter and Muller transport function, Einstein's bed load function, and Parker's bed load function.

Meyer-Peter and Muller Formula. The Meyer - Peter and Muller formula (1948) was developed based on flume experiments using mixed and uniform sand particles, natural gravels, coal particles with a specific gravity of about 1.25 and barite particles with a specific gravity above 4. Sediment sizes in the experiments ranged from 0.02 - 1.2 in, (0.4 mm to 30 mm). The flows used for the experiments contained little or no suspended load. The relationship was developed assuming that the energy slope is a characteristic of the interaction between the solid and liquid motion of a sediment laden flow as indicated by Simon and Senturk (1977). Some of the energy is expended in solid transport and the remaining is expended in liquid transport. The relationship was based on the assumption that the sediment transport process is governed by the same parameters that govern the incipient motion process. The equation was originally presented in the form:

$$\frac{Q_b}{Q}\,\gamma \left(\frac{K_s}{K_r}\right)^{3/2} RS = .047\,(\gamma_s - \gamma)\,d_m + .25\left(\frac{\gamma}{g}\right)^{1/3} q_b^{2/3} \qquad (10)$$

where:

Q = the water discharge (cfs)

Q_b = the water discharge determining the bed load transport rate

γ = the specific weight of the fluid

γ_s = the specific weight of the sediment

$\frac{K_s}{K_r}$ = the ratio of the total bed shear which is utilized in mobilizing the particles

R = the hydraulic radius (units)

S = the energy gradient

d_m = the effective diameter of the sediment = $\Sigma d_i P_i$ with d_i and P_i the size fraction and percentage of the fraction respectively

q_b = the bed load transport rate in submerged weight per unit time per unit width

K_r = Mannings n value determined from the velocity, hydraulic radius and slope of the channel

They also suggest that $K_s = .034\ d_{90}^{1/6}$

where: d_{90} = the bed particle size (in feet) of which 90 percent is finer by weight

The Meyer-Peter and Muller equation is often transformed into the form:

$$q_b = 0.25 \frac{8}{\sqrt{\rho}} (\tau_o - \tau_c)^{3/2} \tag{11}$$

where:

τ_c = the critical bed shear for incipient motion

τ_o = the actual bed shear for flow conditions

ρ = the fluid density

q_b = the bed load transport rate as submerged weight per unit time per unit width.

Equation 11 is in the form of many sediment transport functions which express the sediment transport rate as some function of the excess shear stress ($\tau_o - \tau_c$). Although the Meyer - Peter and Muller relationship is often used for gravel bed rivers, poor agreement between predicted and observed transport rates have been reported by Parker et al. (1982) and Simon and Senturk (1977) for channel slopes above about .001.

Einstein's Bed Load Function. Since the critical point at which bed motion begins is difficult to define, Einstein (1950) took a different approach in the development of a sediment transport formula. Instead, he postulated that the bed load transport is related to turbulent flow fluctuations rather than the average stresses on the sediment particles. He therefore theorized a probabilistic approach to the forces acting on an individual particle. The method provides estimates of the transport rate of individual size fractions that compose the bed material. Consequently, changes in bed material composition can be predicted.

Einstein's Bed Load Function is plotted in Figure B-6 in which:

$$\Psi *_i = \xi_i Y \left[\frac{\log 10.6}{\log \frac{10.6x\ X}{d_{65}}} \right]^2 \frac{(\gamma_s - \gamma) d_{si}}{\gamma r'_b S} \qquad (12)$$

$$\Phi *_i = \frac{1}{P_i} \frac{g_{sbi}}{Y_s} \sqrt{\frac{\gamma}{\gamma_s - \gamma} \quad \frac{1}{g d_{si}^3}} \qquad (13)$$

In these equations ξ_i, = a function of d_{si}/X given in Figure B-7; Y = a function of d_{65}/δ given in Figure B-8:

$$X = 0.77 \frac{d_{65}}{x} \text{ when } \frac{d_{65}}{x\delta} \quad 1.80 \qquad (14)$$

$$X = 1.398\ \delta \text{ when } \frac{d_{65}}{x\delta} \quad 1.80 \qquad (15)$$

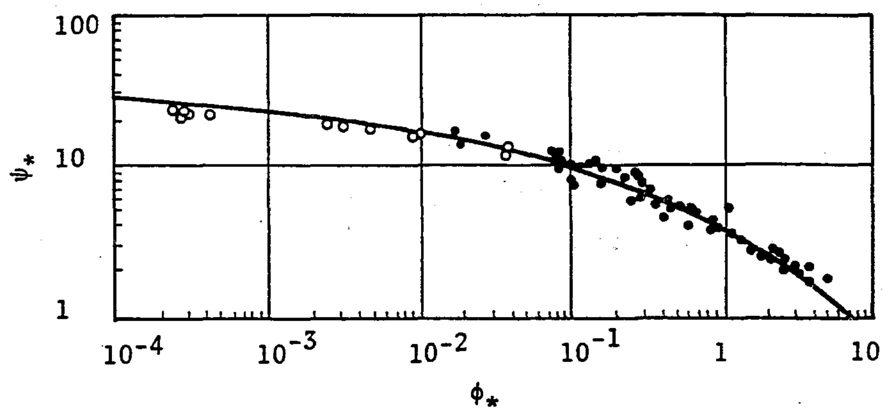


Figure B-6 EINSTEIN'S BED LOAD FUNCTION (MODIFIED FROM RICHARDSON et al, 1975)

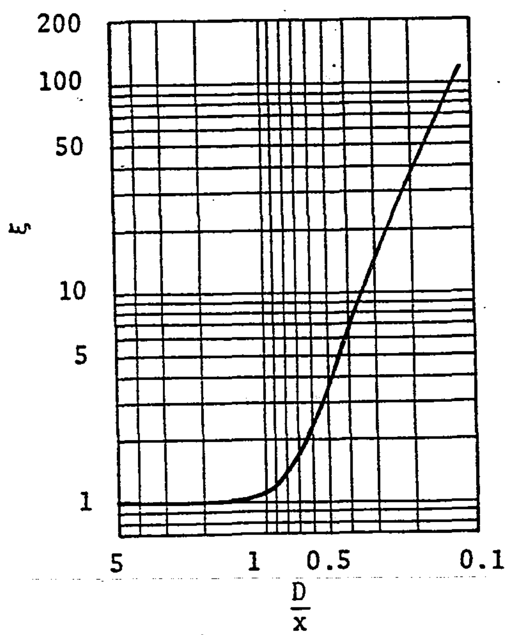


Figure B-7 EINSTEIN'S HIDING FACTOR (MODIFIED FROM RICHARDSON et al, 1975)

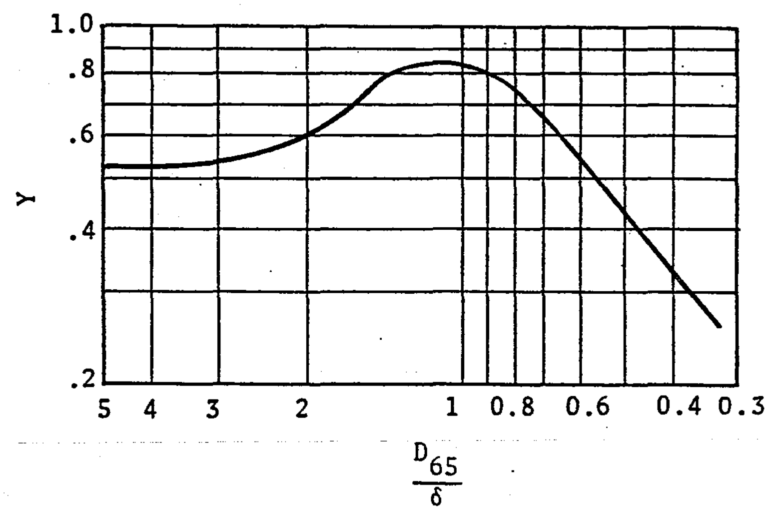


Figure B-8 EINSTEIN'S PRESSURE CORRECTION (MODIFIED FROM RICHARDSON et al, 1975)

$$\delta = 11.6 \frac{\nu}{U'_*} \tag{16}$$

The data plotted in Figure B-6 were taken from flume experiments with two well-sorted sediments with mean sizes 1.1 in, (28.65 mm) and 0.03 in (0.785 mm) respectively.

Parker's Bed Load Function. Parker (1978; 1979) developed a bed-load function which pertains specifically to gravel-bed streams. Using 278 experimental and field data sets Parker fitted the data by eye to the relationship;

$$q^* = 11.2 \left[\frac{\tau * - .03}{\tau_*{}^3}\right]^{4.5} \tag{17}$$

where:

$$q^* = q \; / \; \left(d_{50} \sqrt{R'_g \; d_{50}}\right)$$

R' = submerged specific gravity of sediment (1.65)

d_{50} = grain size for which 50% of sediment is finer by weight

q = volumetric bed load discharge per unit width

$\tau *$ = Shields Stress = $\tau/\left(\rho R'_g \; d_{50}\right)$

Equation 17 is plotted in Figure B-9 along with the data used to derive it. Although this equation has not had widespread use, it has the advantage that it was derived specifically for gravel bed streams.

Duration of Flushing Flows

As previously discussed, the gravel bed must be mobilized in order to release fine sediments for transport. Parker (1982) and Andrews (1983) both indicated that different particle sizes in gravel bed streams commence motion within a very narrow band of discharges. Consequently, once the bed begins to mobilize, most of the fine material should be

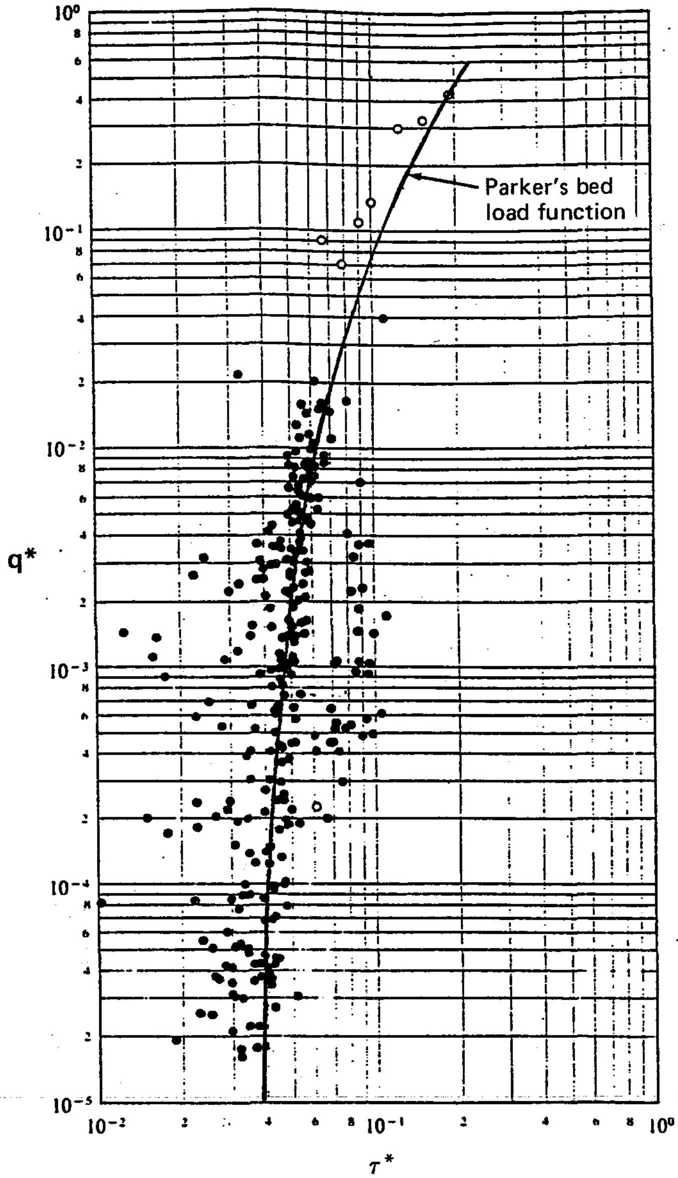


Figure B-9 PARKER BED LOAD RELATION FOR GRAVEL BEDS (MODIFIED FROM PARKER, 1978) entrained rather quickly. If the flushing flows cease, however, the bed will stop moving and the fine sediments will again begin to settle into the gravels. Einstein (1968) derived an expression for the half-life for a fine particle to remain suspended in the flowing water. The expression is:

$$T = \frac{0.692\ d}{w\eta} \tag{18}$$

where:

T = the half-life for any particle size

d = the water depth

w = the particle fall velocity

η = efficiency factor = 1.0 for a long river or canal.

Using a medium silt sized particle of 0.0008 in (0.02 mm) in water of 3.28 ft (1.0 m) depth, the half-life is approximately 40 minutes. Consequently, with the exception of clay sized material, it appears that flushing must continue until the fine material from the uppermost portion of the reach travels through the entire section of stream.

Vanoni (1975) reported a bed load relationship developed by Kalinske (1947) based on the ratio of the mean grain velocity to the water velocity. Figure B-10 shows this ratio as a function of the ratio of the critical shear stress (τ_c) for the material, to the bed shear stress (τ_o). If we assume that the bed shear is just sufficient to mobilize the gravel bed, then the ratio of the diameters of the fine material to the gravel material provides an estimate of τ_c/τ_o. Since this ratio is less than about 0.2 for most conditions of interest, the particle travel velocity should be at least 70 percent of the water travel velocity (from Figure B-10). Consequently, a particle travel time of about 1.5 times the water travel time appears to be a reasonable estimate of the required flushing time.

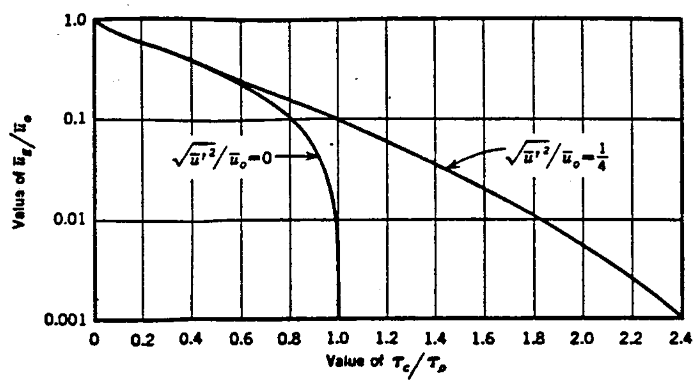


Figure B-10 KALINSKE'S (1947) RELATION FOR THE MEAN GRAIN VELOCITY AS A FUNCTION OF THE CRITICAL SHEAR STRESS (MODIFIED FROM VANONI 1975)

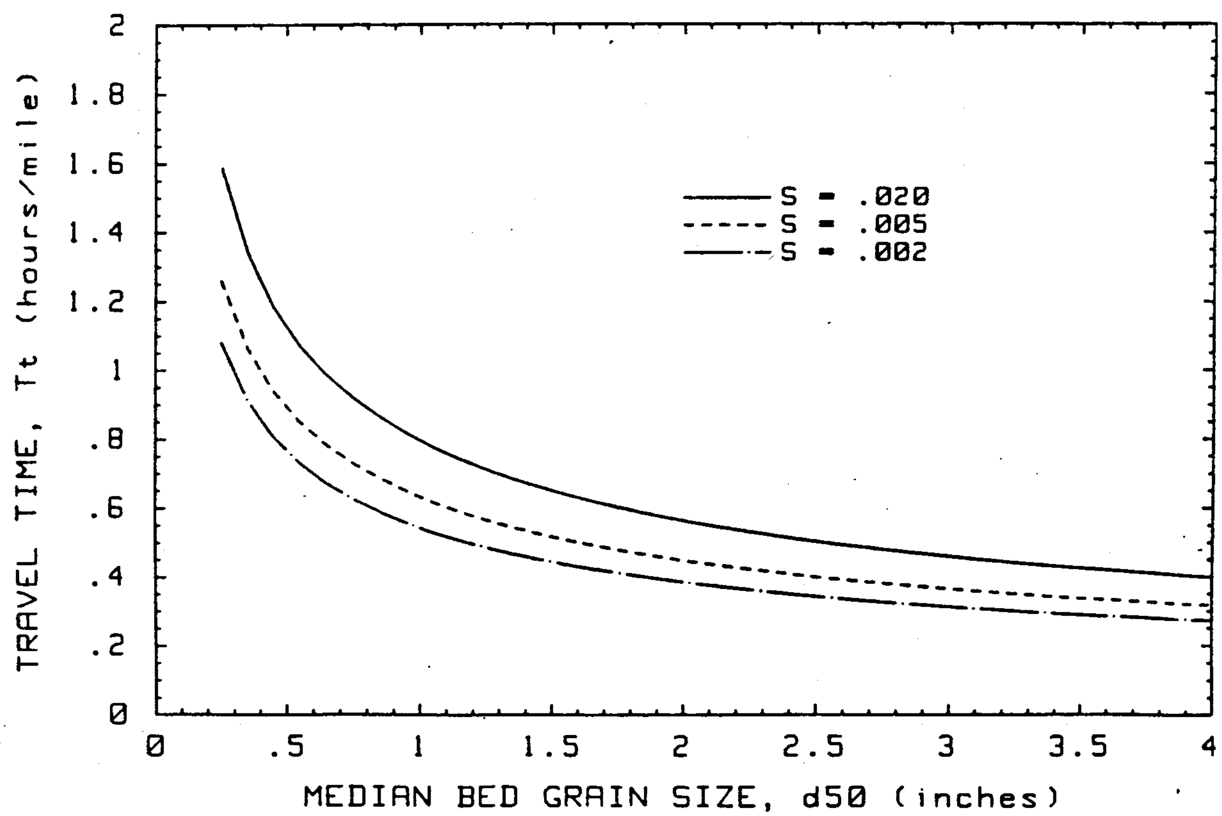


Figure B-11 TIME REQUIRED TO FLUSH FINE SEDIMENTS AS A FUNCTION OF MEDIAN BED GRAIN SIZE AND CHANNEL SLOPE. SEE TEXT FOR LIMITATIONS.

An equation for determining the travel time for a particle can be derived using a similar method to that used to estimate the water velocity at incipient bed motion (V_c). The equation assumes that the fine material particle travel velocity is set at 70% of the water velocity. The equation is:

$$\frac{T_t}{L} = \frac{0.3S^{1/6}}{d_{50}^{\;1/2}}$$

where:

T_t = the particle travel time in seconds

L = length of reach being flushed below water source (ft)

S = the bed slope (ft/ft)

d_{50} = the median particle size (ft)

This relationship is shown graphically in Figure B-11 providing an estimate of the time required to flush fine sediments from the stream (in hours per mile of stream) as a function of the gravel bed d_{50} for various channel slopes. At first glance, this figure appears in error since it implies that a stream with a steeper slope will require a longer flush time. However, this is correct since the magnitude of the flow required for flushing is far less for the steeper gradient stream (Figure B-5). Thus a longer flow duration would be needed.

Using this figure, the required duration of a flushing flow for a stream with a median grain size of 2.0 in (50.8 mm) and a slope of 0.005 would be 0.45 hours/mile of stream; a stream 20 miles (32 km) long would require a flow duration of 9 hours.

This analysis, as with that done for the bed mobilization, is an oversimplification of the process of flushing fine material from the gravels. Some comparison with field data would be necessary before any confidence could be placed in the methodology. Kalinske's work was based on the use of uniform grain sized material. The application of his results to the flushing of fine sediments from gravel beds may not be appropriate. The above analysis also neglects the random process involved when an individual particle is mobilized, embedded in the gravels, and then re-mobilized. In actuality, any material flushed from one location along a stream would be found scattered along the channel downstream of the original location as Einstein (1950) found in flume experiments. The location of these sediment particles should be described by a time-varying distribution function. Consequently, a probabilistic approach to the problem should be considered. The random nature of the phenomenon explains the reason why a longer duration of flushing will remove a greater percentage of the fine material as well as the reason why sections of stream nearer the flushing source would be cleaned better than those farther downstream.

The flushing duration indicated by Figure B-11 may provide a reasonable estimate if the fine material is carried primarily as suspended load (mainly silt and clay sizes). However, for sand-sized fine material, the flushing time is probably greatly underestimated.

Channel Morphology

The morphology of stable self-formed alluvial rivers is determined by the interaction between numerous geologic and hydrologic variables. The interaction between these variables is complex and not fully understood. However, alluvial rivers and streams develop a hydraulic geometry which is dependent on the relationship between the water discharge and the sediment discharge. Generally, these relationships can be applied to channels within one region. The regime theory, developed for irrigation canals in India, formed the basis of hydraulic geometry relationships for rivers and canals (Mahmood and Shen 1971). Generalized hydraulic geometry relationships were developed by Leopold and Maddock (1953) for different types of rivers and different regions of the United States using extensive data from the U.S. Geological Survey. More recently, Parker (1978; 1979) developed a set of dimensionless regime equations for gravel bed channels with mobile stream beds and stable banks. Hydraulic geometry relationships have been developed using the bankfull discharge as a variable. It seems feasible, however, that similar relationships could be established for the critical discharge at which the gravel bed of a stream mobilizes, for a specific region. Parker (1979) also developed a relationship between the bed shear at bankfull conditions ($_{BF}$) and the critical shear stress (τ_c) for bed mobilization in gravel bed streams. The equation is of the form:

$$\tau_{BF} - \tau_c = 0.2 \quad \tau_c$$

$$\text{or} \quad \tau_c = 0.83\,\tau_{BF} \tag{20}$$

where:

τ_{BF} = shear stress at bank full condition

τ_c = critical shear stress for bed mobilization

which indicates that the bed will mobilize when the flow depth is slightly greater than 80 percent of the bankfull depth.

A sequence of natural flow elements determines the shape of an alluvial channel. Although the process is dynamic, many river and stream channels maintain a stable shape. The dominant discharge, defined as the equivalent steady discharge to produce the same dimensions as the sequence of natural events, has been found to be approximately the same as the bankfull discharge for many natural channels. In addition, the bankfull discharge appears to be approximately the same as the frequency of occurrence of the flow which transports the most sediment, ("effective discharge," Simons et al. 1981). For gravel bed channels, the channel-forming discharge is approximately equal to the 1.5 year flood event.

Since the channel-forming process is closely linked to the sequence of flows in the channel, there is some basis for the development of flushing flow methods that use functions of the natural flow sequence. Their applicability, however, would most likely be regional.

Since the regulation of a river or a stream changes both the sequence of flows and the amount of sediment delivered to a river, the morphology of the channel will adjust to the new conditions. The channel bed may degrade or aggrade. The gradation of the bed material will also change. Immediately downstream of a dam, a major source of sediment has been cut off. As a result the channel bed degrades until a stable armor layer forms. If this armor layer is mobilized, some of the finer gravels will move downstream and a new armor layer will form consisting of larger gravels. This implies that repeated flushing of regulated streams may require higher flows to mobilize the bed, and the size of the gravels may eventually become too large for spawning use. In any case, excessively high flushing flows could adversely affect the available spawning habitat in a regulated stream.

Appendix C

WESTERN UTILIZATION AND NEED FOR FLUSHING FLOW METHODOLOGIES

WESTERN UTILIZATION AND NEED OF FLUSHING FLOW METHODOLOGIES

This appendix presents the results of a survey designed to obtain information concerning flushing flows from state and federal resource agencies and research institutions. With the exception of two National Laboratories, Argonne and Oak Ridge, the survey was limited to the western states.

The survey consisted of the submittal of standardized questionnaires to various entities, with a follow-up telephone survey to ensure response. Recipients of the questionnaires were selected based on their potential involvement in projects requiring flushing flows, and on their involvement in relevant past or ongoing research projects (e.g., instream flow, sediment transport). The survey was inclusive of Alaska, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming.

A total of 70 survey forms were submitted for completion; distribution was as follows:

- Federal Agencies (40 forms)

  U.S. Fish and Wildlife Service
  U.S. Forest Service
  U.S. Bureau of Reclamation
  U.S. Bureau of Land Management
  U.S. Geological Survey
  U.S. Soil Conservation Service
  Bonneville Power Administration
  National Marine Fisheries Service

- State Agencies (17 forms)

  State Fish and Game Agencies
  State Water Resource Agencies

- Universities (9 forms)

  Water Research Centers and Laboratories
  Fisheries Departments

- Research Laboratories (4 forms)

  Argonne National Laboratory
  Oak Ridge National Laboratory
  Battelle Northwest
  Weyerhauser Forestry Lab

A complete listing, including addresses of all individuals receiving the survey form is presented at the end of this appendix.

In content, the survey forms were structured to solicit information in four principal areas: awareness and use of flushing flow methodologies, need for flushing flows, need for standardization of methods, and research activities (Figure C-1). A section was also provided to discuss techniques used in evaluating the effectiveness of flows.

Overall, a total of 46 survey forms were completed, some verbally. This represents a 65 percent return ratio and is indicative of the present interest in flushing flows. The following sections present the results of the survey by principle area. Results are summarized in Table C-1.

Awareness and Use of Flushing Flow Methodologies

Of the 46 respondents, 24 (52%) stated an awareness of some type of flushing flow methodology. However, those indicating an awareness were generally those most directly involved in types of projects which might necessitate a flushing flow. These included the state and federal regulatory agencies which would be involved in hydroelectric developments. Positive responses were also obtained from many university research organizations which have been active in the fields of instream flow and sediment transport.

Sixteen of the 24 positive respondents listed one or more of the methods they are familiar with or have used for assessing flushing flow needs.

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FLUSHING FLOW METHODOLOGY
SURVEY FORM

Name: ______________________ Date: ______________

Title: ______________________

Affiliation: ______________________

Address: ______________________

I. Existing Methodologies

A) Briefly describe any methodology(ies) or technique(s) for evaluating flushing flow needs that you are aware of, or which are being used by your organization (please provide a reference if applicable):

(Attach additional sheets if necessary)

Not aware of any methodologies ______ (Check)

None are in-use ______ (Check)

B) What is your primary consideration in making a flushing flow recommendation?

1) sediment; flushing fines from spawning gravels ______
2) sediment; flushing fines from pools (rearing habitat) ______
3) channel maintenance ______
4) riparian habitat maintenance ______
5) Other (specfiy ______________) ______

C) Have you evaluated the effectiveness of the flushing flow?
Yes ____ No ____
If yes, describe how evaluated ______________________

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II. Research

A) Is (Has) your organization (been) involved in any research projects concerned with flushing flows, sediment transport, etc.? Yes ____ No ____
If yes,

Project Title: ______________________

Objectives: ______________________

Methods: ______________________

Report (Publication) Citation: ______________________

B) Do you see a need for the development of a formalized, standard methodology for recommending flushing flows? Yes ____ No ____
If yes, suggested approaches to methodology development ______

III. Comments

Figure C-1 FLUSHING FLOW METHODOLOGY SURVEY FORM

Table C-1

SUMMARY OF AGENCY AND INSTITUTION RESPONSES
ON THE FLUSHING (FF) SURVEY

Agency/Institution (State)	Major Concerns for FF	Aware of FF Methods (method used)	Evaluated FF Effectiveness (method used)	Need for Standard FF Method	Involved in FF Studies/ Research	Comments
U.S. Fish Wildlife Service (Anchorage Alaska) Mr. Keith Bayha	spawning gravels	yes (Tennant)	yes	no (site specific)	no	Standard method unlikely due to the extreme variability inherent in streams.
U.S. Forest Service Forestry Science Laboratory (Juneau, Alaska) Dr. Mason Bryant	spawning gravels	no	no	no	yes	Research is targeted at evaluating effects of sediment on pink and chum salmon spawning, and methods for evaluating intragravel velocity.
Alaska Department Fish and Game (Anchorage, Alaska) Mr. Christopher Estes	spawning gravel rearing habitat channel mainten-ance riparian at habaitat recre-ational use	yes (Tennant, Estes & Orsborn)	yes	yes	yes	Research project focused on determining pre-hydroelectric project effects of mainstem flows on aquatic & terrestrial biota; Susitna hydroelectric project.
Alaska Department Natural Resources (Anchorage, Alaska) Ms. Mary Lu Harle	fishery habitat channel mainten--ance	no	no	yes	no	Standard method desirable but would need field verification.
Alaska Cooperative Fishery Research Unit (Fairbanks, Alaska) Dr. Jacqueline Laperriere	spawning gravels rearing habitat channel mainten-ance	yes (visual observation)	no	yes	yes	Research project on evaluating Placer mining sediment effects on aquatic biota.
Arctic Environmental Information and Data Center (Anchorage, Alaska) Mr. William Wilson	spawning gravels	yes	no	no	yes	Rather than a single standard method, a listing of appropriate methods may be more useful. Research project focused on assessing pre-project sediment dynamics below proposed hydro site.
U.S Forest Service (Flagstaff, Arizona) Mr. Lloyd Barnett	-	no	no	yes	no	The need and purpose of FF's must be determined before they can be quantified.
Bureau of Land Management (Phoenix, Arizona) Mr. Ted Cordery	riparian habitat	no	no	yes	no	A single standard method may not be feasible - would depend on stream type and purpose of flow.

Table C-1 (continued)

SUMMARY OF AGENCY AND INSTITUTION RESPONSES ON THE FLUSHING FLOW (FF) SURVEY

Agency/Institution (State)	Major Concerns for FF	Aware of FF Methods (method used)	Evaluated FF Effectiveness (method used)	Need for Standard FF Method	Involved in FF Studies/ Research	Comments
U.S. Forest Service (Placerville, California) Mr. Jeff Kershner	spawning gravels rearing habitat	yes (flow records; Tennant method)	no	yes	no	Any method developed should be consistent with channel maintenance requirements.
University of California Dept. Forestry and Resource Management (Berkeley, California) Dr. Donald Erman	spawning gravels rearing habitats biological reset mechanisms	no	yes (bedload transport)	yes/no	yes	Standard FF method - no, but a formalized approach to quantifying FF's - yes. Flushing flows are one aspect of high discharge - may be involved in genetic feedback of resident species - life cycles, diversity, productivity.
University of California Dept. of Wildlife and Fishery Biology (Davis, California) Dr. Peter Moyle	spawning gravels rearing habitat riparian habitat limit introduced fishes	no	no	yes	no	--
Army Corps of Engineers (Sacramento, Calif) Mr. George Wedell	--	no	no	--	no	Flushing flows not used or evaluated on any projects within the District. No flushing flow research being conducted at other ACOE stations (Davis, Calif; Vicksburg, Miss)
California Department Fish and Game (Sacramento, Calif) Mr. James Schuler Mr. Ted Vande Sande	spawning gravels rearing habitat channel maintenance riparian habitat	yes (HEC program) (Tennant)	yes (visual observation)	yes	no	On regulated systems, the natural tendency is for the stream to begin assuming a new morphological structure based on the new flow
Colorado State Universtiy Civil Engineering Dept. (Fort Collins, Colorado) Dr. Jim O'Brien	channel maintenance spawning gravels	yes (effective discharge/bank full discharge	yes (visual documentation/transport models)	yes/no	yes	Single, standard method not practical; problems are too site specific; all methods should include the field calibration of data.
U.S. Forest Service (Fort Collins, Colorado Mr. David Rosgen	channel maintenance riparian habitat	yes (USFS-Rosgen)	yes (permanent transects	yes/no	yes	A single standard FF method - no; rather a series of standard methods tailored to specific needs. Research focused on development of procedures for channel maintenance.

Table C-1 (continued)

SUMMARY OF AGENCY AND INSTITUTION RESPONSES
ON THE FLUSHING FLOW (FF) SURVEY

Agency/Institution (State)	Major Concerns for FF	Aware of FF Methods (method used)	Evaluated FF Effectiveness (method used)	Need for Standard FF Method	Involved in FF Studies/ Research	Comments
U.S. Fish Wildlife Service Cooperative Instream Flow and Aquatic Systems Group (Fort Collins, Colorado) Dr. Robert Milhous	spawning gravels channel maintenance rearing habitat riparian habitat	yes	no	no/yes	yes	Need a collection of FF evaluation approaches which are adaptable to different situations. The need for the FF should be carefully evaluated. Research project involved in adopting other investigators data/results into approaches which could be used for FF determination; may be possible to integrate into PHABSIM.
U.S. Geological Survey (Denver, Colorado) Dr. Edmund Andrews	spawning gravels channel maintenance riparian habitat	yes	yes	-	yes	FF studies should be addressed by first defining the critical habitats and geomorphic conditions, and then identifying the flows that form and maintain these.
U.S. Soil Conservation Service Agriculture Research Service (Fort Collins, Colorado) Dr. Fred Theurer	spawning gravels channel maintenance	yes	no	yes	yes	Research project involved with evaluating the deposition and intrusion of fine sediments into gravels; FF problem will require an interdisciplinary approach.
Colorado State University Dept. Fishery and Wildlife Biology (Fort Collins, Colorado) Dr. Kurt Fausch	--	yes (USFS-Rosgen)	no	yes	no	More than peak flushing flows will prove important; smaller flows of greater frequency may do more for channel maintenance.
Idaho Cooperative Fishery Research Unit University of Idaho (Moscow, Idaho) Dr. Ted Bjornn	spawning gravels rearing habitat	no	no	yes	yes	Present research involved with sedimentation and productivity of salmonid streams.
Idaho Department of Water Resources (Boise, Idaho) Mr. Darrel Clapp	--	no	no	yes	no	--

Table C-1 (continued)

SUMMARY OF AGENCY AND INSTITUTION RESPONSES
ON THE FLUSHING FLOW (FF) SURVEY

Agency/Institution (State)	Major Concerns for FF	Aware of FF Methods (method used)	Evaluated FF Effectiveness (method used)	Need for Standard FF Method	Involved in FF Studies/ Research	Comments
Idaho Department Fish and Game (Lewiston, Idaho) Dr. Tim Cochrauer Mr. William Horton	spawning gravels	yes (Tennant)	no	yes	no	Approach used in evaluating FF would probably be different depending on specific drainages.
U.S. Forest Service Intermountain Forest and Range Experiment Station (Boise, Idaho) Dr. William Platts	maintenance of fishery habitat	yes	yes (transect system)	yes	yes	Natural flushing flows (unregulated streams) especially from major events are also important. Present research on natural systems - sediment recovery.
Argonne National Laboratory (Argonne, Illinois) Dr. Richard Olsen	spawning gravels channel maintenance	no	no	yes	yes	Subject of flushing flows and gravel recruitment becoming important considerations in hydroelectric developments and their licensing (FERC)
Montana Cooperative Fishery Research Unit Montana State University (Bozeman, Montana) Dr. Robert White	spawning gravels rearing habitat	no	no	yes	no	Methodology development may utilize average annual discharge, sediment transport models, flume studies.
U.S. Forest Service (McCall, Idaho) Dr. David Burns	spawning gravels rearing habitat channel maintenance riparian habitat	yes	no	yes	yes	Recommends integration of IFIM with USFS channel maintenance methods. Has used PHABSIM with substrate embeddedness values for sediment evaluation.
Montana Department Fish Wildlife and Parks (Bozeman, Montana) Mr. Fred Nelson	spawning gravels channel maintenance	yes (Dominant Discharge)	no	no	no	Development of a single standard method would probably not be possible.
Nevada Department of Wildlife (Reno, Nevada) Mr. William McLelland	spawning gravels riparian habitat	no	no	yes	no	There is a recognized need for assessing flushing flow requirements/little done to date.

Table C-1 (continued)

SUMMARY OF AGENCY AND INSTITUTION RESPONSES
ON THE FLUSHING FLOW (FF) SURVEY

Agency/Institution (State)	Major Concerns for FF	Aware of FF Methods (method used)	Evaluated FF Effectiveness (method used)	Need for Standard FF Method	Involved in FF Studies/ Research	Comments
U.S. Fish and Wildlife Service (Gallup, New Mexico) Mr. Frank Halfmoon	rearing habitat	no	no	yes	no	Methodology development should be preceded by a systematic evaluation of techniques & methods presently in use.
U.S. Fish and Wildlife Service (Albuquerque, New Mexico) Mr. Carl Couret	spawning gravels	yes (indirectly IFIM)	no	yes	no	Has utilized IFIM to indirectly determine flushing flows. A standard method should probably include: sediment transport models and system of field checks to determine duration.
Oregon Fish and Wildlife (Portland, Oregon) Mr. Louis Fredd	spawning gravels	no	yes (Deschutes R. study)	--	--	--
U.S. Soil Conservation (Portland, Oregon) Mr. L. Dean Marriage	spawning gravels	no	no	yes	yes	An approach in developing a methodology may include controlled releases of water in concert with sediment sampling. SCS is funding research on sediment intrusion.
U.S. Fish and Wildlife Service (Portland, Oregon) Mr. Richard Johnson	spawning gravels	yes (visual observation)	no	yes	no	--
Oregon State University School of Forestry (Corvallis, Oregon) Dr. Robert Beschta	spawning gravels rearing habitat	yes	yes (sediment transport)	yes	yes	Research focused on evaluating sediment transport processes in mountain streams and how they influence spawning gravels. Methodology development should be preceded by extensive research.
Bonneville Power Administration Division of Fish and Wildlife (Portland, Oregon) Mr. Thomas Vogel	spawning gravels	no	no	no	no	A single standard method would probably be unrealistic. More emphasis should be placed on prevention of sedimentation problems (e.g. instream structures, deflectors).

Table C-1 (continued)

SUMMARY OF AGENCY AND INSTITUTION RESPONSES
ON THE FLUSHING FLOW (FF) SURVEY

Agency/Institution (State)	Major Concerns for FF	Aware of FF Methods (method used)	Evaluated FF Effectiveness (method used)	Need for Standard FF Method	Involved in FF Studies/ Research	Comments
Oak Ridge National Laboratory Environmental Sciences (Oak Ridge, Tennessee) Dr. Michael Sale	spawning gravels, rearing habitat channel maintenance riparian habitat degradation of rearing habitat	no	no	yes	yes	Studies focused on determining reservoir operating rules to minimize impacts to downstream fish.
Bureau of Land Management (Price, Utah) Mr. Jesse Purvis	--	no	no	yes	no	Development of a standard method would be difficult because of different conditions regionally and nationally. Critical species approach may be useful.
U.S. Bureau of Reclamation Biological Studies Branch (Salt Lake City, Utah) Dr. Reed Harris	spawning gravels channel maintenance	yes	no	yes/no	yes/no	Standard method more useful in large river systems such as those inhabited by Colorado River endemics.
Utah Cooperative Fishery Research Unit Utah State University (Logan, Utah) Dr. Ross Bulkley	--	no	no	yes	no	--
Washington State Department of Fisheries Habitat Management Division (Olympia, Washington) Mr. Ken Bates P.E.	spawning gravels	yes (bed material/ sediment sampling)	no	yes	--	Methodology development should include sediment routing models.
Fisheries Research Institute University of Washington (Seattle, Washington) Dr. Quentin Stober	spawning gravels	no	no	no	yes	Flushing flows may be detrimental if sediment recruitment is nil; therefore spawning gravels may be transported out of system.
Washington Department of Ecology Instream Flow Program (Olympia, Washington) Mr. Kenneth Slattery	spawning gravels	no	no	yes	no	Suggest integration of transport models into IFIM.

Table C-1 (continued)

SUMMARY OF AGENCY AND INSTITUTION RESPONSES
ON THE FLUSHING FLOW (FF) SURVEY

Agency/Institution (State)	Major Concerns for FF	Aware of FF Methods (method used)	Evaluated FF Effectiveness (method used)	Need for Standard FF Method	Involved in FF Studies/ Research	Comments
Battelle Northwest Environmental Sciences Department (Richland, Washington) Dr. C. Dale Becker	spawning gravels	no	no	yes	yes	Research project focused on determining transport of radio-nuclides in organic & inorganic materials. Aerial photography and onsite transects may be useful for evaluatng FF effects.
Albrook Hydraulics Laboratory Washington State University (Pullman, Washington) Dr. John Orsborn P.E.	spawning gravels rearing habitat channel maintenance	yes (Tennant, Estes & Orsborn)	no	yes	yes	Methodology should be based on the fluid mechanics and hydraulic geometry of the reach, including bedload size distribution & cemented condition; also basin characteristics.
Wyoming Water Research Center University of Wyoming (Laramie, Wyoming) Mr. Thomas Wesche	spawning gravels rearing habitat channel maintenance	yes (Bankfull discharge, Wesche)	no	yes	yes	A series rather than a single method will probably need to be developed based on various types of stream classifications, habitat types, geomorphic characteristics etc.
Wyoming Cooperative Fishery Research Unit University of Wyoming (Laramie, Wyoming) Dr. Wayne Hubert	spawning gravels rearing habitat channel maintenance riparian habitat	--	--	yes	yes	--

These include:

o Tennant Methodology	(6 respondents)
o Bankfull Discharge	(3 respondents)
o Visual Observation	(2 respondents)
o USFS Channel Maintenance	(2 respondents)
o Estes and Orsborn Method	(2 respondents)
o IFIM (indirect)	(1 respondent)
o Bed Material Sampling	(1 respondent)
o Effective Discharge	(1 respondent)

These responses suggest that the Tennant methodology is the most common and perhaps most widely used method in the west for recommending flushing flow needs. Reasons for this may include its ease of application (see Tennant Methodology) and/or the general lack or awareness of other techniques.

Although the above methods were cited, very few were listed as being commonly used by the respective agency. The majority of methods listed had been used or were developed on specific projects and their applicability to other conditions had not been tested. Exceptions to this included the Tennant, Bankfull and USFS Channel Maintenance methods, which have been applied on other systems. However, documented use of these methods is sporadic in the different states. It becomes apparent then, that no single method or approach is currently being used for assessing flushing flow needs. From the previous review of methodologies, it is possible that the methods and techniques which are in use today may be providing questionable recommendations.

Over 60 percent of the respondents exhibiting an awareness or use of a flushing flow method were unaware of follow-up studies for evaluating flow suitability. This suggests that relatively few studies have been conducted for evaluating the effectiveness of a given flushing flow. Rosgen (1985, pers. comm. D. Reiser) suggested this is a key element in defining the suitability of flows and should therefore be included as part of the flow assessment process. The USFS is following this procedure in their channel maintenance flow recommendations through installation of permanent cross-sections for monitoring change.

Need for Flushing Flows

Agency and institution concerns and needs for flushing flows were varied and are summarized in Table C-2 as follows:

Table C-2

SUGGESTED NEEDS FOR FLUSHING FLOWS AS INDICATED BY AGENCY/INSTITUTION RESPONSES

Need	No. Respondents[a]	Single Listings
Flush fines from spawning gravels	35	13
Flush fines from rearing habitat	16	1
Channel maintenance	17	--
Riparian habitat maintenance	12	1
Recreational needs	1	--
Limit introduced fish	1	--
High flows degrade fish habitat	1	--
High flows act as biological reset mechanisms	1	--

a/ Respondents were free to indicate more than one need (see Figure C-1).

As indicated, the major need for flushing flows in the western states is clearly for removing fine sediments from important spawning gravels. This was cited by 35 respondents (76%) and included 13 single listings. This is not surprising since the majority of stream systems in the west support coldwater fisheries of salmonid species.

The needs of channel maintenance and rearing habitat were the second and third most frequently cited concerns, followed by maintenance of riparian habitat. Several single concerns were also noted including one which suggested flushing flows may prove useful in limiting introduced fish. This would require a type of biological flushing flow removing either directly or indirectly the introduced species from the system. Direct removal would occur by flushing the organisms out of the system; indirect removal by the disruption of a critical life history stage.

At least four respondents noted that the actual need for flushing flows should be carefully evaluated prior to implementation. All four alluded to the situation of limited gravel recruitment in which flushing flows may be more detrimental than beneficial to the fishery (see Deposition of Sediments in Regulated Streams).

Need for Standardization of Flushing Flow Methods

Of the 43 respondents who answered this question, 31 (72%) indicated a standardized method or approach for estimating flushing flows is needed (Table C-3) The remaining responses were equally divided between not needing a method (14%) and uncertainty of the need (14%).

Table C-3

SUMMARY OF RESPONSES CONCERNING
THE NEED FOR A STANDARD FLUSHING FLOW METHODOLOGY

Need for Standard Method	Number	Percent of Total
yes	31	72
no	6	14
yes/no	6	14
Total	43	100

Respondents in this latter category were generally in favor of a collection or series of methods or approaches (rather than a single method) which could be adaptable to different situations. They reasoned that the development of a single technique would probably not be practical since sediment problems are site specific. Taken in this light, these responses can be considered favorable to methodology or approach standardization, which adjusts the percentage to 86 percent.

Many of the respondents offered specific comments and suggestions on methodology development (Table C-1). A common opinion was that the method(s) will need to accommodate different drainage basin and geomorphic characteristics, as well as biological needs. Mr. T. Wesche (Wyoming Water Research Center) suggested that the development could be based on various types of stream classifications, habitat types, or geomorphic conditions. Dr. J. Orsborn (Allbrook Hydraulics Lab) offered a similar approach stating that a methodology should be based on fluid mechanics and hydraulic geometry of the reach including basin characteristics. At least two respondents suggested the expansion of the IFIM to include flushing flow needs.

Results of this component of the survey clearly indicate that most state and federal resource agencies and research institutions believe there is a need for developing a standardized approach or approaches for assessing flushing flow requirements. In fact, several organizations are actively pursuing research projects along these lines (see next section).

Research Activities

About half (49%) of the respondents referred to their ongoing research activities related to some aspect of flushing flows (Table C-1). Such projects range from evaluations of sediment on fish ecology, to studies directly focused on methodology development. Of the latter, the project being conducted at the Wyoming Water Research Center is perhaps the most germane. This project, entitled Development of a Methodology to Determine Flushing Flow Requirements for Channel Maintenance Purposes was initiated in 1984 and involves both laboratory and field investigations (see REVIEW OF EXISTING METHODOLOGIES).

The Cooperative Instream Flow and Aquatic Sciences Group (CIFASG) is also involved in studies related to flushing flows. According to Milhous (1985, pers. comm. D. Reiser), the CIFASG is reviewing information and data of other investigations with the intent of adopting results into approaches which could be used for flushing flow determinations. It is encouraging that the federal agency which has accomplished so much in the instream flow arena is beginning to address flushing flow needs.

With respect to sediment studies, the Agriculture Research Service (ARS) of the Soil Conservation Service (SCS) in Fort Collins, Colorado, is presently involved in a project which is evaluating the deposition and intrusion of fine sediments into substrates. The purpose of this project is to develop a predictive stream oxygen model incorporating various intragravel parameters including sediment concentrations. The ARS has compiled and reviewed an extensive amount of literature related to sediment deposition and biological effects, and has recently published a summary of their findings (see Chevalier et al. 1984).

In summary, the problems associated with sediment deposition, and the mechanics of sediment transport and flushing flow assessments appear to be receiving renewed attention.

ADDRESSES AND SUMMARY RESPONSES OF INDIVIDUALS RECEIVING THE FLUSHING FLOW SURVEY FORM

NAME	TITLE	ADDRESS	STATE	METHOD	EFFECT	RESEARCH	STANDARD	CONCERNS	COMMENTS
DR. JACQUELINE LAPPERRIERE	ASSISTANT LEADER	ALASKA COOPERATIVE FISHERY RESEARCH UNIT UNIVERSITY OF ALASKA FAIRBANKS,ALASKA 99701	ALASKA	NO	NO	YES	YES	SPAWNING GRAVELS REARING HABITAT CHANNEL MAINTENANCE	AT HIGH FLOW, CHECK HOW MUCH CEMENTED BEDS HAVE CLEARED UP.CURRENTLY EVALUATING SEDIMENT EFFECTS FROM PLACER MINING FOR GOLD. SUGGEST LEAVING RESEARCH TO OPEN CHANNEL HYDROLOGIST AND IN ALASKA, SUPRA-PERMAFROST HYDROLOGISTS.
MR. CHRISTOPHER ESTES	AQUATIC HABITAT AND INSTREAM FLOW PROJECT LEADER	ALASKA DEPT.FISH AND GAME SU-HYDRO PROJECT 333 RASPBERRY ROAD ANCHORAGE, ALASKA 99502	ALASKA	YES	YES	YES	YES	SPAWNING GRAVELS REARING HABITAT CHANNEL MAINTENANCE RIPARIAN HABITAT RECREATIONAL USE	HAS PROVIDED A THESIS ON GRAVEL METHODOLOGY. SUGGEST USING THE % OF 3 DAY AND 7 DAY AVERAGES FOR ANNUAL PEAK EVENT. HAS PROVIDED FURTHER INFORMATION ON THESIS METHODOLOGY. DOES NOT RECOMMEND USING THE DATA FROM INSTANTANEOUS PEAK EVENTS.
MR. WILLIAM WILSON	ASSISTANT PROFESSOR OF FISHERIES	ARCTIC ENVIRONMENTAL INFORMATION AND DATA CENTER 707 A ST. ANCHORAGE,ALASKA 99501	ALASKA	YES	NO	YES	NO	SPAWNING GRAVELS	TERROR LAKE HYDRO FACILITY WILL COME ON LINE SOON. SUBSTRATE CHANGES DUE TO PROJECT FLOW REGIMES CAN BE ASSESSED BY MEASURING VELOCITIES ACROSS TRANSECTS AT VARIOUS POWER PRODUCTION LEVELS AND EXAMINE SUBSTRATE CHANGES.SUSTINA HYDRO MONITORING 30 YRS
MR. KEITH BAYHA	DEPUTY ASSISTANT REGIONAL DIRECTOR	ASSISTANT REGIONAL DIRECTOR U.S.F.W.S. 1011 E. TUDOR ROAD ANCHORAGE, ALASKA 99503	ALASKA	YES	YES	NO	NO	SPAWNING GRAVELS	FEELS THAT THERE CAN NOT BE A STANDARD, FORMAL METHOD UNLESS IT IS FLEXIBLE. WATERSHED MANAGEMENT, BIOLOGICAL FACTORS AND CONDITIONS DEMONSTRATE THE IMPRACTICALITY OF HAVING A SINGLE FORMAL METHOD.
DR. KOSKI		NATIONAL MARINE FISHERIES SERVICE NOAA P.O.BOX 1668 JUNEAU,ALASKA 99802	ALASKA						
MS. MARY LU HARLE	WATER RESOURCES MANAGER	WATER MGT. OFFICER ALASKA DEPT.NATURAL RES. 555 CORDOVA ST. ANCHORAGE, ALASKA 99510	ALASKA	NO	NO	NO	YES	NOT APPLICABLE	FEELS ANY METHOD DEVELOPED WOULD REQUIRE TESTING TO ASCERTAIN THEIR APPLICABILITY TO ARCTIC CONDITIONS. SAYS THE ALASKA POWER AUTHORITY IS EVALUATING FLUSHING FLOWS IN CONJUNCTION WITH THE SUSITNA HYDR. PROJECT AND MAY BE ABLE TO PROVIDE MORE INFO.
DR. MASON BRYANT	FISHERY RESEARCH BIOLOGIST	U.S.FOREST SERVICE FOR.SCI.LAB. BOX 909 JUNEAU,ALASKA 99802	ALASKA	NO	NO	YES	NO	NONE LISTED	INVESTIGATING EFFECTS OF SEDIMENT ON PINK AND CHUM SALMON SPAWNING AREAS AND METHODS TO EVALUATE INTRA-GRAVEL FLOW AND INSTREAM GRAVEL COMPOSITION.
MR. TED CORDERY	WILDLIFE BIOLOGIST	AQUATIC ECOLOGIST BUREAU OF LAND MGT. 2929 W. CLARENDON AVE. PHOENIX,ARIZONA 85017	ARIZONA	NO	NO	NO	YES	RIPARIAN HABITAT MAINTENANCE	FEELS ONE STANDARD METHODOLOGY MAY NOT WORK AND PROBABLY WILL DEPEND ON 1)TYPE OF STREAM AND 2) PRIMARY CONSIDERATIONS (SEE I.B.)
Dr. Jerry Tash		ARIZONA COOPERATIVE FISHERY RESEARCH UNIT UNIVERSITY OF ARIZONA TUCSON, ARIZONA 85721	ARIZONA						
MR. DICK BAUMAN		BIOLOGIST BUREAU OF RECLAMATION 201 N.CENTRAL AVE. PHOENIX,ARIZONA 85017	ARIZONA						

NAME	TITLE	ADDRESS	STATE	METHOD	EFFECT	RESEARCH	STANDARD	CONCERNS	COMMENTS
DR. JOHN RINNE		U.S. FOREST SERVICE ROCKY MTN. STATION FOREST SER. LAB. ARIZONA STATE UNIV. TEMPE,ARIZONA 85281	ARIZONA						
MR. BARNETT LLOYD	FOREST PLANNER	U.S.FOREST SER. COCOHINO NAT. FOR. 2323 E. GREENLAW LANE FLAGSTAFF,ARIZONA 86001	ARIZONA	NO	NO	NO	YES	NONE LISTED	FEELS YOU NEED TO DETERMINE THE OBJECTIVE OF FLUSHING FLOWS E.G.REMOVAL OF SILT AND EXPOSAL OF SPAWNING BEDS OF X GRAVEL SIZES. AFTER THE PURPOSES OF THE FLUSHING FLOWS ARE ESTABLISHED, HYDRAULICS AND HYDROLOGY CAN FOLLOW.
MR. GEORGE WEDDELL	CHEIF, ENGINEERING DIVISION	ARMY CORPS OF ENGINEERS 650 CAPITOL MALL, RM 5400 SACRAMENTO, CALIFORNIA 95715	CALIFORNIA	NO	YES	NO	YES		
DR. THOMAS HASSLER		CALIF. COOP.FISH.RES.UNIT FISHERIES DEPT. HUMBOLDT STATE UNIVERSITY ARCATA, CALIFORNIA 95521	CALIFORNIA						
DR. DON ERMAN	PROFESSOR	DEPT. FORESTRY AND RESOURCE MANAGEMENT UNIVERSITY OF CALIFORNIA BERKELEY, CALIFORNIA 94720	CALIFORNIA	NO	YES	YES	YES	SPAWNING GRAVELS REARING HABITAT UNKNOWN BIOLOGICAL RESET MECHANISIMS.	HAS BEEN INVOLVED WITH CONSIDERABLE RESEARCH. HE FEELS THAT FORMALIZED APPROACH IS FINE, BUT NOT A SINGLE METHOD.
DR. PETER MOYLE		DEPT.WILDLIFE AND FISHERY BIOLOGY UNIVERSITY OF CALIFORNIA DAVIS,CALIFORNIA 95616	CALIFORNIA	NO	NO	NO	YES	SPAWNING REARING HABITAT RIPARIAN HABITAT MAINTENANCE LIMIT INTRODUCED FISHES.	
MR. JEFF KERSHNER		HYDROLOGIST U.S.FOREST SERVICE ELDORADO NATIONAL FOREST 100 FORNI ROAD PLACERVILLE, CALIF. 95667	CALIFORNIA	YES	NO	NO	YES	SPAWNING GRAVEL REARING HABITAT	METHODOLOGY SHOULD BE CONSISTENT WITH CHANNEL MAINTENANCE.
MR. JAMES SCHULER		STATE OF CALIF. DEPT.FISH AND GAME 1416 9TH ST. SACRAMENTO,CALIF 95814	CALIFORNIA	YES	YES	NO	YES	SPAWNING GRAVELS REARING HABITAT CHANNEL MAINTENANCE RIPARIAN HABITAT	HAVE USED TENNANT METHOD AND HEC PROGRAMS. REGULATED SYSTEMS TEND TO ASSUME NEW MORPHOLOGICAL CHARACTERS.
MR. JODY HOFFMAN		U.S.F.W.S. 2800 COTTAGE WAY SACRAMENTO, CALIFORNIA 95825	CALIFORNIA						
DR. ERIC BERGERSEN		COLORADO COOPERATIVE FISHERY RESEARCH UNIT RM 201,WAGAR BLDG. FORT COLLINS, COLORADO 80523	COLORADO						
MR. RICK ANDERSON		COLORADO DIVISION OF WILDLIFE 2126 NORTH WEBER COLORADO SPRINGS, COLORADO 80907	COLORADO						
MR. JOHN WOODLING		COLORADO DIVISION OF WILDLIFE 6060 BROADWAY DENVER,COLORADO 80216	COLORADO						

NAME	TITLE	ADDRESS	STATE	METHOD	EFFECT	RESEARCH	STANDARD	CONCERNS	COMMENTS
DR. KURT FAUSCH	ASSISTANT PROFESSOR	DEPT.FISHERY AND WILDLIFE BIOLOGY COLORADO STATE UNIVERSITY FORT COLLINS,COLORADO 80523	COLORADO	YES	NO	NO	YES	NONE LISTED	BELIEVES MORE THAN PEAK FLUSHING FLOWS WILL PROVE IMPORTANT. LESSER FLOWS OF GREATER FREQUENCY DO MORE TO CHANNEL MAINTENANCE.
DR. CLAIR STALNAKER		INSTR.FLW.AQUAT.SYS.GRP. U.S.F.W.S. 2625 REDWING ROAD FORT COLLINS, COLORADO 80526	COLORADO						
DR. ROBERT MILHOUS		INSTR.FLW.AQUAT.SYS.GRP. U.S.F.W.S. 2625 REDWING ROAD FORT COLLINS, COLORADO 80526	COLORADO	YES	NO	YES	N/Y	SPAWNING GRAVELS CHANNEL MAINTENANCE REARING HABITAT RIPARIAN HABITAT	NEED A COLLECTION OF METHODS RATHER THAN SINGLE STANDARD. IFASG IS INVESTIGATING FLUSHING FLOW NEEDS AND TECHNIQUES FOR ITS ASSESSMENT.
MR. RICHARD MOORE		REGIONAL FISHERY BIOLOGIST U.S. FOREST SERVICE BOX 25127 DENVER,COLORADO 80225	COLORADO						
DR. JOHN PETERS		U.S. BUREAU OF REC. ENGINEER.RES. CENT. P.O.BOX 25007 DENVER FED. CENT. DENVER,COLORADO 80225	COLORADO						
MR. JAMES WEATHERRED		WATERSHED SYSTEMS DEV. GRP USDA FOREST SERVICE 3825 E. MULBERRY ST. FORT COLLINS,COLORADO 80524	COLORADO						
DR. FRED THEURER	RESEARCH ENGINEER	U.S. SOIL CONSERVATION SVC. AGRICULTURE RESEARCH SERVICE FORT COLLINS,CO 80522	COLORADO	YES	NO	YES	YES	SPAWNING GRAVELS CHANNEL MAINTENANCE	INVOLVED IN PROJECT EVALUATING SEDIMENT INTRUSION AND DEPOSITION.
DR. EDMUND ANDREWS	RESEARCH HYDROLOGIST	U.S.G.S. BOX 25046,DFC DENVER, CO. 80225	COLORADO	YES	YES	YES		SPAWNING GRAVELS CHANNEL MAINTENANCE RIPARIAN HABITAT	NEED TO DEFINE CRITICAL HABITATS AND FLOW CONDITIONS NEEDED TO MAINTAIN
DR. JIM O'BRIEN	PROFESSOR	CIVIL ENG. DEPT. COLORADO STATE UN. FORT COLLINS, CO.	COLORADO	YES	YES	Y/N	YES	CHANNEL MAINTENANCE SPAWNING GRAVELS	A SINGLE METHOD IS PROBABLY NOT PRACTICAL. INVOLVED IN SEDIMENT STUDIES ON YAMPA RIVER.
MR. DAVID ROSGEN	HYDROLOGIST	U.S.F.S. REGION2 FORT COLLINS, CO.	COLORADO	YES	YES	Y/N	YES	CHANNEL MAINTENANCE RIPARIAN HABITAT	USFS IS PUBLISHING A PROCEDURE DOCUMENT FOR RECOMMENDING CHANNEL MAINTENANCE FLOWS.
MR. DARRELL CLAPP	BUREAU CHIEF(TECHNICAL SERVICES BUREAU)	DIRECTOR IDAHO DEPT. WATER RESOURCES STATEHOUSE BOISE,IDAHO 83720	IDAHO	NO	NO	NO	YES		
DR. TED BJORNN	Leader, ICFRU	IDAHO COOPERATIVE FISHERY RESEARCH UNIT UNIVERSITY OF IDAHO MOSCOW, IDAHO 83843	IDAHO	NO	NO	YES	YES	SPAWNING GRAVEL REARING HABITAT	THEY HAVE BEEN INVOLVED WITH STUDIES ON SEDIMENTATION AND PRODUCTIVITY OF SALMONID STREAMS.
DR. TIM COCHNAUER	FISHERIES RESEARCH BIOLOGIST	IDAHO DEPT. FISH AND GAME 1540 WARNER AVE LEWISTON, IDAHO 83501	IDAHO	YES	NO	NO	YES	SPAWNING	PRESENTLY USE TENNANT'S METHOD(200% OF THE MEAN ANNUAL DISCHARGE OVER A TWO WEEK PERIOD).EXPANSION OF TENNANT'S RECOMMENDATION MAY PROVIDE A BETTER GENERALIZED APPROACH.FEELS THAT EVERY SYSTEM WOULD BE DIFFERENT DEPENDING ON GRADIENT,DEPOSITION,ETC.

NAME	TITLE	ADDRESS	STATE	METHOD	EFFECT	RESEARCH	STANDARD	CONCERNS	COMMENTS
MR. WILLIAM HORTON	FISH RESEARCH BIOLOGIST	IDAHO DEPT. FISH AND GAME 2320 GOVERNMENT WAY COEUR D' ALENE, IDAHO 83814	IDAHO	YES	NO	NO	YES	SPAWNING GRAVELS	TENNANT METHODOLOGY TO ASSIGN FLUSHING FLOWS, HOWEVER, HAVE NOT EVALUATED RECOMMENDATIONS ON SPAWNING GRAVEL CLEANSING.RECOMMENDS CONTROLLED EXPERIMENTS IN IDENTICAL CHANNNELS EVALUATING DIFFERENT VELOCITIES AND DISCHARGES ASSOCIATED WITH HIGH FLOWS.
DR. DAVID BURNS	FOREST FISHERIES BIOLOGIST	U.S.FOREST SERVICE MCCALL,IDAHO 83638	IDAHO	YES	NO	YES	YES	SPAWNING REARING HABITAT CHANNEL MAINTENANCE RIPARIAN HABITAT MAINTENANCE	RECOMMENDS INTEGRATION OF IFIM WITH F.S. CHANNEL MAINTENACE METHODS. HAS USED PHABSIM WITH SUBSTRATE IMBEDDEDNESS REFERENCES PROVIDED, NEXT STEP IS TO GET THE HYDRAULIC SIMULATION FOR FLUSHING FROM F.S. METHODOLOGY BUILT INTO I.F.I.M.
DR. WILLIAM PLATTS	RESEARCH BIOLOGIST	U.S.FOREST SERVICE INTER.FOREST AND RANGE EXP. STN. BOISE, IDAHO 83702	IDAHO	YES	YES	YES	YES	MAINTAINING GOOD FISHERY HABITAT CONDITIONS	TRANSPORT SYSTEM ON S.F. SALMON RIVER TO FOLLOW SEDIMENT CHANGE VS. USGS GAUGE STATION. FEELS NATURAL FLUSHING FLOWS ARE ALSO IMPORTANT IN DETERMINATION OF REQUIRED FLOWS OF SIGNIFICANT MAGNITUDE.
DR. RICHARD OLSEN		ARGONNE NATIONAL LABORATORY ENVIRON.RES.DIV. 9700 S.CASS AVE. ARGONNE,ILLINOIS 60439	ILLINOIS	NO	NO	YES	YES	SPAWNING GRAVELS CHANNEL MAINTENANCE	FLUSHING FLOWS BECOMING IMPORTANT IN HYDROELECTRIC DEVELOPMENTS (FERC)
MR. PAT GRAHAM		FISH.RES.AND SPEC.PROJ.BUR. MONTANA DEPT.FISH.WILD.AND PARKS BOX 67 KALISPEL,MONTANA 59901	MONTANA						
DR. ROBERT WHITE	LEADER	MONTANA COOPERATIVE FISHERY RESEARCH UNIT DEPT. BIOLOGY MONTANA STATE UNIV. BOZEMAN, MONTANA 59717	MONTANA	NO	NO	NO	YES	SPAWNING GRAVELS REARING HABITAT	SUGGESTS MEAN HISTORICAL DISCHARGE-SEDIMENT TRANSPORT MODELS. ALSO TO INCLUDE FLUME STUDIES.
MR. FRED NELSON	FISHERIES BIOLOGIST	MONTANA DEPT. FISH,WILD.,AND PARKS 8695 HUFFINE LANE BOZEMAN MONTANA 59715	MONTANA	NO	NO	NO	NO	SPAWNING GRAVELS CHANNEL MAINTENANCE	ATTACHED INSTREAM FLOW METHODOLOGY FOR WATERWAYS IN WESTERN MONTANA. METHODOLOGY FOR HIGH FLOW PERIOD-STREAM AND RIVERS. DOMINANT DISCHARGE.
MR. PAUL BROUHA		U.A. FOREST SERVICE P.O.BOX 7669 MISSOULA,MONTANA 59807	MONTANA						
MR. WILLIAM McLELLAND	FISHERIES BIOLOGIST	CHIEF OF FISHERIES NEVADA DEPT. OF WILDLIFE BOX 10678 RENO, NEVADA 89520	NEVADA	NO	NO	NO	YES	SPAWNING GRAVELS RIPARIAN HABITAT MAINTENANCE	THEY HAVE NO FUNDING FOR STUDIES OF THIS TYPE.
DR. CLARENCE SKAU		DEPT. INTERDISCIPLINARY HYDROLOGY UNIVERSITY OF NEVADA RENO,NEVADA 89557	NEVADA						
DR. PAUL TURNER		DEPT.FISHERY AND WILDLIFE SCIENCES NEW MEXICO STATE UNIVERSITY LAS CRUCES, NEW MEXICO 88003	NEW MEXICO						
MR. FRANK HALFMOON	PROJECT LEADER	U.S.F.W.S. P.O.BOX 1403 GALLUP,NEW MEXICO 87301	NEW MEXICO	NO	NO	NO	YES	REARING HABITAT	FEELS THAT THERE SHOULD BE A SYSTEMATIC EVALUATION OF TECHNIQUES AND METHODOLOGIES WHICH ARE CURRENTLY IN USE.

NAME	TITLE	ADDRESS	STATE	METHOD	EFFECT	RESEARCH	STANDARD	CONCERNS	COMMENTS
MR. CARL COURET	FISH AND WILDLIFE BIOLOGIST	U.S.F.W.S. P.O.BOX 4487 ALBUQUERQUE, NEW MEXICO 87196	NEW MEXICO	YES	NO	NO	YES	SPAWNING GRAVELS	ADEQUATE FLOW IS SOMEWHAT LESS THAN THAT WHICH WOULD TRANSPORT SPAWNING MATERIAL(E.G. GRAVEL). HAS USED I.F.I.M. METHODOLOGY. SEDIMENT TRANSPORT MODEL SHOULD BE DEVELOPED FOR FLOW RANGES AND FIELD CHECKS TO NARROW RANGES AND DETERMINE DURATIONS.
MR. TOM VOGEL		FISHERIES BIOLOGIST BONNEVILLE POWER ADM. P.O.BOX 3621 PORTLAND, OREGON 97208	OREGON	NO	NO	NO	NO	SPAWNING GRAVELS	SUGGESTS MORE EMPHASIS BE PLACED ON PRACTICAL MEASURES WHICH PREVENT SEDIMENT DEPOSITION.
DR. HIRAM LI		OREGON COOP.FISH.RES.UNIT DEPT.FISH.AND WILD. OREGON STATE UNIVERSITY CORVALLIS,OREGON 97331	OREGON						
MR. FRED LOUIS	FISH AND WILDLIFE BIOLOGIST	OREGON DEPT.FISH AND WILD. 506S.W.MILL ST. P.O.BOX 3503 PORTLAND,OREGON 97208	OREGON	YES	N/A	N/A	N/A	NONE INDICATED	REFERRED TO STUDY ON REGULATED FLOW EFFECTS ON FLUSHING AND SEDIMENTATION ON THE DESCHUTES RIVER MAIN STREAM.
MR. DEAN MARRIAGE	BIOLOGIST	REGIONAL BIOLOGIST SOIL CONS. SERV. 209 FEDERAL BLDG. 511 N.W. BROADWAY PORTLAND,OREGON 97209	OREGON	NO	NO	YES	YES	SPAWNING GRAVELS	WAS INVOLVED IN A STUDY ON SEDIMENT TRANSPORT, WATER QUALITY AND CHANGING BED CONDITIONS, TUCANNON RIVER, WASHINGTON. SUGGESTS APPROACH OF CONTROLLING RELEASES OF WATER FROM STORAGE AND SAMPLING DOWNSTREAM BOTH SEDIMENTS AND SUBSTRATE.
MR. RICHARD JOHNSON	HYDRAULIC ENGINEER	U.S.F.W.S. LLOYD 500 BLDG. SUITE 1692 500NE MULTNOMAH ST. PORTLAND, OREGON 97232	OREGON	YES	NO	NO	YES	SPAWNING	USES VISUAL OBSERVATION METHODS FOR EVALUATING FLUSHING FLOW NEEDS.
Dr. Robert Beschta	ASSOCIATE PROFESSOR OF FOREST HYDROLOGY	SCHOOL OF FORESTRY OREGON STATE UNIVERSITY CORVALLIS,OREGON 97331	OREGON	NO	YES	YES	YES	SPAWNING REARING HABITAT	INVOLVED IN SEDIMENT TRANSPORT(SUSPENDED AND BEDLOAD)AND HOW THEY INFLUENCE SPAWNING GRAVELS AND CHANNEL MORPHOLOGY.FEELS THAT ADDT'L RESEARCH IS REQUIRED BEFORE DEVELOPING STANDARD METHODOLOGY.
DR. FRED EVEREST		U.S.FOREST SERVICE FOR.SCI.LAB. 3200 JEFFERSON ST. CORVALLIS, OREGON 97330	OREGON						
DR. MICHAEL SALE	RESEARCH ASSOCIATE	ENVIRONMENTAL SCIENCES DIVISION OAK RIDGE NATIONAL LABORATORY OAK RIDGE, TENNESSEE 37830	TENNESSEE	NO	NO	YES	YES	SPAWNING GRAVELS REARING HABITAT CHANNEL MAINTENANCE DEGRADATION OF HABITAT IF FLOWS TOO HIGH	HAS PARTICIPATED IN TWO PROJECTS INVOLVED WITH DETERMINATION OF RESERVOIR OPERATING RULES TO MINIMIZE IMPACTS TO DOWNSTREAM FISHERIES. INDICATES NOT MUCH WORK HAS BEEN DONE IN THIS AREA.
MR. JESSE PURVIS	HYDROLOGIST	BUREAU OF LAND MGT. 249 N. 300 EAST PRICE, UTAH 84501	UTAH	NO	NO	NO	YES	NONE PROVIDED	FEELS ESTABLISHING A METHODOLOGY WILL BE DIFFICULT BECAUSE OF DIFFERENT CONDITIONS REGIONALLY AND NATIONALLY. A CRITICAL SPECIES APPROACH MAY BE BEST FOR BIOLOGICAL NEEDS.RECREATION,WATER QUALITY,NAVIGATION ETC. WOULD REQUIRE A DIFFERENT APPROACH.
MR. JOHN BOAZE		FISHERY BIOLOGIST U.S F.W.S. 1422 FEDERAL BLDG. 125 S. STATE ST. SALT LAKE CITY, UTAH 84138	UTAH						

NAME	TITLE	ADDRESS	STATE	METHOD	EFFECT	RESEARCH	STANDARD	CONCERNS	COMMENTS
DR. REED HARRIS	CHIEF, BIOLOGICAL STUDIES	U.S. BUREAU OF RECLAMATION P.O.BOX 11568 SALT LAKE CITY, UTAH 84147	UTAH	YES	NO	NO	YES	SPAWNING GRAVEL CHANNNEL MAINTENANCE	THEY FIND FLWS ASKING FOR SEASONAL HIGH FLOWS TO SCOUR SPAWNING GRAVELS. NO FORMAL METHODOLOGY HAS BEEN DEVELOPED TO SATISFY USBOR STANDARDS.
DR. ROSS BULKLEY	UNIT LEADER	UTAH COOPERATIVE FISHERY RESEARCH UNIT UTAH STATE UNIVERSITY LOGAN, UTAH 84322	UTAH	NO	NO	NO	YES	NONE LISTED.	THEY HAVE NOT DONE ANY WORK IN THIS AREA.
Dr. John Orsborn	PROFESSOR	ALBROOK HYDRAULICS LAB WASHINGTON STATE UNIVERSITY PULLMAN, WASHINGTON 99164	WASHINGTON	NO	NO	YES	YES	SPAWNING GRAVELS REARING HABITAT CHANNEL MAINTENANCE	MUST BE BASED ON THE FLUID MECHANICS AND HYDRAULIC GEOMETRY OF THE REACH INCLUDING THE BED SIZE DISTRIBUTION AND CEMENTED CONDITION, AND BASIN CHARACTERISTICS INCLUDING USES.FEELS THAT TENNANTS USE OF 200% IS NOT RIGHT,FLOOD RANGES ARE 600-1500 % .
DR. DALE BECKER	SENIOR RESEARCH BIOLOGIST	BATTELLE PACIFIC NORTHWEST LABORATORIES BATTELLE BLVD RICHLAND,WASHINGTON 99352	WASHINGTON	NO	NO	YES	YES	SPAWNING GRAVELS	AERIAL PHOTOGRAPHY AND ON SITE STUDIES HAVE BEEN USED TO QUANTIFY ENCORACHING VEGETATION. SUGGEST USE OF RADIOACTIVE SPIKES TO MONITOR EFFECTIVENESS.
MR. JAY HUNTER		DISTRICT FISHERIES BIOLOGIST WASHINGTON DEPT. GAME 905 HERON ABERDEEN, WASHINGTON	WASHINGTON						
DR. QUENTIN STOBER	PROFESSOR OF FISHERIES	FISHERIES RESEARCH INSTITUTE SCHOOL OF FISHERIES UNIV. WASHINGTON SEATTLE,WASHINGTON 98195	WASHINGTON	NO	NO	YES	NO	SPAWNING GRAVELS	INVOLVED WITH STUDIES OF THE EFFECT OF MT. ST. HELENS ASH, CLEARWATER RIVER EFFECTS OF LOGGING STUDIES AND TOUTLE RIVER VOLCANIC EFFECTS STUDIES. FLUSHING FLOWS MAY BE DETERMINED IF SEDIMENT RECRUITMENT IS NIL.
DR. RICHARD WHITNEY		WASHINGTON COOP.FISH.RES.UNIT SCHOOL OF FISHERIES UNIV. WASHINGTON SEATTLE, WASHINGTON 98195	WASHINGTON						
MR. KENNETH SLATTERY	INSTREAM FLOW PROGRAM LEADER	WASHINGTON DEPT. OF ECOLOGY MAIL STOP PV-11 OLYMPIA, WASHINGTON 98504	WASHINGTON	NO	NO	NO	YES	SPAWNING GRAVELS	FEELS HYDRAULIC MODELING WILL BE NEEDED TO RELATE VELOCITY OVER THE STREAM BED TO TOTAL CHANNEL FLOW. THIS PERHAPS COULD BE TIED TO IFIM STUDIES IF SCOPED IN ADVANCE.
MR. KEVIN BAUERSFIELD		WASHINGTON DEPT. OF FISHERIES 3939 CLEVELAND TUMWATER, WASHINGTON 98504	WASHINGTON						
DR. PETER BISSON		TECHNICAL CENTER WEYERHAUSER COMPANY TACOMA,WASHINGTON 98477	WASHINGTON						
DR. HUBERT WAYNE	ASSISTANT LEADER	WYOMING COOPERATIVE FISHERY RESEARCH UNIT UNIVERSITY OF WYOMING LARAMIE,WYOMING 82071	WYOMING			YES	YES	SPAWNING GRAVELS REARING HABITAT CHANNEL MAINTENANCE RIPARIAN HABITAT	INVOLVED IN RESEARCH DIRECTLY RELATED TO FLUSHING FLOWS.
MR. THOMAS WESCHE	SENIOR RESEARCH ASSOCIATE	WYOMING WATER RESEARCH CENTER UNIVERSITY OF WYOMING P.O.BOX 3067 LARAMIE,WYOMING 82071	WYOMING	YES	NO	YES	YES	SPAWNING GRAVELS REARING HABITAT CHANNEL MAINTENANCE RIPARIAN HABITAT	DOES NOT KNOW WHETHER ONE METHOD WILL BE ADEQUATE OR SEVERAL METHODS WILL BE NEEDED FOR VARIOUS TYPES OF STREAM APPLICATIONS,HABITAT TYPES,GEOMORPHIC CHARACTERISTICS,ETC. INVOLVED IN RESEARCH PROJECT FOCUSED ON METHODOLOGY DEVELOPMENT.

Appendix D

ADDITIONAL REFERENCES NOT CITED IN TEXT RELATED TO FLUSHING FLOWS/SEDIMENT TRANSPORT

ADDITIONAL REFERENCES

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