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Aquatic Ecosystems: Fish Passage and Protection

THE ADVERSE EFFECTS TO FISHES OF PILE-DRIVING - THE IMPLICATIONS FOR ESA AND EFH CONSULTATIONS IN THE PACIFIC NORTHWEST

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Abstract

Piles are integral components of many overwater and in-water structures, providing support for piers and bridges, functioning as fenders and dolphins to protect other structures, and are used to construct breakwaters and bulkheads. While treated-wood and concrete piles are commonly used for construction of these structures, there is a growing trend toward the use of hollow steel piles. In the Pacific Northwest, several recently-reported fish-kills that occurred during the installation of piles have raised concern among Federal and state agencies charged with protecting aquatic resources. Federal concern centers primarily on implementation of Section 7 of the Endangered Species Act (ESA) and the Essential Fish Habitat (EFH) provisions of the Magnuson-Stevens Fishery Conservation and Management Act.

Injuries to fishes inflicted by pile driving are poorly studied, but include rupture of the swim bladder and internal hemorrhaging. The mechanism of injury appears to be the intense underwater pressure wave generated during some pile-driving activities. The type and intensity of the underwater sounds produced depend on a variety of factors, including, but not limited to, the type and size of the pile, the firmness of the substrate and depth of water into which the pile is being driven, and the type and size of the pile-driving hammer. In general, driving steel piles with an impact hammer appears to generate pressure waves that are more harmful than those generated by impact-driving of concrete or wood piles, or by vibratory-hammer driving of any type of pile. Of the reported fish-kills, all have occurred during impact-driving of steel piles. However, conditions required to produce sound pressure waves that can injure or kill fishes are not presently understood.

Recent reports of fishes killed during pile driving are producing changes in the way that such activities are being viewed by the Washington State Habitat Branch of the National Marine Fisheries Service during ESA and EFH consultations. These changes include requirements for hydro-acoustic monitoring of the sound pressure levels generated during pile driving, and, if maximum thresholds are exceeded, the incorporation of measures to reduce those sound pressure levels. This presentation discusses the approach taken by the Washington State Habitat Branch to address the uncertainties associated with pile driving and the adverse effects this activity may have on ESA-listed salmonids and EFH.

Biographical Sketch: In 1984, John Stadler a received B.S. degree in biology from the University of Oregon. In 1988, he received his M.S. from the School of Fisheries, University of Washington. The title of his thesis was “Feeding Biology of the Northern Clingfish, *Gobiesox maeandricus*: Diet, Morhpology and Behavior.” In 1990, John began his doctoral studies in the Department of Marine Biology and Fisheries, at the Rosenstiel School of Marine and Atmospheric Sciences, University of Washington. In 1991, he took a leave of absence from the University of Miami to work for the Interamerican Tropical Tuna Commission, at the Achotines Laboratory in the Republic of Panama. During this period, John directed the larval tuna survey program, and conducted at-sea sampling to investigate the distribution and abundance of larval Eastern Pacific tunas off the Pacific coast of Panama. John returned to the University of Miami in 1994, and received his Ph.D. degree in 2000. The title of his dissertation was “Species Recognition and Sex Discrimination by Males of the Notchtongue Goby, *Bathygobius curacao* (Pisces: Teleostei)”. Since then, John has been employed at the Washington Habitat Branch of the National Marine Fisheries Service in Lacey, Washington, where he is the Washington State Coordinator for Essential Fish Habitat.

DESIGN AND CONSTRUCTION OF AQUATIC ORGANISM PASSAGE AT ROAD-STREAM CROSSINGS

ECOLOGICAL CONSIDERATIONS IN THE DESIGN OF RIVER AND STREAM CROSSINGS

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Abstract: As long linear ecosystems, rivers and streams are particularly vulnerable to fragmentation. There is growing concern about the role of road crossings – and especially culverts – in altering habitats and disrupting river and stream continuity. Most of the culverts currently in place were designed with the principal objective of moving water across a road alignment. Little consideration was given to ecosystem processes such as the natural hydrology, sediment transport, fish and wildlife passage, or the movement of woody debris. It is not surprising then that many culverts significantly disrupt the movement of aquatic organisms.

Survival of individual animals, facilitation of reproduction, and the maintenance of population continuity are important functions of movement at a population level. Dispersal of individuals provides a mechanism for regulating population density. These dispersing individuals maintain gene flow among populations and may supplement populations where recruitment is unable to keep pace with the loss of individuals. For many small species (especially invertebrates), dispersal of individuals provides a mechanism for colonizing habitat, allowing local populations to come and go as habitat is created or eliminated, while maintaining viable regional populations.

Much attention has been focused on passage for migratory fish, especially in the northwestern U.S. In some cases, considerable resources have been invested in projects addressing fish passage only to find that accommodations made for adults did not address the needs of juvenile fish. Long-term conservation of fish resources will depend not only on passage for both adult and juvenile fish but also on maintenance of healthy stream and river ecosystems. Essential to this approach is a focus on habitat quality and strategies for aquatic organism passage based on communities rather than individual species. Without an ecosystem-based approach to river and stream crossings we will be at risk of facilitating passage for particular fish species while at the same time undermining the ecological integrity of the ecosystems on which these fish depend.

Stream simulation is an approach to culvert design that both avoids flow constriction during normal conditions and creates a stream channel within culverts that resists scouring during flood events. Designing culverts to avoid channel constriction and to maintain appropriate channel conditions within the structure is a relatively simple and effective approach for accommodating the normal movements of aquatic organisms and preserving (or restoring) many ecosystem processes that maintain habitats and aquatic animal populations.

Road networks and river systems share several things in common. Both are long, linear features of the landscape. Transporting materials (and organisms) is fundamental to how they function. Connectivity is key to the continued functioning of both systems. Ultimately, our goal should be to create a transportation infrastructure that does not fragment or undermine the essential ecological infrastructure of the land.

Introduction

As long linear ecosystems, rivers and streams are particularly vulnerable to fragmentation. A number of human activities can disrupt the continuity of river and stream ecosystems. The most familiar human-caused barriers are dams. However, there is growing concern about the role of road crossings – and especially culverts – in altering habitats and disrupting river and stream continuity.

Road and highway systems, as long linear elements of the transportation infrastructure, can result in significant fragmentation of river and stream ecosystems. Road systems and river and stream networks frequently intersect, often with significant negative consequences for river and stream ecosystems. On U.S. Forest Service and Bureau of Land Management land in Washington and Oregon alone, there are over 10,000 culverts on fish-bearing streams (US GAO 2001). Based on GIS analysis it is estimated that there are over 28,500 road and railroad crossings affecting Massachusetts streams (Pers comm. Michael Merrill, MA Riverways Program).

Most of the culverts currently in place were designed with the principal objective of moving water across a road alignment. Little consideration was given to ecosystem processes such as the natural hydrology, sediment transport, fish and wildlife passage, or the movement of woody debris. It is not surprising then that many culverts significantly disrupt the movement of aquatic organisms. For example over half of the culverts assessed on U.S. Forest Service and Bureau of Land Management (BLM) lands in Oregon and Washington are considered barriers to juvenile salmonid fish passage (US GAO 2001).

Road crossings can affect river and stream ecosystems through the loss and degradation of habitats and by disrupting ecological processes that structure and maintain these systems over time. The movement of organisms within rivers and streams is an important ecological process that can be significantly affected by road crossings.

Much attention has been focused on passage for migratory fish, especially in the northwestern U.S. In some cases, considerable resources have been invested in projects addressing fish passage only to find that accommodations made for adults did not address the needs of juvenile fish. Long-term conservation of fish resources will depend not only on passage for both adult and juvenile fish but also on maintenance of healthy stream and river ecosystems. Essential to this approach is a focus on habitat quality and strategies for aquatic organism passage based on communities rather than individual species. Without an ecosystem-based approach to river and stream crossings we will be at risk of facilitating passage for particular fish species while at the same time undermining the ecological integrity of the ecosystems on which these fish depend.

Stream simulation is one approach to road crossings that protects habitats, maintains many ecological processes, and sustains aquatic communities. With an understanding of ecological concepts, ecosystem processes, and the importance of movement for sustaining populations of aquatic organisms, it is possible to design road and highway systems that ensure the continuity of both our transportation and ecological infrastructure.

Ecology of Rivers and Streams

For an organism to survive it must have access to appropriate habitats. Habitat is a combination of physical and biological characteristics of an area (or areas) essential for meeting the food and other metabolic needs, shelter, breeding, and over-wintering requirements of a particular species. For some species habitat can be as small as individual rocks or pebbles in the streambed. For others it can include many miles of rivers, streams, floodplains, wetlands, and ocean.

At any scale – from individual rocks in a streambed to particular habitat types (riffles, pools, cascades) to an entire river system – the particular characteristics of an area will determine what species are likely to be present. The tendency of areas to form structurally and functionally distinct portions of the landscape (e.g., riffles, pools, runs, floodplains, headwater streams, tidal rivers) means that organisms that inhabit these areas often form distinct assemblages of species called communities. These communities of organisms plus the physical environment they inhabit are what constitute ecosystems.

Natural communities are more than just collections of organisms. Species that make up communities are interconnected by a variety of ecological relationships, such as nutrient cycling and energy flow, predator-prey relationships, competition, and interdependency. For example, a single stream reach may support a variety of salmonid fish species competing with each other for food and appropriate habitat. Diverse communities of invertebrates are essential for providing a food base throughout the year for fish. Disease organisms, parasites, or predators that differentially affect species will affect the balance of competition among these fish.

The presence or absence of fish can affect whether other species are able to utilize river or stream habitats. Many amphibians require aquatic habitats that are free of fish in order to successfully breed. These species may utilize floodplain pools or intermittent sections of streams as long as fish are not regularly present. On the other hand, numerous species of North American freshwater mussels require specific fish hosts in order to complete reproduction. Larval stages of these mussels, known as glochidia, attach themselves to the gills or fins of host fish (or in one case, host salamanders), a process essential for dispersal and proper development. The nature of these interdependencies is such that freshwater mussels are unable to occupy otherwise appropriate habitat if their particular fish hosts are not present.

Other ecosystem processes that affect the composition and balance of organisms within a community include hydrology, the movement of sediment, woody debris, and other organic material, and natural disturbances that can significantly change the physical and biological characteristics of ecosystems.

As the defining feature of aquatic systems, the amount, distribution, movement and timing of water is a critical factor shaping aquatic communities. Many organisms time their life cycles or reproduction to take advantage of or avoid specific hydrological conditions. Flowing waters also transport sediment downstream, changing the substrate characteristics of areas contributing and receiving the material. Sediment lost downstream is generally replaced by material transported from farther upstream. Woody debris is both a habitat feature for many species and a factor that can significantly change the physical and biological characteristics of streams. Debris dams or partial dams (deflectors) can create pools and scour holes, and change patterns of sediment deposition within the stream channel.

Natural disturbances such as floods, drought, and ice scour can disrupt more regular cycles of stream flow, sediment transport, and the amount and distribution of woody debris. However, even these disturbances are part of larger patterns of physical and biological change that help define aquatic ecosystems. In fact, these more extreme events are generally responsible for defining channel characteristics.

Importance of Animal Movement

Organisms too, move through river and stream ecosystems. These range from regular movements necessary to access food, shelter, mates, nesting areas, or other resources, to significant shifts in response to extreme conditions brought about by natural disturbances.

Animals move through rivers and streams for a variety of reasons. Some are regular daily movements to find food and avoid predators. It is not unusual for aquatic animals to forage at night and seek shelter during the day. Changes in habitat conditions, such as temperature, water depth or flow velocity, may require organisms to move to areas with more favorable conditions. During the summer, for example, many salmonid species move up into cool headwater streams to avoid temperature stress in mainstem waterways. When conditions become too dry, these animals shift to areas with suitable water.

Some animal movements are seasonal in nature and are linked to the reproductive biology of the species. During the breeding season animals move to find mates and smaller individuals may have to move to avoid areas dominated by larger, territorial adults. A common strategy among river and stream fishes is to segregate habitats used by adults from those used by juvenile fish. Adult fish typically use habitats in areas of deeper water and more stable hydrology than those in which they spawn. They migrate to spawning areas that have higher productivity or fewer predators such as floodplains and headwater streams. In these areas recently hatched fish can take advantage of decreased predation or higher productivity with the large number of juveniles compensating for the risks inherent in these more variable habitats.

Adult salmon live in the ocean until the breeding season when they migrate long distances to reach spawning streams. As they become larger, juvenile salmon hatched in these streams make their way downstream to the ocean, where the large marine food base can support much higher growth rates than can be supported in freshwater environments. Other fish species make similar, but less dramatic migrations to reach spawning habitats. Pike and pickerel move into vegetated floodplains to spawn. Many "non-migratory" fish (e.g., some species of trout, suckers, and freshwater minnows) utilize headwater streams as spawning and nursery habitat.

In contrast to fish, many stream salamanders utilize intermittent headwater streams as adults, but deposit their eggs in areas with more stable hydrology. The semi-aquatic adults can readily move up into headwaters to exploit the productivity of these areas. Their less mobile larvae are aquatic and need areas of more stable hydrology.

In dynamic environments, like rivers and streams, the location and quality of habitats are ever-changing. Flooding and woody debris work together to shape river and stream channels, water depth, and flow characteristics, creating a shifting mosaic of habitats within riverine systems. For a time, fisheries biologists thought that fish like trout generally stayed put, except for specific periods of movement for breeding or to avoid unfavorable conditions. However, it now appears that a significant proportion of these fish make regular movements that allow individuals to locate and exploit favorable habitat within this ever-shifting mosaic.

Animal movement has several important ecological functions responsible for maintaining populations, and ecosystems. In the flowing waters of rivers and streams there is a tendency for organisms and nutrients to shift downstream. The upstream movement of individuals counters this biological displacement and returns nutrients to upstream portions of these systems. Among aquatic communities, the movement of animals helps maintain the balance between predators and prey and facilitates more efficient utilization of food-based energy within the system.

Although movement and migration present obvious advantages for organisms, individual animals live and die. It is populations, operating in the context of ecosystems, which persist over time. Animal movements are important for maintaining continuous populations and it is constraints on movement that typically delineate one population from another. The ability of a population to remain genetically viable and persist over time is related to its size and the degree of interaction with other populations of the same species.

Because smaller and more isolated populations are vulnerable to extinction, conservation biologists use general rules of thumb for populations that are likely to remain viable in the short term and over the long term. *Minimum viable population* is a concept based on computer models of population change over time. Over the short term, depending on a species' life history characteristics, the minimum viable population size ranges from 50 to 200 or more individuals (Franklin 1980, Soulé 1980). For long-term viability, estimates of minimum population size range from 500 to 5,000 or more individuals. Given the narrow, linear configuration of streams and rivers, animal movements are critical for maintaining populations large enough to remain viable.

Smaller populations may be able to persist, despite their small size, if they are connected to larger, regional populations. Connections occur when individuals move from one population to another. For some species, dispersing juveniles are responsible for these movements between populations. For other species dispersal occurs via adults. Such movements maintain gene flow among populations, helping to maintain genetic health. They may also represent movements of surplus animals from one population to another, perhaps one that could not support itself on its own reproduction. This supplementation of failing populations from "source" populations is referred to as "the rescue effect." Finally, areas of appropriate habitat that may be temporarily vacant due to local extinctions, can be re-colonized by individuals from populations nearby.

Movement Capabilities of Aquatic and Riparian Organisms

The timing of some animal movements may be predictable – reflecting daily or seasonal movements – but vary according to species. Seasonal spawning migrations can be affected by environmental conditions, such as water temperature or velocity. Other movements are in direct response to changing conditions (food availability, temperature, oxygen levels, water levels and flow velocities) either to take advantage of opportunities (access to floodplains) or to avoid adverse conditions.

All animal species within river and stream ecosystems must move for populations to persist. Movements may be between areas of shallow and deeper water or between the water's edge and mid-stream areas. Animal movements may be downstream (intentionally or unintentionally) or upstream. Also important are movements between the stream channel and adjacent floodplains. For rivers with large floodplains these movements are especially important.

Some organisms are capable of moving only relatively short distances unless displaced by floods or when attached to other animals or woody debris. Others – such as migratory fish – are strong swimmers with the capacity for long-distance movements and the ability to move upstream against strong currents. In between, are a whole host of species: some with the capacity for strong bursts of swimming, but with a tendency to stay put, and others – some crayfish for example – that are capable of long-distance movements, but typically crawl rather than swim.

For fish, swimming ability is highly variable among species. The danger in using data on the swimming abilities of fish to design river and stream crossings is that we have the most information about strong swimmers (migratory fish) and know very little about the majority of fish species, especially small fish (including juveniles). We know even less about the swimming abilities of non-fish species that inhabit rivers and streams.

There are a number of relatively large aquatic animals that inhabit streams and rivers but are rarely considered in terms of barriers to movement. Much of the U.S. supports large species of aquatic salamanders. Mudpuppies, waterdogs, hellbenders, sirens, and amphiumas are salamanders that are fully aquatic and range in adult size from about a foot to over three feet in length. The Oklahoma salamander and the Pacific giant salamanders of the west coast are other aquatic or semi-aquatic salamanders that are vulnerable to movement barriers. Significant portions of the U.S. support softshell and musk turtles, aquatic reptiles that rarely travel overland. Amphibians and reptiles are not strong swimmers (relative to migratory fish), yet movement and population continuity is essential to the survival of their populations.

Although some crayfish can travel overland, many species are fully aquatic. Some have been documented moving long distances within streams and all probably depend on smaller scale movements to maintain continuous and interconnected populations. In headwater stream systems of the Ozarks and southern Appalachians, crayfish are dominant components of these ecosystems, rivaling aquatic insects in importance. Many headwater populations have been isolated long enough (due to natural conditions) to become separate species. In these regions of the U.S., headwater streams support many rare crayfish with very limited distribution. Further population fragmentation could imperil entire species of crayfish.

As a group the most vulnerable animal species in the U.S. are freshwater mussels. Over 70 percent of the 297 species native to the U.S. and Canada are endangered, threatened or of special concern (Williams 1993). Although adult mussels have a very limited capacity for movement, dispersal typically occurs when larvae (glochidia) attached themselves to host fish or salamanders. Therefore, survival and persistence of freshwater mussel populations is dependent on the capacity of host fish to move through river and stream systems. As it turns out, many of the most endangered mussels depend on small, sedentary host fish that are typically weak swimmers, and therefore, highly vulnerable to movement barriers.

River and stream ecosystems contain many other species for which we know little except that they probably have limited capacities for movement. These include worms, flatworms, leeches, mites, amphipods, isopods, and snails. Collectively, these often overlooked taxa account for a significant amount of the biomass and diversity of river and stream ecosystems. For most, swimming ability is less relevant than the ability to move through streambed substrates. Although large numbers of invertebrates can often be supported in relatively small areas, appropriate habitats may be patchy and dynamic. In these situations, a regional population is generally maintained through regular cycles of local extinction and recolonization.

Many weak swimmers and crawling species take advantage of boundary zones along bank edges and the stream bottom where water velocities are much lower than in the water column. Maintenance of unfragmented stream bottom and bank edge habitats is the best strategy for maintaining continuous and interconnected populations for these species.

In addition to aquatic organisms, rivers and streams are used as travel corridors by riparian wildlife. These include semi-aquatic species such as muskrat, mink, otter, frogs, stream salamanders, turtles, and snakes. River and stream systems provide vital links for both aquatic and semi-aquatic riverine species within the larger landscape. In developed areas, rivers and streams often represent the only available travel corridors for many terrestrial species as well.

Potential Adverse Impacts of River and Stream Crossings

There are a number of ways for a road to cross a river or stream. These include bridges, fords, open-bottom or arch culverts, box culverts, and pipe culverts. Depending on the type of crossing, its size, method of installation, and maintenance, a road crossing may have many or relatively few adverse impacts on a river or stream ecosystem.

Habitat Loss and Degradation

Replacement of natural streambed and banks with an artificial crossing structure will usually result in the loss of some habitat value. Culvert crossings provide very little habitat within the culvert. Some habitat can be provided if the culvert is sufficiently embedded such that the substrate in the culvert resembles that in the natural streambed. Open-bottom or arch culverts and bridge crossings often maintain natural streambeds, although some habitat may be lost to footings, piers, and abutments. Fords may or may not significantly affect habitat at the crossing, depending on how much the streambed and banks were altered to create the ford.

Erosion and sedimentation are two significant impacts of road crossings. Some of this may occur during construction if best management practices (BMPs) are not used. On-going erosion of embankments, the road surface, and drainage ways are of more long-term concern. Sedimentation degrades river and stream habitats by increasing suspended solids in the water and altering downstream substrate and channel characteristics. Increased turbidity in the water can adversely affect visual predators and increase the amount of inorganic particles (relative to organic particles) available to filter feeders downstream.

Stormwater runoff from the road surface may contain contaminants that are toxic to aquatic organisms. Crossings may also have hydraulic effects on stream systems. Where crossings constrict the stream or river, water typically ponds upstream and may result in the accumulation of sediment above the crossings. Below crossings, increased velocities caused by the constriction can scour streambeds, creating scour pools and removing all but the coarsest substrate from channels. Scouring at the downstream end of these crossings may undermine the culvert or necessitate riprap or other armoring techniques to prevent scouring. Such scouring can also result in drops at culvert outlets that function as barriers to animal movement.

Alteration of Ecological Processes

Depending on the degree to which road crossings constrict the river or stream channel, crossing structures can change the hydrology of the system by increasing the detention time of water upstream of the crossing. The more crossings on a particular river or stream the greater the potential impact on hydrology. With changes in hydrology may come changes in sediment transport (bed loading) and natural scouring of the channel during storm events or spring floods.

Large, woody debris is an important component of stream ecosystems. Where crossing structures restrict the ability of woody debris to pass downstream, crossings can inhibit or prevent the formation of natural debris dams and deflectors that are important habitat features for fish and wildlife, and play an important role in shaping channel characteristics.

The movement of organisms within rivers and streams is an important ecological process that can be significantly affected by road crossings. There are a variety of ways that crossing structures can impede or prevent the movement of animals.

Inlet or outlet drop. Elevation drops at either the inlet or outlet of a crossing structure can represent physical barriers to many animal species. Piping (water flowing through the fill material rather than the culvert) and scouring can result in culverts that are perched above the stream channel making passage impossible for most aquatic species.

Physical barriers. Animal movement can be blocked by clogged or collapsed culverts. Also, weirs or baffles associated with crossing structures can create barriers for some species.

Excessive water velocities. Water velocities can be too high to pass fish or other organisms during some or all of the year.

Absence of bank-edge areas. Passage by weak-swimming organisms can be inhibited or prevented by the absence of bank-edge areas within crossing structures.

Excessive turbulence. Flow contraction at the inlet can create turbulence that inhibits or prevents animal passage.

Insufficient water depth. Absence of a low-flow channel can result in water depths too shallow to allow passage for fish or other organisms.

Discontinuity of channel substrate. Crossing structures that lack any natural substrate or contain substrates (including riprap or other armoring) that contrast with the natural stream channel create discontinuities in streambed habitats. Many benthic (streambed-dwelling) organisms are confined to the streambed and can only move through appropriate substrates. Streambed discontinuities caused by crossing structures disrupt and fragment populations of these benthic organisms.

Effects on Individual Animals and Populations

If not properly designed, road crossings can block animal movements, delay migration (a process made worse where there are many crossings), and cause physiological stress as animals expend energy passing both natural and artificial obstacles. If crossing structures are not large enough, or lack banks or other dry passage, riparian wildlife may choose to cross over the road surface rather than pass through the structure. If physical barriers are present (fencing, Jersey barriers), passage across the roadway may be blocked. Where passage over the road surface is not physically blocked but the road supports high traffic volumes, individual animals are likely to be killed trying to cross the road. For some long-lived species with low reproductive rates, such as turtles, roadkill can significantly undermine the viability of populations.

As barriers to animal movement, crossings can reduce access to vital habitats. These vital habitats can be spawning areas, nursery habitat for juvenile fish, foraging areas, refuge from predators, deepwater refuges, or seasonal habitats. With restricted access to vital habitats we would expect populations of affected fish or wildlife to be reduced in size or lost altogether.

To the extent that road crossings act as barriers to animal passage, they can fragment and isolate populations. Smaller and more isolated populations are vulnerable to genetic change and extinction due to chance events. Genetic changes may result from sampling error (“genetic drift”) that occurs in small populations, or via inbreeding depression in very small populations. Local extinctions can result from demographic chance events (e.g., change in sex ratio), natural disturbances, or human impacts. As road crossings contribute to population fragmentation and isolation they undermine the viability of animal populations.

Decreased animal movement can undermine processes that help maintain regional populations over time. Barriers to movement can block the exchange of individuals among populations, eliminating gene flow and disrupting the ability of “source” populations to support declining populations nearby. Barriers to dispersing individuals also eliminate opportunities to re-colonize vacant habitat after local extinction events.

Time and Geography

When road crossings result in the loss or degradation of habitat, impacts – such as those caused by erosion and sedimentation – are immediately obvious. Portions of streams or river may no longer provide habitat for certain species. As a result, the abundance and diversity of aquatic organisms inhabiting those stream sections changes. By contrast, adverse impacts that result from the disruption of ecosystem processes, including the restriction of animal movement, are not as obvious and may take years to fully manifest themselves.

The loss or degradation in habitat conditions that result from changes in hydrology, sediment transport, or the movement of woody debris within a stream or river, may occur over many years. The result may be the loss of critical habitat features with immediate consequences for some species. It may also result in gradual changes that, over time, reduce the amount of suitable habitat for other species. With less available habitat, populations will become smaller and more vulnerable to genetic changes or local extinctions. As these smaller areas of suitable habitat become separated by increasing amounts of unsuitable habitat, animal movements become even more important for maintaining the viability of populations.

The problem of dams, culverts and other barriers to fish passage is an obvious concern for anadromous fish. Because anadromous fish travel such long distances and must often pass many potential barriers to reach their spawning grounds, barriers to passage can result in significant and immediate impacts on these species. Where barriers prevent non-migratory animals from accessing vital habitats, populations of certain species may quickly disappear from river and stream systems. These losses may or may not be noticed, depending of whether or not the species is closely monitored. As changes in habitat or barriers to movement cause other populations to become smaller and more isolated, we can expect a gradual and continual loss of species over time. Because mechanisms for the re-colonization of habitat made vacant by local extinctions have been disrupted, species loss is most likely a cumulative process that will eventually undermine the stability of ecosystems.

The effects of population fragmentation and isolation may take years to occur, but this does not mean that they are not important. A Canadian study found that the diversity of birds, reptiles, amphibians, and plants in 30 Ontario wetlands was negatively correlated with the density of paved roads on land up to 1.2 miles from the wetlands (Findlay and Houlahan 1997). The study calculated that an increase in hard-surface road density of less than one linear mile per acre would have approximately the same impact on species richness as the loss of half the wetland area. Further analysis of the data revealed an even more significant negative relationship between roads and species richness when the road network from 1944 was used (Findlay and Bourdages 2000). The inference drawn from this was that lower species diversity today may be the result of roads and highways built many years ago. These studies indicate that, although it may take decades for the ultimate impact of roads to be apparent, the impacts can be quite significant.

Another important consideration of scale is that of landscape position and the geographic extent of impacts. Culverts are the crossing structures most often used for small streams. Little consideration is typically given to the ecology of these small streams, probably because they are perceived as being less important than larger streams and rivers. However, small streams are extremely important to the ecology of river and stream ecosystems, and they support species of fish and wildlife that are not found in larger waterways.

Small streams account for most of the total stream miles within any watershed and cumulatively provide much more habitat for aquatic organisms than large rivers. Small streams are also highly productive systems, owing to their relationships with adjacent upland habitats. These areas of high productivity are often used for spawning and nursery habitat by fish that normally inhabit larger waterways as adults. Small streams also provide important summer habitat for cold-water fish that move up into headwater streams to escape unfavorably warm conditions in ponds and rivers.

In addition to providing critical habitat for many fish species, small streams support many animals that do not occur in larger streams and rivers. These include many species of stream salamanders and crayfish, and probably countless other invertebrate species. Many rare species of crayfish are confined to a very limited number of small streams.

When considering the impacts or potential impacts of a stream crossing it is important to take into account the cumulative effect of all crossings and other barriers to movement (e.g., dams) as well as significant discontinuities (channelized or piped sections) within the watershed. The greater the number of artificial barriers and discontinuities, the more threatened the ecosystem. Because small streams make up the larger proportion of stream miles within a watershed, these headwater systems are particular vulnerable to fragmentation by road crossings. On the other hand, due to the convergent nature of stream systems, a passage barrier low down in the watershed (close to confluence with the ocean or other important water body) can block migratory fish access to entire stream networks. In setting priorities for limited resources it is critical to use a watershed perspective, evaluating restoration opportunities in terms of both habitat quality and river and stream continuity.

A Case in Point

The lack of population data over long periods of time (decades or hundreds of years) means that our understanding of population viability and vulnerability is largely based on theoretical concepts and population modeling. These theories and models predict that population extinction is more likely to occur in smaller populations and that the dispersal of individuals between populations is important for the maintenance of genetic viability and for maintaining local and regional populations in the face of population extinctions (Leigh 1981, Shaffer 1981, Fahrig and Merriam 1985, Shaffer and Samson 1985, Hanski and Gilpin 1991).

Data from field studies provide evidence to support the theories. Studies of pool-breeding amphibians for example, have shown that the probability that pool habitat will be occupied by breeding amphibians is related to the distance to, or degree of isolation from, other pools (Sjögren 1991, Edenhamn 1996, Lehtinen et al. 1999). A study of pool-breeding frogs in Europe, found that degree of isolation was correlated with genetic variability and documented remarkably high genetic distances for one population that was surrounded by roads, a motorway, and a railroad line (Reh and Seitz 1990). Other studies provide evidence for the importance of dispersal and metapopulation dynamics for maintaining amphibian populations (Gill 1978, Breden 1987, Hecnar and M"Closkey 1997, Storfer 1999, Lowe and Bolger 2002). These studies support theoretical predictions that small, isolated populations are vulnerable to genetic change and population loss, and highlight the importance of animal movement (dispersal) for maintaining local and regional populations.

One recent study provides an excellent illustration of the risks of fragmentation in riverine systems. The study by Kentaro Morita and Shoichiro Yamamoto (2002), focused on populations of white-spotted charr (*Salvelinus leucomaenis*) occupying mountain streams in Japan. The white-spotted charr is a salmonid fish that occurs as both large migrant individuals and small resident fish that normally interbreed in undammed streams. Many of the mountain streams used by charr have been fragmented by small erosion-control dams that, while they do not impound the stream, do prevent fish from moving upstream. Above these dams, charr populations are sustained only by the smaller, resident fish.

Morita and Yamamoto surveyed both dammed and undammed stream segments for the presence of charr in appropriate habitat. Based on habitat conditions they concluded that charr should have been able to establish populations in all dammed sites. Charr populations were found in all undammed sites that they surveyed, but were absent in 32.7 percent of dammed sites. The results indicated that the probability of charr occurring in dammed stream segments decreased with decreasing watershed area and increasing isolation period. Further, this study also found evidence of genetic deterioration in populations above dams, including lower genetic diversity, higher morphological asymmetry, and genetically-based lower growth rates, compared to populations below dams.

Results of this study of white-spotted charr are consistent with predictions of increased vulnerability for smaller and more isolated populations. Genetic and population consequences due to fragmentation occurred over a relatively short period of time (30-35 years). The fact that the probability of occurrence was related to watershed size indicates that the smallest populations were the most vulnerable. The relationship between isolation period and probability of occurrence suggest that additional populations may well be lost over time.

The situation of small dams on headwater streams in Japan may be comparable to watersheds in the U.S. that contain road crossings with sub-standard culverts. Culverts that block the upstream movement of fish and other organisms effectively isolate populations above these crossings. Areas with relatively small amounts of habitat upstream of the crossing will be most vulnerable to population loss. Over time, it would be expected that more and more populations will fail, and due to the disruption of metapopulation dynamics, these areas of suitable habitat are likely to remain unoccupied.

An Ecosystems Approach

The impacts of substandard crossing structures on migratory fish affect rivers and streams up and down the Atlantic, Pacific, and Gulf coasts of the United States. The importance of migratory fish as fisheries resources and the status of some as federally "threatened" or "endangered" species has focused much attention on the issue of fish passage for migratory species. As a result, a large amount of time, money, and effort have been expended to address passage barriers. Unfortunately, some efforts to promote upstream passage for adult fish have failed to provide passage for the juvenile stages of migratory fish. Strategies that focus solely on adult fish and that do not address all life stages for a particular species are unlikely to maintain populations over time.

As strategies are adjusted to address passage issues for both adult and juvenile stages of migratory fish, we must avoid replacing one type of short-term thinking with another. Even when a particular species is the primary target for management, it is impossible to develop successful management strategies that ignore the community and ecosystem context for that species. Conservation strategies that focus too much on target species – without careful planning to maintain habitat quality, passage for a broad range of aquatic organisms, and other ecosystem processes – may succeed in the short term even as they undermine long-term prospects for success.

Given the large number of species that make up river and stream communities and the almost complete lack of information about swimming abilities and passage requirements for most organisms, it is impractical to use a species-based approach for designing road crossings to address the movement needs of aquatic communities. An ecosystems approach is the most practical way to maintain viable populations of organisms that make up aquatic communities and maintain the fundamental integrity of river and stream ecosystems. Such an approach focuses on maintaining the variety and quality of habitats, the connectivity of river and stream ecosystems, and the essential ecological processes that shape and maintain these ecosystems over time.

Stream simulation is an approach to culvert design that was developed in Washington State and is now being adapted for use elsewhere. It is a design process that both avoids flow constriction during normal conditions and creates a stream channel within culverts that resists scouring during flood events. Designing culverts to avoid channel constriction and to maintain appropriate channel conditions within the structure is a relatively simple and effective approach for accommodating the normal movements of aquatic organisms and preserving (or restoring) many ecosystem processes that maintain habitats and aquatic animal populations.

Road networks and river systems share several things in common. Both are long, linear features of the landscape. Transporting materials (and organisms) is fundamental to how they function. Connectivity is key to the continued functioning of both systems. Ultimately, our goal should be to create a transportation infrastructure that does not fragment or undermine the essential ecological infrastructure of the land.

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DESIGN AND CONSTRUCTION OF AQUATIC ORGANISM PASSAGE AT ROAD-STREAM CROSSINGS

SITE ASSESSMENT AND GEOMORPHIC CONSIDERATIONS IN STREAM SIMULATION CULVERT DESIGN

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Abstract: Jackson (2003, current volume) describes the types of damage to aquatic populations and metapopulations caused by barriers to aquatic species movement along stream corridors. Road-stream crossing culverts designed in the traditional way---sized for some rare flood flow---also have predictable detrimental effects on stream channels themselves. These occur not only during floods, when culverts may plug or be overtopped, but also over time if the culvert impedes downstream movement of woody debris and sediment.

This paper describes common stream responses to culverts, such as chronic aggradation and degradation; long-term changes in stream stability due to interruption of woody debris transport; and sedimentation sustained when culverts plug and fail, etc. It also describes the range of approaches to crossing design, from a culvert sized only to pass a certain flood to valley-spanning bridges and viaducts. Stream simulation is placed in the context of other design approaches that provide more or less biological and geomorphic connectivity. Biological and geomorphic priorities and risks must be weighed against site constraints and costs to select the appropriate level of continuity for each site.

Site assessment procedures for stream simulation design are then described. These include surveying and describing the longitudinal profile and valley cross-sections, bed material assessment, and reference reach selection. Channel stability interpretations needed for design are also discussed.

Introduction

Streams are transport corridors for water, sediment, debris, and nutrients moving downstream and laterally across the floodplain, as well as for fish and other animals moving upstream. When a rigid culvert is placed in a highly dynamic stream environment, perhaps the greatest challenge involves ensuring passage continuity over time, as the stream adjusts to variable flows and other environmental changes. Observing the effects of large storms on mountain roads over the past several decades, it has become clear that traditional methods of culvert design, which size culverts to convey only floodwaters, have resulted in substantial damage to channels, roads, and aquatic and riparian habitats (Furniss et al. 1998). Such culverts typically are much smaller than the stream channel itself, and even in the absence of large floods the backwatering and scour they cause is often detrimental to aquatic habitat and to channel stability. During large floods they frequently plug with debris and may overtop the road or flow down the road ditch, adding tremendous quantities of sediment and debris to downstream reaches. A portion of the cost of this damage can be seen in ERFO (Emergency Relief Federally Owned) flood damage reports, although those reports usually do not consider the costs to aquatic species nor their habitats.

Stream simulation is a culvert design method in which the diversity and complexity of the natural streambed are created inside a culvert in such a way that the streambed maintains itself across a broad range of flows. The premise is that if streambed morphology is similar to that in the natural channel, water velocities and depths will also be similar, and the crossing should be invisible to aquatic species. The design process begins by gaining a thorough understanding of the form and process of the stream to be crossed: its hydrology, stability, adjustment potential, and history. Careful scrutiny of channel history and current form permit an understanding of the processes that maintain the channel, and of the potential changes that must be accommodated or compensated for to ensure long-term structural integrity and passage success.

Dynamic Streams -- Rigid Culverts

Except for streams that flow over non-erodible materials like bedrock or colluvium, channels are "self-formed." Wherever bed and banks are erodible, a stream adjusts its width, depth and slope to transport just the amount of water and sediment supplied by the watershed. Over the decade-to-century time scales road managers are interested in, what we normally think of as "stable" streams are actually in *quasi equilibrium* (Leopold and Maddock 1953). This refers to the fact that, although streams adjust as water and sediment inputs fluctuate, channels tend to maintain approximate equilibrium dimensions. Most crossing structures alter flow dimensions and slope, thereby changing water velocity and sediment transport capacity. Channel segments up- and down-stream often respond dramatically, with sediment depositing above and the channel bed eroding below. This can result in large elevation differences between the culvert inlet and outlet, and it can create a passage barrier at each end of the crossing. In sensitive (flat and/or erodible) channels, crossings can generate such disequilibrium that these adjustments can sometimes propagate long distances up and downstream.

Fig. 1. Channel degradation downstream (left) and fig. 2 aggradation upstream (right) of a road crossing a wide floodplain on the Superior National Forest, Minnesota.

Crossing structures also lock the stream in place in meandering streams that naturally move across the floodplain over time. As the stream continues to shift laterally, it enters the inlet at a greater and greater angle enhancing the tendency for sediment deposition and debris plugging.

During floods, narrow or poorly aligned crossings interrupt the flow of water, sediment and debris. Especially if a culvert plugs, the roadfill may fail, sometimes causing substantial damage to aquatic habitat. Cascading roadfill failures turning into debris torrents have been observed in the Pacific Northwest (Furniss et al. 1998). A plugged culvert can cause a stream to be diverted down the road ditch, and even more damage may occur as it spills over a hillside or increases flood flow in the adjoining drainage.

Fig. 3. Woody debris plugging culvert inlet.

In valleys with wide floodplains, floodwater, sediment and debris may all flow down the floodplain, too, and roadfills built up to cross the stream effectively dam the overbank flows. The channel and floodplain downstream of such a road receive less sediment and debris, and water and energy are distributed differently. The section downstream may be less able to create and maintain diverse habitats in channel and floodplain.

Progressively or catastrophically, these geomorphic effects not only put the road at risk; they also create passage barriers and damage to aquatic habitat.

What geomorphic principles can be used to fit a rigid structure into a dynamic stream/valley system? The key is to permit water, sediment and debris transport through the crossing by maintaining natural channel dimensions and slope through the structure, and considering flow through the entire riparian area.

- Locate crossings to avoid unstable landforms and those where river channel change is expected, such as wide flat valley floors.
- Maintain channel dimensions and slope through the crossing structure in order to maintain sediment and debris transport capacity during frequent high flows. Otherwise, channel adjustments will occur that can (1) require maintenance or replacement, and/or (2) cause severe damage to stream and/or floodplain habitats.

- The adjacent valley floor must be considered in design of both the crossing structure and its approaches. Overbank and down-valley flows of water, sediment and debris over the floodplain need to be maintained to allow the valley to continue to (1) form diverse habitats and (2) regulate water quantity and quality in channel.
- Design all crossings for failure, acknowledging the possibility that any design peak flow may be exceeded and that road washouts can add significant quantities of sediment to the aquatic system. All crossings should be designed either to sustain overtopping flows or to fail in a predictable way that minimizes channel damage.

There may be conflicts between accommodating fluvial processes through the crossing vs. traffic on the road. The necessary compromises should be made with a clear understanding of risks to both systems, and the cost/benefit trade-offs, including effects on aquatic habitats and populations.

Setting Specific Objectives for Crossing Replacements

Design objectives for a site control what structure type and design approach are selected. They involve biological, geomorphic, traffic access, and financial considerations. Establishing them requires balancing the costs, benefits and risks in all those areas. It is truly an interdisciplinary exercise.

There is a continuum of design approaches to achieving biological and geomorphic continuity at stream crossings, depending on the degree of continuity the interdisciplinary team desires at a site (figure 4).

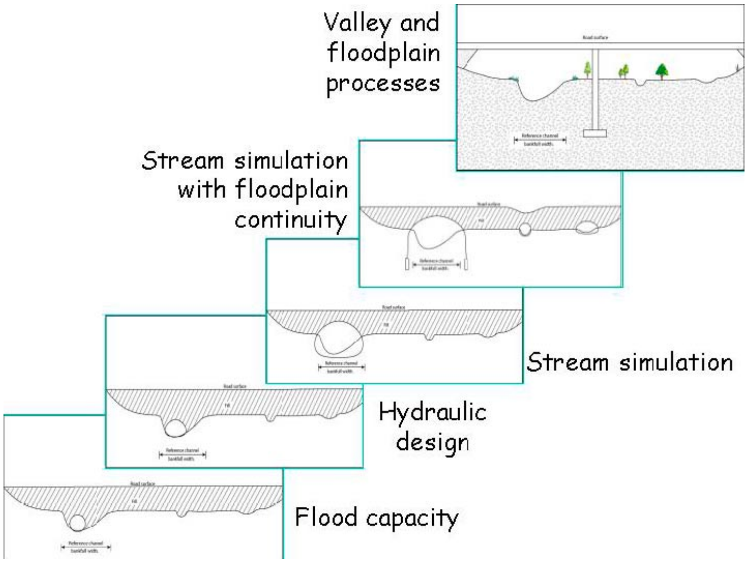

Fig. 4. Various road-stream crossing design approaches.

In valleys with very active floodplains, and especially where the valley flat may be a migration corridor for large mammals or where the full range of riparian habitat diversity must be maintained to provide critical habitat, a bridge and/or viaduct that spans the entire meander belt (or more) may be selected. On very low volume roads where traffic interruptions are acceptable, there may be other less expensive ways to maintain a high level of valley and channel connectivity, such as by the use of fords and dips.

A lesser degree of floodplain connectivity can be maintained using a stream simulation culvert or bridge with floodplain culverts or dips. In this case, floodplain pipes are placed to connect side channels, overflow channels, or swales, among other locations. This is particularly important when floodplains are wide and convey large amounts of water and debris, and/or where floodplain habitats are critical to some species or lifestages. Channel transport of debris and sediment is assured with this approach, and the streambed inside the culvert is less at risk from large flood flows than if all the flow detained by the roadfill were forced through the main channel pipe. Even so, the main pipe will probably be designed wider than bankfull width, and banks might be constructed inside. This would not only offset the higher erosive forces expected as more water is concentrated through that opening, but would also permit passage of animals preferring dry riparian passage. Side channel culverts should also be designed as stream simulation structures where aquatic species use them for refuge, rearing, etc.

Stream simulation culverts are used where passage is desired for all aquatic organisms present in the channel. These culverts have streambeds of at least bankfull width with bed longitudinal profiles and structure similar to the natural channel. Flow hydraulics at least up to bankfull must be similar to the natural channel in order to freely transport sediment and debris, and to maintain a streambed structure that offers a similar diversity of water velocities, depths, cover and bed material. The degree of match in gradient, streambed material size, distribution, and structure between channel and culvert depends again on river and site conditions. For example where an aggraded area upstream (caused by the previous structure) is desired as valuable wetland habitat and the downstream reach has downcut, a large elevation drop may need to be maintained across the structure. While some grade control work could be done on the downstream section to bring it up to original grade, the structure will still be steeper than the natural channel. In such a case, a tradeoff may be made by, for example, increasing the bed material size inside the pipe to sustain the higher shear stresses of a steeper gradient. In a different situation, such as where a narrow floodplain is present, it may be wise to expand culvert width beyond bankfull and/or slightly increase particle sizes to avoid the potential for concentrated overbank flows to erode the bed material inside the pipe.

The least inclusive approach to aquatic organism passage is hydraulic design. The objective here is passage of a target fish. Hydraulic design aims to hold velocities over a specified flow range below those believed negotiable by most individuals of a target species and lifestage. The goal is achieved by balancing culvert width, slope and roughness to produce no more than the specified velocity. It can be done with baffles and weirs, by "oversizing" the culvert (compared to those designed to pass water only), or by embedding the culvert and adding oversized roughness elements (usually rocks) to the streambed. For fish with 'known' swimming capabilities, hydraulic design may result in culverts that can pass many individuals, but weaker individuals may not pass. Weaker-swimming species or crawling species that may provide 'ecosystem services' needed to sustain the target fish over the long term may not be able to pass either.

Except for some hydraulic designs like baffled culverts, all these approaches provide larger structures that pose less of a risk to the road itself (from plugging or capacity exceedance) than culverts designed in the traditional way for flood capacity. In many environments, these structures probably have lower maintenance requirements for the same reason.

Understanding the Watershed Context

Watershed-Scale Considerations and How They Influence Structure Type Selection and Design

Culverts are non-adjustable structures in the most dynamic part of the landscape—the stream. Designers must anticipate future channel changes and design for them; if not, they risk losing the structure or its ability to pass aquatic organisms, or both. Predicting channel change requires assessment at both the watershed and project site scales. Watershed-scale assessments should occur first, to set the context for project-scale assessment.

The large-scale assessment should answer key questions about watershed and channel history, stability and sensitivity:

- Is the channel highly responsive to climatic events or watershed changes? Both may alter runoff amount and distribution and/or sediment load.
- What events and processes led to the current channel form? Is the channel "stable" or is it still responding to past events?
- What channel changes are possible during the service life of the structure? What changes are likely during the design event? Larger events?

Is the Channel Responsive?

It is useful to classify stream segments based on their sensitivity to climatic events or watershed changes. The following classes were developed by Montgomery and Buffington (1993). In mountainous areas of the Pacific Northwest, channel classes at this general level usually correspond to watershed location.

> *Source reaches* are colluvial channels at the tips of drainage networks, where sediment from the hillslopes is stored until scour occurs during large flow events or debris flows. Such channels are unresponsive until a threshold for erosion of the accumulated material is reached. These areas of the watershed are introduced here only because it is important to recognize the potentially massive effects on downstream channels when infrequent transport events—such as debris avalanches—do occur.

[Note: Strictly speaking, the term *colluvium* means materials transported to the valley floor by gravity (AGI 1962). In this article, we use it to include large rock transported to its current position by processes other than fluvial transport by the current river (e.g., debris flows, landslides, glaciofluvial transport). As used here, colluvial particles in the streambed are those that are too large for the current river to move, and that therefore act as key structural elements in a streambed.]

Transport reaches are higher gradient streams, typically with step-pool or cascade type morphology. They have persistent bed and bank structures dominated by large rock or embedded wood, and therefore tend to resist erosion. These streams are usually steep enough to transmit all the sediment supplied by the watershed to lower gradient reaches without large changes in channel size, shape or slope. They are usually (but not always) the smaller tributary streams located in the upper parts of watersheds. Floodplains are usually narrow if they exist.

Response reaches are generally found lower in the drainage network. They are lower gradient reaches with pool-riffle, plane bed or regime type morphology, and often have associated floodplains. Sediment transport capacity is low relative to supply, so when watershed or climatic changes alter sediment supply or flow regime, they often respond by making large adjustments in size, shape, slope or pattern. Because of this sensitivity, understanding off-site conditions that may affect response channels is critical for stream simulation design.

What Geologic Hazards are Present?

Each site should be evaluated for its proximity to currently or potentially unstable landforms. Look for features like

- slope stability problems such as mass wasting, debris flows, or earthflows
- inherently unstable landforms such as alluvial fans, deltas, tidal flats
- downcut channel downstream, migrating headcut
- glaciers, avalanche tracks

In general, sites like these are unsuitable for any type of culvert because of risks of plugging, channel relocation, or downcutting. For example, channels on active alluvial fans frequently change location as sediment accumulates on the fan. If an unstable site cannot be avoided, the preferable crossing structure might be a bridge rather than a culvert, to accommodate the foreseeable changes as much as possible.

Even where no “geologic hazard” is present, it is important to recognize channels that transport large volumes of woody debris and/or bed material load since this might determine whether a culvert or bridge is more practical at a site. Locations prone to deposition are especially critical to recognize, since both debris and bedload deposition can affect structure capacity and even change the local streambed slope through the crossing.

Watershed History/ Event Chronology

Knowing the history of significant episodic events (such as mass wasting, floods, dredging), as well as chronic influences--such as bankfull flows, upstream logging, road construction and mining, sedimentation, drought, and so on--contributes valuable insights about current conditions and the direction of potential future changes in the stream. Understanding how these events have altered stream plan-form and base level in the past will assist in determining structure type, site layout and structural responses to anticipated channel adjustments.

For example, in Therriault Cr in Montana, anecdotal and field evidence was used to unravel a classic story of channel degradation and plan an appropriate solution (Watershed Consulting LLC 2002). A highly sinuous, relatively stable stream channel that meandered across a wide alluvial flat had been straightened in the 1940s to increase hay production. Severe channel downcutting resulted. The headcut progressed upstream, but was stopped by a culvert, which protected the upstream channel from degradation, but prevented fish passage at the culvert. Understanding the channel degradation as a human-caused disturbance that would damage upstream reaches if allowed to progress led to a decision to maintain the elevation control at the culvert. To solve the fish passage problem, a floodplain side channel with a separate culvert was built.

Is the Channel Stable?

Taken together, these watershed-scale investigations will go a long way toward building an understanding of how much the channel may change over the life of the structure, and how sensitive the channel will be to flow changes caused by the structure. Once past responses to watershed changes are understood, responses to potential future climatic or land use changes can be predicted.

It is particularly important to identify system-wide instability, such as the downcutting described on Therriault Cr, since the design will have to account for predicted changes in the channel to achieve the goal of long-term structure stability. If a headcut is migrating upstream toward the culvert, for example, grade control structures may need to be installed downstream to avoid developing a perch and losing streambed continuity in the pipe. Distinguishing large-scale channel change from the noise of 'natural' variability in channel width, depth and slope can be difficult because variability can be large even in channels in quasi-equilibrium. This is usually accomplished using a series of historical aerial photos and any other historical accounts of the stream and watershed. System-wide instability usually can be seen on aerial photos as noticeable changes in channel width, rapid growth and movement of depositional bars, alluvial fans at tributary mouths, and so on (Grant 1988). These signals are frequently associated with observable land use changes such as mining, agriculture, subdivision and road development, or forest harvest.

Assessing the Project Stream Reach: Is Stream Simulation Appropriate?

In addition to ecological connectivity objectives, channel stability is the most important factor determining whether a stream simulation culvert is a wise choice for a site. In most cases, the same considerations apply to siting any culvert, although the larger pipes used in stream simulation may reduce the failure risks associated with smaller culverts. Some of the most common inherently unstable channel types and landforms that are best avoided are listed below.

> *Active alluvial fans* are usually located where a confined channel emerges into a wider valley, spreads out, and deposits sediment. During high debris-laden flows so much sediment may be deposited that the major channel is blocked, and flow jumps to a new location and carves a new channel. Several channels may be active at once. Crossing structures placed on fans can be isolated when the channel changes location. They can also increase the likelihood of channel shift if they frequently plug.
>
> *Very steep channels prone to debris-torrents* are another example of a landform where large sediment and debris transport events can be expected to cause significant channel changes. Even stable channel reaches, if they are immediately downstream of a slope prone to mass wasting or severe bank erosion, can be expected to undergo flow events where sediment loads are high enough to cause plugging and overtopping failure. In steep terrain, where there are many crossings on a single channel, the domino effect of a single crossing failure can cascade downstream and may actually cause a debris flow.
>
> *Braided stream valleys* where high flows can simultaneously occupy several channels are another example. These streams often have little deep-rooted, stabilizing vegetation, so streambanks erode and permit channels to shift location frequently. Crossings are frequently constructed only on the major channel with upstream levees acting as funnels to route water under the road. Downstream effects of this kind of flow concentration can include severe channel downcutting (degradation).
>
> *Unconfined meandering streams on wide floodplains* migrate across the floodplain, as banks on the outsides of meander bends erode while deposition occurs on bars on the insides of bends. Such streams are still considered stable so long as they maintain equilibrium channel dimensions and slope. Nonetheless, land development and management frequently accelerate this natural process of channel migration, and one should bear this in mind before investing in a crossing structure. A shifting channel can move such that it no longer approaches the crossing perpendicularly, and an oblique angle of approach tends to increase sediment deposition above the inlet by forcing the water to turn. Likewise it increases the potential for debris blockage and therefore overtopping failure. An additional effect of crossings on such channels is that their approaches often are built up to cross seasonally wet or inundated floodplains. Damming the floodplain obstructs the erosional and depositional processes that construct floodplains and their diverse habitats. It may obstruct side channels that are essential habitats for fish. Forcing the overbank flows to concentrate in the constricted crossing also causes bed and bank scour around the crossing.

Channels that are actively changing---aggrading, degrading, widening, etc.---whether the reason is management-related or natural, may be difficult or impossible to simulate in a culvert with any long-term success. Channels can go through a series of complex responses to environmental change, and the rate and magnitude of adjustment may not be predictable (Schumm 1977). Such channels should be spanned if they cannot be avoided, not only to preserve the crossing structure, but also to allow the channel to freely adjust toward a new equilibrium form.

Some channel types are more easily simulated inside a culvert than others (Gubernick and Bates this volume). Since the streambed inside a pipe will not have the stabilizing effects of bank vegetation, channels that are highly dependent on vegetation for stability will require its function to be simulated by some other mechanism.

The same is true of streams where woody debris plays an important role in bed stability and sediment retention. This does not mean these channels cannot be simulated, but other materials, such as rock, must replace the stabilizing functions. On very steep streams, large bed structures are hard to maintain inside a confined pipe because of extremely high stream power during larger than bankfull flows. Bedforms in such streams may be mobilized and reconstructed naturally during rare floods (Wohl 2000). Hydraulic conditions during such high flows cannot be simulated inside a confined pipe because flow cannot widen with increasing depth. Where these conditions are critical, a bridge with adequate width may be a more suitable choice than a culvert. On very low traffic or seasonal use-only roads, some types of fords may function adequately for traffic, and create only minor obstructions to channel processes and aquatic species passage.

Site Assessment for Stream Simulation Design

A stream simulation culvert must fit into the reach both laterally and longitudinally. Ideally, the streambed inside the pipe should be able to retain sediment and adjust its elevation (sustain local aggradation and scour) in the same way as the upstream and downstream reache. It must also be able to convey flood flows, including overbank floodplain flows, or the floodplain itself must be connected through the road approaches by dips or additional pipes.

The site reach assessment has two basic objectives.

- Develop a thorough understanding of reach stability and adjustment potential during flows that mobilize the streambed.

  The assessment helps the practitioner estimate how much change is likely over the life of the structure, and how sensitive the channel will be to the structure's effects. It helps the design team decide whether additional channel structures are necessary to maintain grade control downstream of the structure, and how floodplain connectivity should be provided for.

- Develop a template for bed design inside the pipe, including longitudinal profile, bedforms and cross section.

  The assessment is the source of information needed to determine channel dimensions as well as the size, slope and arrangement of streambed material inside the pipe.

The streambed design template is taken from the reference reach, which is a reach similar to the crossing reach that is judged to be in quasi-equilibrium with prevailing flows and sediment loads. Generally the reference reach can be located upstream of the crossing, out of the existing crossing influence zone if any. If so, it is included in the longitudinal profile of the site reach. Where this is not possible, such as where land use changes dramatically upstream of the crossing, or where road-induced aggradation extends long distances above it, the reference reach might be a reach morphologically similar to the crossing site, but located at some distance up- or downstream. In unusual cases, the reference reach might be a similar channel in the near vicinity. Channel types (Rosgen 1996 level II size; Montgomery and Buffington 1993) can help in judging similarity, but they should be interpreted with great care, since even nearby watersheds may have different land use and flood histories (Juracek and Fitzpatrick 2003). All the extrinsic influences on channel morphology—including drainage area, geologic context, and land use/vegetation—should be similar for a reference reach.

The site and reference reach surveys include longitudinal profile and cross section surveys, and observations of bed material and bed structure. During the surveys, we "read" the stream for clues about the magnitude of channel-forming flows, frequency and type of sediment transport events, and other channel processes like woody debris transport, beaver influences, bank erosion, and streambed aggradation and degradation potential.

The Longitudinal Profile

For the longitudinal profile, the thalweg (a line connecting the deepest parts of the channel) is surveyed with a surveyors' level in enough detail to capture all slope breaks along the channel length. The profile is usually the single most valuable tool during the design process. It shows not only the average reach gradient and major slope breaks at the site, but also any aggradation and/or degradation around existing culverts. These conditions determine elevation change required through the crossing, which can affect selection of a reference reach. In cases where the elevation difference is large, it is sometimes necessary to set the culvert at a slope steeper than the adjoining segments. For a simulation design template, one would then look for a stable reach elsewhere with the desired slope, and similar geomorphic context and materials. If one can be found, it would be used as the template assuming there is no dramatic discontinuity with the adjoining reaches.

The profile may be uniform, but in less ideal situations, grade may change dramatically near the crossing. Traditional road layout for low-volume forest roads tends to follow landscape contours, and roads are often located on flat ground at the edge of a steep slope, or on a natural bench. These different situations result in four types of stream profiles through crossings, with different culvert-related risks and design implications:

> *Concave profile:* steep stream grade transitioning to milder grade downstream (e.g., edge of valley flat). Sediment deposition above the crossing is expected here. This may steepen the grade locally, creating an adverse inlet condition for fish passage. If the area is an active alluvial fan, large-scale deposition might occur and the culvert might be plugged. Alternatively if the new culvert excavation cuts into the bed of the steeper reach and there is no upstream grade control, a headcut can form, destabilizing the upstream reach.
>
> *Convex profile:* mild slope transitioning to steeper grade downstream. Many times this is associated with a bedrock control at the break to the steeper slope. This type of profile could also occur, however, at the edge of a terrace in unconsolidated and erodible materials. Depending on how close the crossing outlet is to the grade break, the disturbance created by excavation for an embedded stream simulation culvert could destabilize the channel materials at this sensitive location. It is wise in this situation to move the road back from the grade break if at all possible.
>
> *Concave- convex profile:* steep stream grade transitioning to mild grade, then back to steeper grade (e.g., alluvial/colluvial bench). This situation has the same upstream problems as the concave type, and the same downstream problems as the convex type.
>
> *Uniform profile:* uniform grades with no abrupt transitions through the crossing. This is the ideal crossing situation.

Gubernick and Bates (this volume) give examples of design treatments for concave and uniform situations.

Permanent or persistent controls on streambed elevations in the vicinity of the crossing must be identified, and the ends of the surveyed long profile should be tied into them. The range of possible design project profiles (slope through the crossing) will be constrained by these hard controls if they exist. In general, persistent grade controls, such as a boulder step or a large piece of embedded wood, are usually frequent in transport reaches, and the surveyed long profile can be relatively short. In response reaches, though, they may be hard to find or nonexistent. Channel grade and elevation may be controlled by relatively mobile small woody debris or simply by valley slope and stream sinuosity. In these cases, the profile should be quite long to get a good idea of how bed elevations may vary over the long term.

In many alluvial streams, bedforms such as pools, riffles, and steps tend to be spaced regularly (Montgomery and Buffington 1993). Their functions---energy dissipation (velocity control) and sediment retention---are essential to simulate, and the culvert streambed must fit into their spacing pattern and match their dimensions as closely as is feasible. The survey catches all longitudinal slope breaks, including smaller scale differences such as the top and bottom of wood or boulder steps or, for a pool, the head, deepest point and tail crest elevation (figure 5).

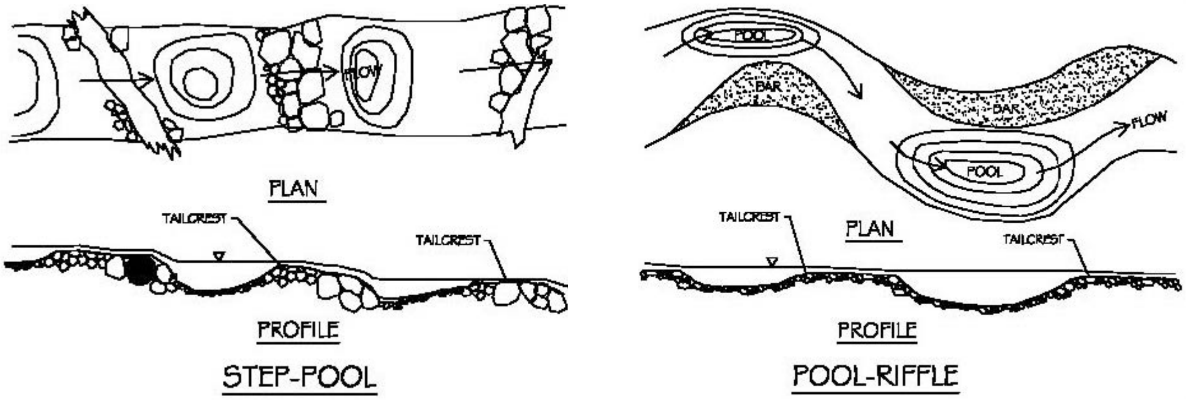

Fig. 5. Natural grade control structures and bedforms.

Streambed elevations adjust locally when grade-controlling bedforms or structures (e.g., embedded woody debris, boulder steps, etc.) shift or are washed away. The culvert streambed must be able to scour to depths similar to those in the adjoining reaches to maintain similar bed structure and water velocities. In a reach with a uniform profile, a line connecting the lowest bed elevations ---generally the bottoms of pools---represents the adjustment potential line (figure 6): the minimum elevation to which the streambed would adjust if local grade-controls move. Embedding the culvert invert below this line allows the bed material inside the structure to adjust within the range of expected changes in bed elevation. This is especially important in low-gradient response channels, which adjust their slopes more frequently than steeper channels normally do. To confidently identify the adjustment potential line, it is critical to survey pool bottom elevations, even if they are deeper than it is possible to stand.

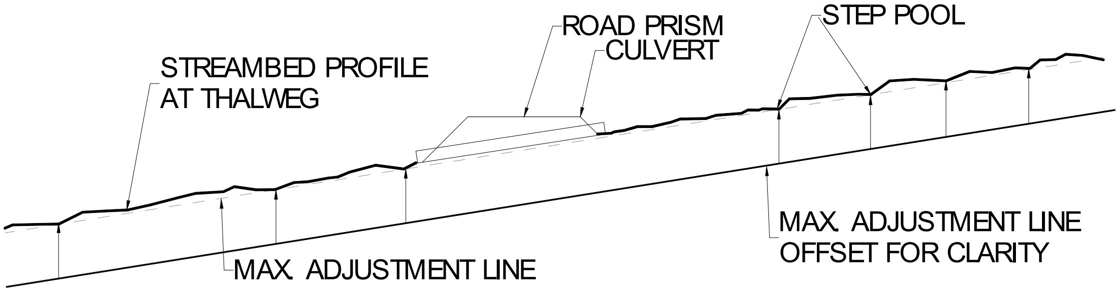

Fig. 6. Longitudinal profile and maximum adjustment line.

The designer must understand bedform stability, organization, and composition in the local channel. As the longitudinal profile is surveyed, the rod-holder makes notes on the types of bed structures and their apparent stability, as well as other significant features affecting channel stability, grade and sediment retention. As noted above, some bed structures are transitory, such as pools controlled by small decaying wood, beaver dams or steps composed of gravel. Others, like step-pools controlled by boulders or pieces of large embedded wood, can be quite stable and persistent for long periods of time (Zimmerman and Church 2001; Swanson and Lienkaemper 1978).

Stability of these bedform structures can be judged by considering the following factors:

1) Material strength
    a. Rock durability
    b. Substrate angularity
    c. Diameter and condition of wood (sound or decayed)
2) Orientation and size of particles and pieces
    a. Does the wood have roots attached? Is it embedded in bed and/or banks?
    b. Length of the wood in relation to stream width (longer is usually less mobile)
    c. How is the step formed? What are the key pieces: boulder, cobble, gravel? A combination of wood and rock? How large are they? Do the logs span the channel? Can the stream cut around the end of the log?
    d. Are particles imbricated and what is the degree of embeddedness? Are they loose on the surface and readily available for transport?
3) Relationship to other bedform structures
    a. If one structure is lost, will it undermine the next structure?
    b. Are there key structures in the reach that govern the extent of vertical and lateral adjustment?

In the Pacific Northwest, it has been helpful to identify the reference reach and project site channel type in terms of the classification offered by Montgomery and Buffington (1993). At the channel reach level, their classification of alluvial channels is directly descriptive of the bed profile and structure (cascade, step-pool, pool-riffle, plane bed, regime, and braided). These channel types are associated with qualitatively distinct frequencies of bed material mobilization, a characteristic that is essential to understand in designing a stream simulation streambed. Channel type should be identified in the site assessment notes.

Any component of an alluvial channel that is not transportable by the current river (colluvial or glaciofluvial rocks, stable embedded wood, log jams, bedrock outcrops) forces flow around or over it, and may control channel shape, stability, and local grade. Forcing features often create backwater and add roughness, so that sediment sizes in a “forced” reach may include much smaller particles than would be expected if only the overall average slope of the channel were considered. This has tremendous implications for stream simulation design, and the surveyors should note each forcing feature as it is passed, as well as its effects on sediment storage, and channel width and slope.

Roughness is an aggregate term for those channel features that create drag on the flow, slowing its velocity and increasing turbulence. It is the single most hard-to-quantify component of a flow velocity model, which the designer may use to verify culvert flow capacity. The site assessor can best assist the designer by observing in detail and photographing the components of roughness that exist in the channel. These include some already mentioned, such as forcing features, bedforms, and bedrock outcrops. Other features are overhanging bank vegetation and exposed roots, bank irregularity (undercuts, alcoves), woody debris of all sizes, and channel bends. Bed material particle size distribution is also essential information for roughness estimations.

Bed Material

The design process uses reference reach particle size distributions to specify in-pipe bed material composition. The information is usually collected by means of a standard 100-particle Wolman pebble count that samples all portions of the reference reach (pools, riffles, both key pieces and sediment stored behind steps). For step-pool channels, Bunte and Abt (2001) recommend systematically sampling at regular intervals to avoid observer bias. Where bed material size distribution is distinctly different between large-scale channel segments---say, between long riffles and pools---separate pebble counts should be done to characterize each phase. This gives the designer all the information needed to design a riffle or (less frequently) a pool section inside the pipe. In gravel bed streams, visually note whether the surface of the streambed is armored. Observations of particle hardness, color, angularity, imbrication and embedding can all help in assessing bed mobility.

Channel Cross Section Profiles

Cross sections are surveyed at intervals along the longitudinal profile and, with the profile, they provide a three-dimensional picture of the reach, including how the channel cross section changes with gradient. The number of cross sections surveyed should correspond to the complexity and risk of the site. At complex sites where the cross sections and local slopes vary greatly, or where the risk of structure failure is high, more cross sections are needed than in uniform reaches. Reference reach cross sections provide the template for the stream simulation cross sectional topography, and project site cross sections show how the pipe will relate to adjoining reaches in the cross-valley dimension.

At the reach scale, Rosgen channel types are useful in describing the relationship of the channel to adjacent hill slopes or valley flats. The entrenchment ratio is a key parameter distinguishing channel types. It is defined as the ratio of *floodprone* width (width at an elevation above the streambed of twice maximum bankfull depth) to the bankfull width, describing the degree of flow confinement (or spreading) at fairly high flows (Rosgen 1996). Streams with high entrenchment ratios---Rosgen types C, E, and F---have relatively wide floodplains, and require special design consideration to avoid concentrating overbank floodplain flows through the stream simulation pipe. Rosgen types A, B and G are in this respect easier to simulate.

The relative volume of water that is conveyed down the floodplain at high flows depends on both entrenchment ratio and the resistance to flow offered by riparian vegetation or other roughness elements on the floodplain. Again, this is important because it affects the degree to which the culvert and roadfill may block floodplain flows and concentrate flow through the crossing structure. For this reason, floodplain vegetation and other obstacles to flow should be observed as cross sections are surveyed at several points along the longitudinal profile (both reference reach and project site, if they are different). Cross sections should be long enough to show floodplain features and elevations at least out to the limit of the floodprone width. Where side channels or floodplain swales are present, these features should also be included in the survey. Side channels may require stream simulation culverts of their own in many cases.

Points to survey and document in the survey notes include:

- Top and bottom of banks
- Gravel bars
- Pool bottom
- Undercut banks
- Bankfull elevations
- High water marks
- All grade breaks along the cross section profile
- Changes in materials
- Floodplain features, vegetation type boundaries

Descriptive comments and sketches are essential aides to understanding and interpreting the profiles when they are plotted later.

Structure design must consider potential lateral channel shift at the site during the service life of the structure. Together with entrenchment ratio, bank resistance (including that of riparian vegetation) determines a reach's inherent lateral adjustment potential. Unstable banks are susceptible to erosion, which can increase the rate of lateral migration or increase the overall width of the stream. Both processes can lead to fish passage impediments due to aggradation at the culvert inlet, and must be considered in design. A bank stability assessment also helps determine what bank protection will be needed in the regraded sections adjacent to the crossing.

Bank stability indicators include:

- Bank material composition (types of materials - cohesive or non-cohesive)
- Average bank slope
- Extent of bank undercutting – infrequent, continuous
- Amount and type of existing bank failures – infrequent or continuous, deep or shallow failures, rotational failures, slab/block failures
- Amount and type of vegetation - root density, depth, and size
- Bank stratigraphy - vertical sequence of material composition, layering, unconsolidated or overconsolidated materials, ground water seepage

Bank instability can also indicate recent channel incision (Castro 2003). It is extremely important to identify and note this if it exists at a site. Other extrinsic factors, such as debris and bedload deposition potential, are also important in many streams and must be evaluated to determine actual lateral and vertical adjustment potential in the project reach.

Conclusion

To avoid the detrimental consequences to channel stability, diversity and aquatic habitat quality that traditional road crossings often cause, stream simulation culverts are sized to accommodate at least bankfull dimensions, and a streambed with similar slope and structure is constructed inside. Bed and bank transitions to the adjacent channel sections are as smooth as possible, and where necessary include grade controls or channel restoration measures to ensure the crossing streambed can maintain itself over time. If designed with due consideration of site-specific fluvial processes, stream simulation culverts can provide a degree of geomorphic process continuity over the long term, and passage for aquatic species at the times they are moving in the stream. However, passage for terrestrial species may or may not be provided. Also, active large-scale valley processes, such as meander migration and alluvial fan construction, can be constrained by any rigid structure in the dynamic valley environment. Determining site-specific design objectives, structure type and design approach is a complex task that requires balancing benefits and costs to all the resources involved. It is inherently interdisciplinary.

The success of a stream simulation design will be judged by whether aquatic species can travel through it at the times they are moving in the natural channel, and also on its stability and flexibility over the long term. The in-pipe streambed must fit into the geomorphic context of the stream and adjust with it. For that to happen, stream structure, materials and processes must be thoroughly understood and the essential functions must be simulated. The site assessment described here provides the context and the template for design. The design process is described in the following paper (Gubernick and Bates this volume).

Stream simulation practice is a developing art/science. The recommendations presented here were developed based on experience in the Pacific Northwest, and the authors anticipate that practitioners in different geographic regions will progressively add to or modify them as experience is gained elsewhere.

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DESIGN AND CONSTRUCTION OF AQUATIC ORGANISM PASSAGE AT ROAD-STREAM CROSSINGS

DESIGNING CULVERTS FOR AQUATIC ORGANISM PASSAGE: STREAM SIMULATION DESIGN

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Abstract: Stream simulation is a culvert design method to economically emulate the diversity and complexity of a natural channel inside a culvert. Gubernick et al. (current volume) discuss evaluating site suitability for stream simulation culverts. This paper also describes site assessment procedures to gather the detailed information on the project site and reference reach that are needed to establish the design context and to design the culvert streambed and transitions to adjacent reaches.

In this paper, we discuss how interdisciplinary design teams use that geomorphic information to design culverts that ensure passage continuity for aquatic animals as well as water, sediment and debris, and that can be expected to maintain that continuity over the structure lifetime (barring extreme flood events). We recommend methods for determining design parameters for stream simulation culverts, including culvert size, slope, bed material size and arrangement, and channel transitions. The design process includes a bed stability analysis that depends on channel type and slope. Special issues such as steep channels, bedforms, and floodplain contraction are briefly discussed.

Introduction

The intent of stream simulation design is to mimic natural stream form and function in a culvert, so as to provide passage conditions similar to those in the natural channel. Sediment and woody debris transport are intended to function as they would in the natural channel. Since the streambed longitudinal profile and cross section in the pipe are similar to the natural channel, water velocities and depths at flows up to bankfull are also similar, and the crossing should be essentially invisible to migrating aquatic organisms. Culverts designed for stream simulation are sized wide enough to include either channel margins or banks. The most basic stream simulation culvert is a bottomless culvert placed over a natural streambed. Other culverts are filled with a sediment mix that emulates the natural channel and adjusts similarly during most flows. In steep channels, the bed may be designed to resist erosion during very large floods.

Information gathered during the watershed and site-scale assessments (Gubernick et al. this volume) allows us to determine if the site is suitable for simulation. If so, it provides the basis for selecting design parameters: pipe gradient, structure type and size, substrate size, bedform key piece sizes, type and extent of channel regrading needed to tie into the up and downstream channels.

General Limitations on Stream Simulation

As with any engineering design, there are limitations as to what we can successfully construct. Whether stream simulation can be applied to any specific instance depends on channel stability (Gubernick et al. this volume), and on engineering/project limitations, such as site accessibility or other infrastructure at the site.

Site constraints can determine to what degree it is physically or financially practical to simulate channel functions as they would have been in the absence of the road. For example there may be a large elevation change across the road caused by aggradation above and degradation below an existing crossing. If it is not possible to correct this situation by regrading the up and downstream channel (e.g., there may be no equipment access), the culvert may have to be placed at a steeper slope than the adjacent reaches.

Certain channel features cannot be duplicated directly or can be simulated only partially in a culvert. Examples are channel-spanning wood, embedded wood, bank vegetation, cohesive bank stability, debris jams and rigid bed forms. Bank vegetation stabilizes most natural streambanks. Large wood that spans the channel provides roughness and complexity, as do bedrock exposures and other rigid bedforms. Debris embedded in the natural channel may anchor bed material and in some cases controls all of the elevation change. Bank vegetation cannot grow inside a pipe; trees will not fall into them; and large, woody debris is difficult and risky to install. While vegetation and large wood are often critical to channel stability, it is usually possible to replace these functions with large rock to create a stable streambed inside a pipe.

Riparian functions such as overbank flooding, side channel construction, and nutrient and debris exchange between stream and floodplain are not simulated within the culvert. The impact of floodplain contraction on up- and downstream floodplains may be reduced with a larger culvert, additional culverts in the floodplain, and/or overflow dips in the road. It is essential to understand what stream functions are critical at a site, as well as the consequences to the stream of placing a culvert and interrupting them to some degree. If any of these essential functions cannot be adequately simulated by the design, other road alignments and/or crossing structures should be considered.

As with all culverts, longer ones are riskier because the stream's ability to adjust its width, depth and slope within the culvert section is limited. The longer the project, the more likely it is that design compromises will accumulate, possibly creating structural and/or passage problems. This risk can be managed by adding safety factors in bed width and other design parameters, but it cannot be eliminated.

Design Process

The stream simulation design process uses the reference reach as the model for the streambed inside the pipe. As indicated in figure 1, it is an iterative process in which completed design steps or decisions may need to be revisited at various points to ensure they are compatible with the evolving design.

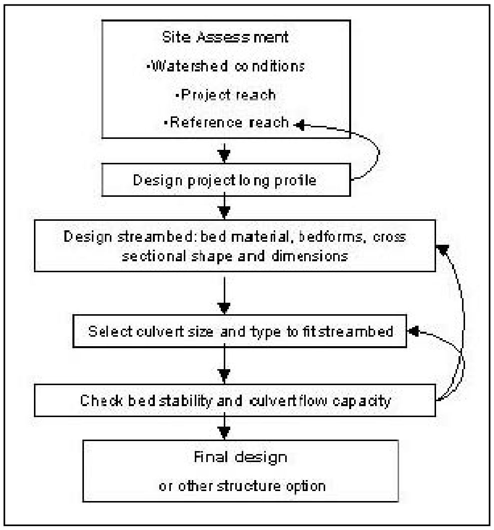


Fig. 1. Stream simulation design process.

To demonstrate the basic design steps, we will design a replacement culvert on Demo Cr, a transport channel (stable, unresponsive to changes in sediment loads or discharge: see Gubernick et al. this volume). Demo Cr is an entrenched Rosgen (1996) A3, step-pool channel on a uniform 4% grade with steps formed of cobble and boulders (figure 2). Table 1 shows some results of the site assessment for the Demo Cr project site and reference reach.

Fig. 2. Demo Cr

Stream simulation design methods vary with channel type, especially between transport and response channels, and major considerations for treatment of response channels are briefly discussed at each step.

This paper is only an introduction to the most basic steps of a complex design process; an in-depth treatment can be found in Bates (in preparation).

1. Determine project design profile and site layout

A culvert's alignment with the channel affects flow dynamics and sediment transport into and through it. If flow width narrows, or if the culvert is at an angle to the channel, the stream may be backwatered, causing sediment and debris to deposit above the inlet. Bank erosion can also occur above or below the site because of velocity accelerations where cross sectional area or flow alignment changes abruptly.

Ideally, transitions into and out of the structure should be smooth and straight. No abrupt changes in cross sectional channel area should occur and culvert sections should transition and tie back into the existing stream banks.

Figure 3 shows a site layout sketch of the Demo Cr project. The stream through the project site is straight and uniform in width. There is some minor inlet and outlet bank erosion caused by the undersized culvert. The alignment is good, but some bank reconstruction is needed to narrow the approach to prevent sediment deposition upstream, to repair eroded banks downstream, and to assure channel margin connectivity through the structure.

Table 1.
Demo Cr site and reference reach data

Montgomery & Buffington Channel Type	StepPool, Transport	Rosgen Channel Type	A3	Stream Bed Substrate	Cobble / Boulder
Bankfull Width (Bfw)	2.4m	Existing stream gradient	4%	Ref reach D84	150mm
Max. Bankfull Depth	300m	Step height	200mm	Ref reach D100	300mm
Flood Prone Width (Fpw)	2.7m	Step Pool Depth	250mm	Ref reach D50	50mm
Q50 Discharge	1.5cms	Existing Step Stability	Very Stable	Ref reach D16	15mm
Hydraulic Radius at Q50 (in the new stream sim. culvert	0.5m	Bankfull Discharge	0.6cms	Depth to Bedrock	2m
Replacement Culvert Length	10m				

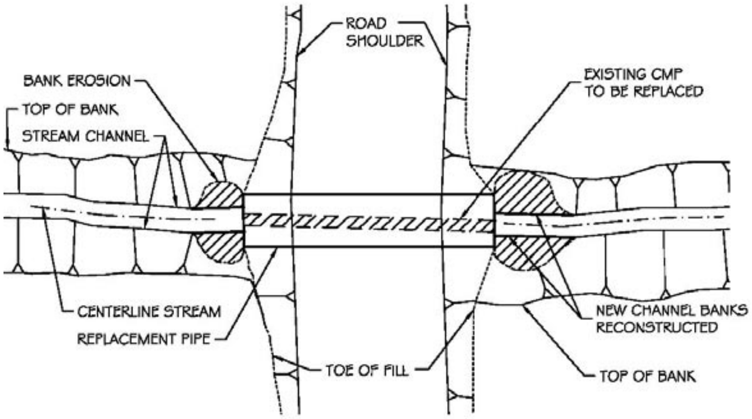


Fig. 3. Demo Cr site layout.

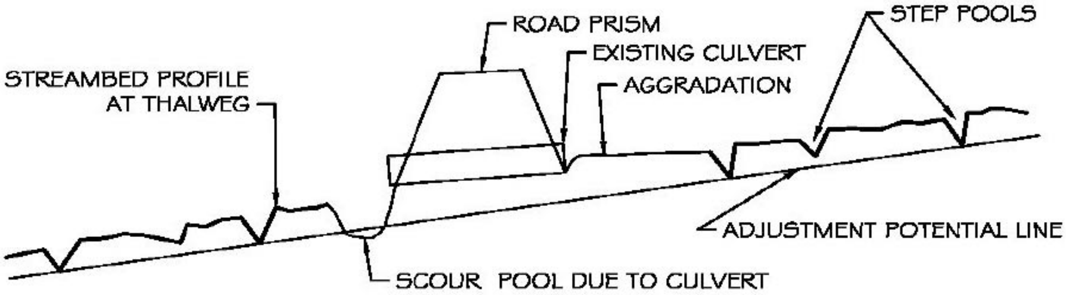


Fig. 4a. Demo Cr site longitudinal profile and adjustment potential line.

The profile shows the frequency and height of steps and pools in the natural channel away from the influence of the culvert. The line connecting the lowest points of the long profile is the Adjustment Potential Line (APL). In vertically stable channels this line is taken to be the slope and elevation to which the streambed will adjust locally as boulders or other grade controls move over time. Demo Cr (figure 2) has a uniform natural channel grade with a perched culvert due to local scour from the undersized culvert. The short aggraded section immediately upstream of the culvert is also distinguishable.

In a transport reach such as this, the project profile can be relatively short, as it blends seamlessly into the existing channel at persistent bedforms such as stable steps (figure 2b). The project profile shows that the scour pool will be filled in with material from the excavation and upstream wedge of deposited sediment The step-pool morphology will be reestablished through both the culvert and the aggraded section upstream.

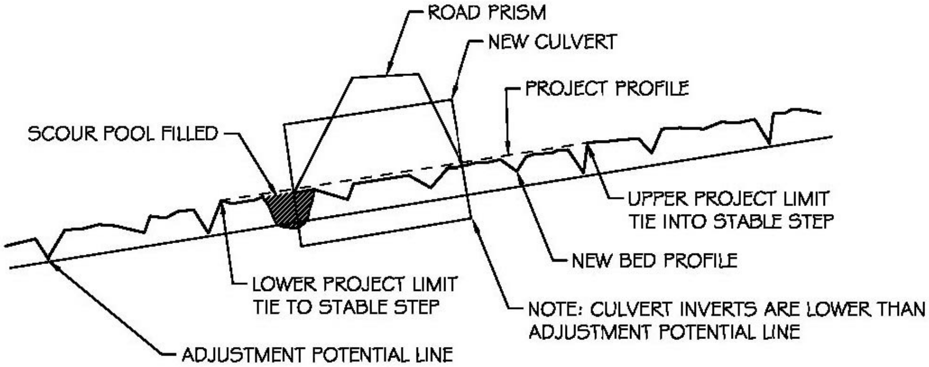


Fig. 4b. Demo Cr project profile.

In a response reach, the project profile must be longer than in the stable example of Figure 4. In response channels, as the channel readjusts to a new---usually lower---structure, a headcut will be initiated upstream, and may move a long distance above the crossing. A longer project profile is needed to estimate the effects of the headcut and whether and where channel grade controls may be needed.

A longer profile is also needed to distinguish broad-scale channel incision from the local aggradation and degradation we observe in figure 4. In disturbed channels, downstream incision may have occurred due to changes in flow, sediment transport, debris recruitment, urbanization, etc. (Castro 2003). The existing culvert may be a valuable artificial grade control preventing an active headcut from moving further upstream. The project design profile may include a major modification of the existing reach. It may be possible to realign the channel to restore the natural meander pattern and channel length. Alternatively, the project profile may include measures to stabilize the downstream channel gradient and elevation, such as boulder or log weirs (figure 5).

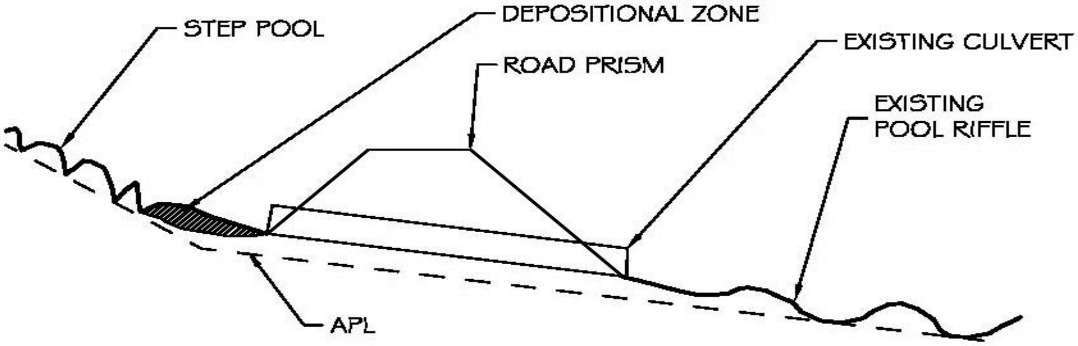


Fig. 5. Regraded incised channel downstream of new culvert.

In disturbed or incising stream channels such as those described above, or where the natural stream grade changes in the vicinity of the crossing, the designer is faced with choosing among several possible project profiles. For example, if the stream profile is concave across the crossing (figure 6), as at the edge of an alluvial fan, sediment deposition and consequent changes in long profile should be anticipated in the future. For the culvert, a profile in-between the profiles of the two segments might be selected.

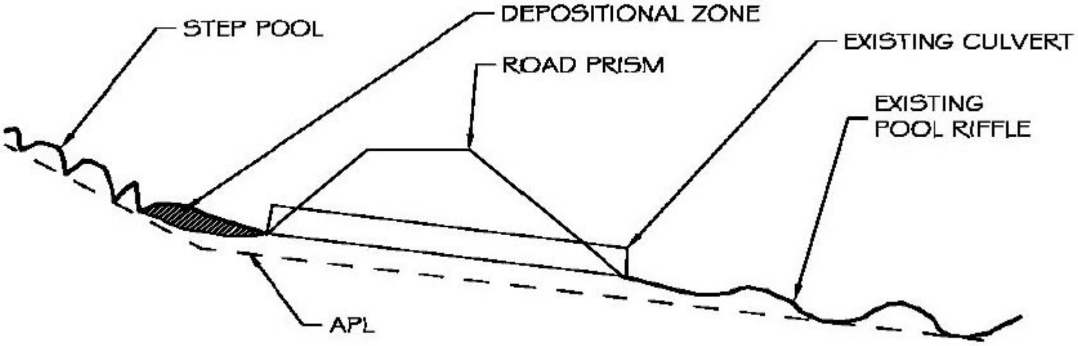


Fig. 6a. Anticipate debris and sediment deposition where culvert is at a concave slope break.

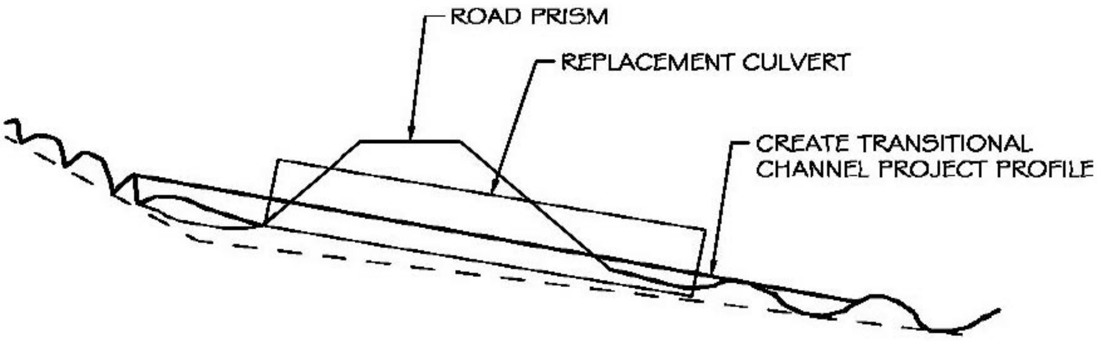


Fig. 6b. Transitional project profile on concave stream profile.

Another situation in which the design team must select from a range of possible project profiles is where aggradation and degradation caused by an existing undersized culvert creates a very large elevation drop across the crossing. This situation requires either oversteepening the new culvert, or regrading the adjacent channel segments, or both. Some oversteepening may be feasible if a reference reach matching the selected grade can be located to serve as the design template for the simulation streambed. Where the design slope exceeds that of the reference reach, a hydraulic bed stability analysis is recommended.

2. Bed design

Once the project profile is determined, the streambed morphology is designed. To simulate the natural bed-maintaining processes at the site and maintain the substrate materials over the long term, reference reach characteristics are used as the model for the simulated bed. Bed material, bedforms, channel shape, forcing functions, and bed permeability are all important, and are simulated in the culvert. The design must be modified in channels that are not purely self-formed---that is, channels controlled by bedrock, vegetation, woody debris, cohesive clays, or very large colluvial rock. The stabilizing functions of those factors must be incorporated into the design.

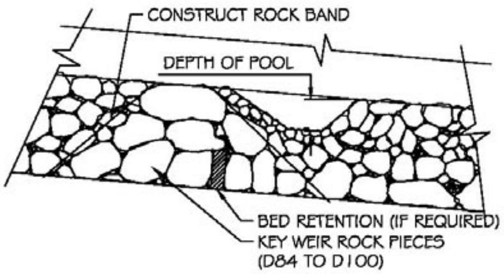
In-Pipe Bed Profile Features

Bed material mobility is related to channel gradient. In low- to moderate-gradient channels where bed material is mobile at flows approaching bankfull, culvert bed materials and arrangement can be modeled directly on those in the channel. Culvert bedforms will then be subject to mobilization and reconstruction by flows at the same frequency as the natural channel. For these streams, it is particularly important to account for the grade- and bed material-stabilizing functions of any forcing (immobile) features, such as woody debris and colluvial rocks. Those functions will need to be incorporated in the culvert bed using alternative materials, such as large rock.

In streams steeper than about 3 percent, the major structural elements of the bed--such as boulder steps or cascades--may not move except during rare (30-yr to 100-yr) floods (Montgomery and Buffington 1993), although smaller bed material moves over them frequently. In the confined space of the culvert, shear stresses during these rare floods are higher than in the open channel and in-pipe steps may move at lower flows, when they cannot be naturally reconstructed by large material moving into the pipe from upstream. For this reason, the key pieces that compose the bedforms may need to be larger than those found in the stream, and a hydraulic bed stability analysis is recommended to support the empirical design (see design step 4). Sills may also be used to support the toe of constructed large-rock steps inside a pipe.

Demo Cr is a stable step-pool channel on a 4 percent-grade without significant forcing features. We will establish rock steps within the culvert bed and through the aggraded section upstream. Schematic diagrams of the steps, including rock retention sills, are shown in figures 7a and b. Their dimensions and spacing will simulate the natural channel profile, approximating the average step-pool spacing and step height found in the reference reach just above the culvert influence zone (figure 1b). This allows the stream to maintain bedload transport and energy continuity and provides grade control and stability during storm events. Since the reach is stable, no additional measures are necessary to control grade at the downstream end of the project.

a) profile view



b) cross-section view

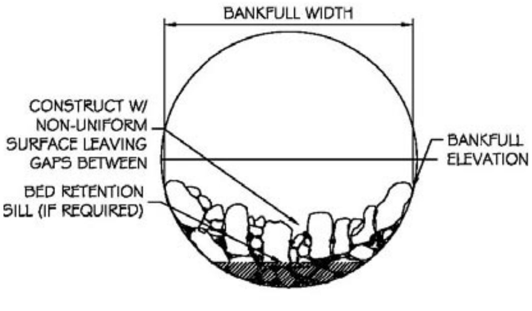


Fig. 7. Step construction details. Bed retention sills are used if needed to increase the bed's resistance to sliding.

Bed Material-Size and Type

Rock for the pipe-bed infill must be durable. It should be similar to that in the reference reach and, for bed stability, at least as angular. If it is more rounded, it may be more mobile than the natural bed material. The key element for bed design is a well-graded bed material mix, which approximates the bed material size of the reference channel. This method for bed design is appropriate for gravel, cobble and boulder-bedded streams.

In coarse gravel to boulder-bed streams (reference reach D_{84} larger than 1 inch), the larger grain sizes (D_{84} to D_{100}) are the most critical to channel form and function. They best represent the roughness, and therefore the hydraulics, of the channel and play a major role in the stability of higher gradient channels (Chinn 1998, Costa 1983). The larger sizes provide channel stability, and control the most persistent bed forms. The fines in the mix are needed to fill the interstices and provide a matrix for the larger pieces, as well as to insure the bed is not so porous that all of the flow is lost through it. Where the bed mix does not contain enough fines, low flows may be subsurface for many years after construction. The issue is especially critical in spring-fed streams where there may be little bed material transport, and in steep channels where the hydraulic slope can drive the flow subsurface. Because fine sediments in the mixture may be entrained during rewatering after construction, care needs to be exercised to prevent transport into local spawning beds.

The reference reach D_{84} and D_{100} are used directly as the corresponding sizes for the stream simulation bed mix. Rather than duplicating the remaining grain size distribution from the reference channel bed, the smaller grain sizes can be calculated based on a typical gradation developed using data from a wide variety of gravel to boulder-bed streams in different environments (Bob Barnard, Washington Department of Fish and Wildlife, Habitat Program, personal communication, 2001).

$D_{50} = 0.4*D_{84}$
$D_{16} = 0.125*D_{84}$
D_5 = sand and silt

The bed material mix need not meet these ratios exactly, as long as the larger particles are represented and a broad range of size classes is included. The D_{100} pieces usually are those making up the stable bedforms in the stream. The quantity of the D_{100}-size material needed will depend on how much is needed to construct bankline and channel features within the culvert.

For Demo Cr, the bed mix based on the reference reach D84 of 150 mm is only slightly coarser than the reference reach distribution (table 1), with a D_{50} of 60mm and D_{16} of 19mm. To maintain stability and reduce permeability, the bed mixture is placed in lifts and compacted without segregating materials. As shown previously, the steps are constructed of the largest boulders, which are partially embedded in the bed mix (figure 8). During higher flows, the bed mixture will naturally redistribute.

This bed gradation design method does not pertain to streams with other bed material types. Bed material from the site, or similarly graded borrow (preferably not crushed), may be used for response streams with finer, more mobile bed material. Look for embedded woody debris in the reference reach that may function to control grade in medium-gravel and finer streambeds. This function, if present, must be reproduced in the culvert. If the wood is small enough to be redistributed during frequent high flows, with time it may wash into the pipe and set itself up as in the natural channel. Often, however, there are large, stable woody debris accumulations that cannot be reproduced in a culvert. Usually, large rock is used to simulate the grade control functions of wood, even if rock is not common in the reference reach.

In bedrock channels, if the bedrock is sound and continuous throughout the site, stream simulation may consist merely of placing a bottomless culvert. Depending on the shape of the rock surface, the entire footing might be anchored to it with a stem wall extending up to the bottom of the prefabricated culvert. The height of the footing and stem wall take up any variation in the bedrock surface. Geotechnical investigation is needed to determine the location, elevation, and suitability of the bedrock for a foundation.

Bed width and cross section shape

The cross-sectional shape of the reference channel, including the low flow channel, is also simulated within the culvert. Banklines or margins should be included where needed to meet passage objectives. It is generally accepted that slow, shallow water near channel margins is critical for migration of weak-swimming species, juvenile fish, and amphibians (Jackson this volume). Some mammals prefer banks or dry channel margins. Also, when steps, banks or roughness features (such as grouped boulders) along the margins are not constructed, especially in low gradient culverts, the streambed tends to be flat, and there may be a deep chute along one wall.

Without root structure, cohesive soils, or the ability to scour into parent bed material, banks will not form naturally inside the culvert, so, if needed, they must be constructed. To simulate a bankline, a line of large rock may be placed along each wall of the culvert, and the spaces between and behind the rocks filled with the bed mix. Another way to create margins is to place boulder groups on alternating sides of the culvert to encourage a meandering low flow thalweg (figure 8). Bank rock should be stable at all flows, and may be D_{100} or larger. Additional culvert width is required to accommodate bank construction and still maintain the bankfull cross section. The culvert walls themselves may simulate the nearly vertical walls bordering an incised channel.

Demo Cr is an entrenched channel with little or no floodplain. Its banks are discontinuous at best, but the channel margin is rough, with boulders and vegetation exposed to the flow. We decide to match the reference reach width of 2.4m, and to construct channel margins by placing some coarser materials near the culvert wall (Figure 8). The margins are not banklines that form an actual shelf; but material that will be dry at normal flows and will resist moving at higher flows. The culvert wall will represent the steep upper stream banks. At Demo Cr, the low flow channel shape is formed as the steps are built, with the low area somewhere other than at the culvert wall. This shape will be rearranged in flood events.

Fig. 8. Constructed step and boulder groups at margins inside culvert similar to Demo Cr.

In lower gradient channels, the initial low flow channel can be set up using rock bands. This avoids formation of a temporary featureless bed where spreading flow can constitute a fish barrier. Bands are made of well-graded rock that is one to two times D_{100}, depending on channel width. The crests of the bands are lower in the middle, encouraging the channel to remain in the central part of the culvert.

Again, rock clusters along the culvert walls or similar structures may be substituted for the rock bands. In either case, the objective is to create cross section shape and diversity in water depths and velocities. The bands are not expected to be permanent. As the pipe experiences a diverse range of flows, bed material will redistribute and some of the larger pieces are expected to set up into bedforms similar to those in the natural channel.

3. Determine culvert size, slope and elevation

Once the streambed is designed, the culvert is set to:

- Contain the stable channel streambed profile and possible adjustments to it.
- Provide the width required to build the bankfull channel (at minimum) inside the pipe and to accommodate floodplain flows, if any.
- Have sufficient bed depth to sustain normal scour and fill without baring the metal floor (for full-bottom structures).
- Provide the capacity and headroom needed to pass the design flood and debris.

Ideally, the culvert should be embedded or the footing depth should be set so that the culvert will function throughout the range of possible channel profile adjustments that might be expected over the life of the structure. Depending on the risk and the uncertainty of the range of profiles, a safety factor can be added for depth of burial and/or height of the culvert. For example, the footings of a bottomless structure in a channel controlled by mobile woody debris are more at risk of being undermined than in a bedrock-controlled channel. Avoiding that risk may require a substantially deeper footing. Full-bottom structures should also be larger where substantial profile change or scour is likely.

To avoid the water surface narrowing inside the pipe as flow volume increases, the point of maximum culvert width should be set above the bed surface throughout the length of the pipe. If and when flow width does narrow as depth increases in the confined pipe, shear stress will be higher in the pipe than in the natural channel, putting the culvert streambed at risk of erosion during high flows. As a practical guide, circular culverts are generally embedded about 30 percent to 40 percent of their rise. In pipe arches, two feet or 20 percent of the rise (whichever is greater) is commonly used, subject to the bed depth needed to accommodate long-term vertical bed adjustments. The size of the bed material may affect the depth of the culvert bed; for the bed material to be well integrated and able to structure itself, the bed should be at least twice as deep as the largest particles in the bed mix.

The culvert itself may be installed flat or at channel grade or at any slope between the two. A steep culvert might be set at a slope less than the channel slope to minimize the risk of the bed sliding out of the culvert. However, in steep gradient channels, culverts installed flat must be very large to maintain a stream simulation streambed at the correct grade. Bed depth at the upper end of such a pipe will be very deep if depth at the outlet is sufficient (rule of thumb 30 percent embedment) to sustain expected adjustments.

Several structure types (round, arch, or bottomless) might be considered for Demo Cr (figure 9). Site assessment data (table 1) indicate that depth to bedrock is about 2m, and the design bed width is 2.4m, with some additional width needed for channel margins. As a first iteration, we might try superimposing on the designed streambed a round 2.7m culvert embedded 35 percent. This would be an embedment depth of almost 1m, plenty to accommodate the expected pool scour depth of 0.25m. Since there is adequate room to install a round culvert, it would most likely be selected on the basis of cost and to maximize bed depth. A bottomless structure would also be satisfactory, but it would require excavation to 2m depth to tie the footings into bedrock. Cost is less for a round pipe installation at this site, and if traffic interruption during construction were a concern, the round pipe is easier and quicker to install.

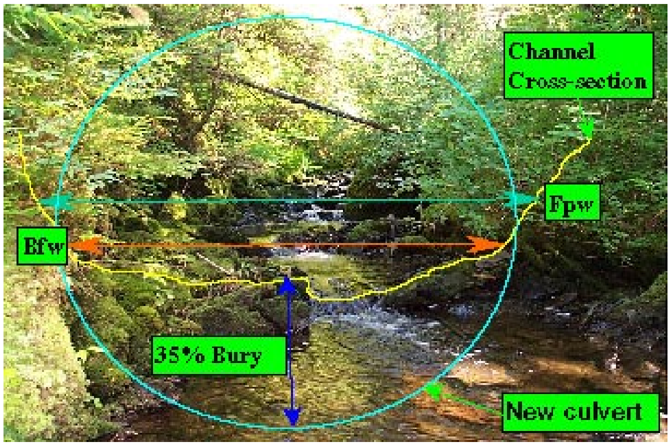


Fig. 9. Culvert embedment in Demo Cr.

Two checks are needed at this point. First, at bankfull depth above the simulated bed, the culvert must be at least as wide as the bankfull width in the stream. At bankfull depth, culvert width is 2.4m (figure 5), equal to the bankfull width of the reference reach. This selection leaves plenty of room for vertical adjustment and allows space for large rock to be used for roughness and diversity along the culvert margin without constraining bankfull width. Second, bed depth should be at least twice the size of the D_{100} pieces that must be incorporated in the fill, to ensure their stability in the bed matrix. The 1m bed depth is more than twice the D_{100} diameter of 0.3m.

So long as bed width and depth are adequate to sustain expected adjustments over the structure lifetime, there is little difference between culvert shapes and materials when considering passage of aquatic organisms. Site conditions can be as or more important cost controls than structure type and material. Project costs are affected by traffic control, ease of dewatering, soil structural loading capability, location and availability of materials, excavation volume, and excavation limitations such as bedrock. The size, shape and material of a culvert also substantially affect the cost of many projects, however. For example, major cost increases do occur at the size break between helically corrugated and structural plate pipes (144" or 3.7m).

4. Assess bed stability

A bed stability analysis is critical where

- the culvert streambed is narrower or steeper than the reference reach
- floodplain contraction will be significant and floodplain continuity cannot be provided by secondary pipes and armored dips
- the culvert will be longer than the length of a straight reference reach in the channel

These analyses are described in Bates (in preparation).

At the high flows that mobilize large-rock bed structures, flow is more confined in the culvert than in the open channel, so that shear stresses are higher. For this reason, bed stability analysis is also often done to check stability of rock used for banklines or in boulder clusters at culvert margins in high flows. The goal is to avoid losing key rocks from the culvert at flows lower than those that will replace it from upstream. The analysis consists of comparing unit discharge (discharge/width of active channel) or shear stress in the culvert to critical unit discharge or average boundary shear stress that initiates motion of a particle the size of D_{84} or D_{100}. Since the variability in most stream environments challenges the assumptions of the available models, the same comparison should be done on the reference reach, as a check of validity. If the culvert is found to be less stable than the reference reach at a relevant flow, the culvert might be enlarged, D_{84} might be increased, or the project profile might be modified and a more appropriate reference reach located.

Which flows are used for these analyses depends on the stream and bed material type, and the level of failure risk that can be tolerated. Where large rocks are used to construct banklines or other stable bedforms, an analysis might be done to check their stability in the 50-year or the 100-year flow. These are the types of flows that would mobilize stable, large-rock structures in the natural channel, and they have relatively high chances of occurrence (45 percent and 26 percent, respectively) over a 30-year culvert lifetime. This analysis would be particularly important if the stream has a wide floodplain and the culvert will confine high-flow width. In that case, the flow that moves D_{84} in the confined space of the culvert may be much lower than in the natural channel, and modifications would be needed in the crossing design.

For Demo Cr, a modified Bathurst equation (Bates in preparation) can be used to evaluate stability of the key pieces on the channel margins. The 2.7m diameter round pipe is embedded to 35 percent depth at a 4 percent slope. At the 50 yr flow of 1.5cm, hydraulic modeling (such as CulvertMaster or FishXing) of flow over the culvert bed indicates that flow width is 2.6m. The equation predicts a 123mm particle would be about to move at this flow. The Demo Cr design bed D_{84}---based on D_{84} of the reference reach---is 150mm, and therefore it should be stable. However, we are very close to the threshold for movement, and another check on stability is recommended before accepting the design mix results. Other methods of bed stability analysis that can be used to verify these results are discussed in detail in Bates (in prep). If the consequences of failure at the site were large, design modifications may be in order with this low factor of safety. However, we should recognize that if a conservative choice is made at every step, these will compound to produce an oversized or overhardened structure.

The 100-year flow is a commonly used flood capacity requirement for culverts. Experience with stream simulation culverts in the Pacific Northwest has shown that the 100-year flow does not produce---or usually even approach---a headwater-to-depth ratio of 0.8. Nonetheless, it is wise to check the pipe to ensure design flow capacity especially when large bedforms are constructed.

It is important to remember that estimates of rare flows like the 100-year flood are extremely uncertain, especially in small, ungaged watersheds. Also, as noted above, there is a surprisingly high (26%) chance that the 100 yr storm will occur over a 30 yr structure lifetime. Because of this, it is crucial to recognize the possibility that the culvert may fail, and to design it in such a way that the consequences of failure (such as overtopping, or diversion down the road ditch) are minimized.

Conclusion

Stream simulation design is based on the geomorphic form and function of the stream and, to succeed long-term, it requires a thorough understanding of the stream including past, present and possible future conditions. To successfully implement this design strategy, an interdisciplinary team should balance the biological, geomorphic and economic benefits and risks of different stream simulation design alternatives. Reference reaches provide the channel dimensions and slopes that are the templates for channel and bed design. Nonetheless, it is important to realize that flood flows confined within a culvert exert higher shear stresses on the bed than in the open channel. For this reason, except in low-gradient channels with highly mobile streambeds, key substrate pieces that maintain bed stability will usually be sized larger than those found in the reference reach.

At the present time the upper limit of channel slope feasibility for stream simulation is unknown. There have been many recent installations at grades of 7 to 15 percent; however, none has been installed for any length of time, and monitoring is badly needed to determine long-term success. Much success has been achieved on sites at or below 6 percent.

The methods briefly summarized here will be thoroughly described in a guide currently in preparation for the USDA Forest Service San Dimas Technology and Development Center. Construction techniques that are especially important or unique to stream simulation culverts are discussed in the following paper (Johansen this volume) and will be the subject of a companion guide, also currently in preparation.

Biographical Sketch: Robert Gubernick is an engineering geologist for the Alaska Region of the USFS. He is a member of the FishXing development team and the San Dimas technical fish passage team. He received his BS in geology at Utah State University in 1983. Robert did his Graduate Study in Geomorphology Univ of Washington in 1997. Robert had been with the USDA Forest Service 20 years and is currently located at Tongass National Forests. His primary duties include geomorphic and geologic assessments for road and hydraulic projects: hydraulic engineering (fish passage designs, contract admin, inspections, training, and monitoring); remote sensing; and engineering liaison to regulatory agencies.

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DESIGN AND CONSTRUCTION OF AQUATIC ORGANISM PASSAGE AT ROAD-STREAM CROSSINGS

CONSTRUCTION CHALLENGES AND CASE STUDIES OF STREAM SIMULATION STRUCTURES FOR AQUATIC ORGANISM PASSAGE

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Abstract: This paper presents guidance for constructing stream simulation structures capable of passing most aquatic organisms, amphibian and some terrestrial species. Bridges are not addressed specifically in this document but many of the construction details, including the stream simulation bed, apply to bridges. To simulate a stream the structure must have been designed to fit well with and have minimal impact on stream dynamics and processes. Traditional construction methods are used for both embedded pipe and open bottom arch construction. In chronological order, the primary structure construction steps include prework meetings, surveys, traffic controls, dewatering, erosion control, clearing, excavation, foundations, bedding, pipe assembly, backfill and embankments, and rewatering. The single most important and unique detail to stream simulation structures is the simulated streambed inside the embedded pipe or open bottom arch. The bed is typically shaped to have a low water channel, margins, and banks and may include other large rocks added to simulate streambed roughness, stable banks and step pool. Bed construction requires unique effort and a combination of machinery and skilled hand labor to fit and arrange pieces to match the design interlock well and be durable. Protection of the aquatic environment is emphasized through minimizing turbidity and sedimentation. Additional aquatic organism protection can include collection and transport of species from the dewatered area, slow rewatering to avoid stranding, limiting toxic substances and noise, and reducing blasting effects. Communication among designers and contract administrators is emphasized to improve understanding of design objectives, maintaining a feedback loop to address site problems and transferring wisdom gained from the project's construction.

Background

There has been an accelerated effort made to remove stream barriers at stream crossings since the mid '90's. Various design philosophies have been tried and refined. Many constructed fish passage projects met stated project goals, yet many did not allow migration of aquatic organisms other than adult fish. It became clear that weak swimming species or life stages of fish, eels, and amphibians were unable to negotiate some fish passage structures. Flood events demonstrated the need to pass sediment and debris on many sites and indicated the need for channel-wide and larger pipe widths to allow streams to function naturally. As a result of these observations and organized monitoring efforts, various sources began refining design methods. Washington Department of Fish and Wildlife published *Design of Road Culvert for Fish Passage* in May 2003. This document serves as the guide to many US Forest Service projects in the northwest.

Stream simulation is a design method that creates a streambed inside a structure that has most of the key channel characteristics of the adjacent channel (Gubernick and Bates, this volume). Key features may include banks, margins, a low water channel, boulder fields, steps, or clusters of large rocks. Because the structure looks like the adjacent stream, it is presumed to pass aquatic species present and possibly some amphibian and terrestrial species.

Introduction

Construction of stream simulation structures involves many techniques and materials common to other culvert and open bottom arch projects. Other techniques and materials are unique and require extra care on the part of the contractor. If both standard and unique aspects are executed well, the result will be an effective, durable structure capable of passing many aquatic species. The project will have minimized damage to riparian and aquatic habitat and will have negligible impacts in the future.

Construction Sequence

The following table provides a general outline of a stream simulation construction project along with the primary concerns about construction for each stage. Project details will vary with site location, topography, soils, road width, and traffic, etc. On larger, multiple-lane highway projects items such as traffic bypass construction, traffic control, and dewatering details can become major contract items. Traffic control, bypass roads, and road travel way reconstruction are not covered in this document.

The format of this document follows the process described in table 1. The sequence of events and some details may change from project to project. Included are common practices and challenges. The report concludes with case study examples. Many typical construction aspects of culvert construction are not covered in this document. The reader is referred to the National Corrugated Steel Pipe Internet site www.ncspa.org/tech.htm, and manufacturer's literature for the specified project pipe.

Table 1
Contract Work Items and Primary Concerns

WORK ITEM	PRIMARY CONCERN
Prework meetings with the contractor	Communication, orientation
Construction Surveys	Verification, aid construction, quality assurance.
Traffic Controls at Stream Crossings	Safety, public relations, roadway stability, structure integrity
Dewatering	Constructability, turbidity, protect aquatic species
Erosion & Sedimentation Control	Turbidity and sedimentation, protect aquatic species
Clearing	Erosion, material conservation
Excavation	Sedimentation, turbidity, blasting effects
Foundations	Structural, concrete in stream effects.
Bedding	Structural, gradation
Pipe Assembly	Structural
Backfill and Embankments	Structural, compaction, gradation, erosion, sedimentation
Streambed Materials, Construction	Meet aquatic species passage needs, details, permeability
Rewatering	Protect aquatic species

Prework Meetings and Other Considerations

There are subjects that can be emphasized to help smooth administration of a successful project. For example, explain any project objectives not obvious in other contract language such as meeting specific stream entry permit requirements or public concerns. These may be qualitative items not described specifically in specifications, drawings, or the contract language. Try to make contract language as clear as possible. Items that should be specifically addressed at the prework meeting include:

Protection of Water Quality – Prevention of direct runoff of sediment containing water into streams, proactive prevention of erosion, qualitative design expectations relating to construction area drainage and treatment, preparation and protection of the site from potential storms during the work period.

Protection of Habitat – Preservation of riparian habitat, minimization of damage to existing vegetation, preservation and use of cleared large wood with stumps.

Dewatering Method Performance - Expectations of erosion control methods, sediment trapping and turbidity treatment of runoff, expectations of possible subsurface flow in the excavation and the method for handling it, including payment method. Capture and rescue of aquatic organisms may be an important part of dewatering that could be the responsibility of the contractor. Discuss expectation and coordination with other specialists (fish biologist).

Quality of Stream Bed Simulation Rock Placement – Emphasize that the intent is to reconnect the channel and create as natural a channel inside the pipe as possible. Photos of the site showing stream segments with similar channels to what is in the contact plans can be helpful. Discuss the proposed method of placing of bed material; this often requires hand labor and specialized equipment. The quality of labor and effort put into fitting and interlocking individual pieces of rocks together can have a substantial effect on their durability. Material dimensions, gradation, and permeability are vital to the simulated streambed's performance. Special specification and pay items are vital to describe and administer this area of work. These items may be a minor cost item in the overall contract, but they have a major impact on the effectiveness of the structure.

Surveys

The original site survey should have at least three durable reference points for location of all other site features and establishing additional references. Remote projects that are surveyed, then delayed for years, may lose reference points to vandalism, storm events or road maintenance activity. Site topography may also change, especially in stream channels due to flood events. Lost references have to be replaced. Existing culvert inverts and drill holes can be useful project references.

Preconstruction Survey

An early review of project plans in the field with the contract administrators and designers can help prevent surprises later on by answering specific questions and verifying that the design still fits if some site changes have occurred.

Enough references and data points should be surveyed to be able to locate the structure and reestablish the road surface and embankment geometry. Assure the road surface is adequately described by existing survey information; otherwise, survey additional points to assure that super elevation, vertical curves, curve widening, or any other critical geometric elements can be reestablished. A straight road segment is easy to recreate with a minimum of survey data, but others such as a super-elevated "S" curve are not.

Examine site plans and design elevations carefully. The project site may not seem to match the site plan or stream profile. If survey points near the existing or new structure are not marked and the channel is very rough, this may lead to confusion and uncertainty as to design elevations and assumptions. A stream classification system may be helpful in describing channel conditions. This could be due to the software used to generate the contour map. Rough channels can be confusing unless you know exactly what points were surveyed in the channel. The "stream channel elevation" used to design the new structure invert can vary a foot or even more depending on where the survey rod was placed originally. Was it held on top of a boulder or between boulders? Are boulders dominant? Do they seem to define elevation more than the spaces between boulders? Some additional surveying may be needed. The designer and administrator should communicate and verify design assumptions on the ground and during the contract as necessary to reduce potential questions such as these, and to prevent inappropriate "last minute" changes during construction. This is especially important when the decision affects the new structure elevation, orientation or gradient. Figure 1 shows areas where some confusion may arise during construction surveys over contract drawings, survey points, elevations and design assumptions.

Construction Surveys

Additional surveys by the contract administrator may be helpful before excavation to help locate any additional specific features or objects not in the contract drawings or original survey. Surveys performed during construction to determine specific locations of the structure and details are extremely important and are in a larger sense verifying that the design meets the site geometry. Contractor survey accuracy should be checked. Contract administrator should be skilled in survey methods and able to verify contractor surveys. Survey errors can lead to costly construction mistakes and, therefore, should be caught as soon as possible. For instance, if the structure is placed at the wrong elevation, when the stream channel is constructed and reconnected to the adjacent channel, slopes into or out of the pipe may cause channel scour or passage problems that are difficult to mitigate. A structure placed in the wrong location may create road alignment problems later on.

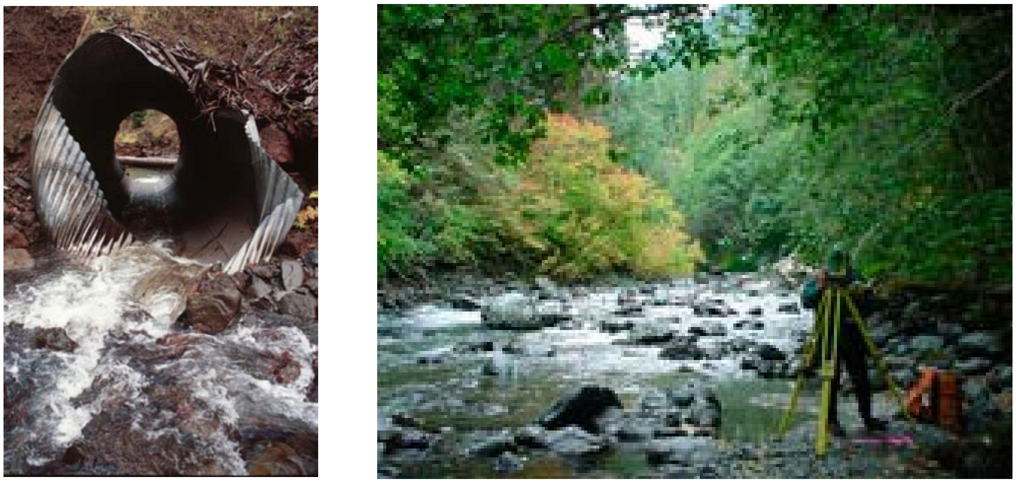


Fig. 1. Possible confusing survey areas - folded pipe invert, high relief boulder stream.

Traffic Controls at Stream Crossings

The contract will have provisions for blocking, diverting or accommodating traffic during construction. If traffic must be allowed over the site, a separate bypass road may be required, often having the secondary function of creating a draw down pool for dewatering purposes. Dewatering is normally provided before this bypass road is constructed to reduce stream impacts. Other sites, such as double lane or wider roads may be better suited to allowing traffic to drive the road while one half of the structure is constructed. Traffic is then switched to the reconstructed side, and the remaining structure is completed. This option may require the use of a retaining wall to help support traffic during construction. These features are described in detail in the contract. Sites with high speed, or high volumes of traffic during any phase of construction should be well marked with traffic control signs, lights and/or personnel. Concern for safety at remote sites may require similar traffic controls, especially where weekend traffic or hunting seasons overlap with construction seasons and the roadway changes abruptly due to construction. Traffic controls must be maintained diligently. Accommodating traffic has a higher degree of risk for everyone.

Dewatering

Protecting aquatic organisms during dewatering should be considered for every project. Aquatic organisms can be removed by setting up block nets above and below the project. Organisms can be moved by techniques such as "herding," gentle electro shocking, or netting. During dewatering, water should drop slowly in the stream to avoid stranding organisms. A fish biologist should guide this effort and generally would be on hand to perform this work. The contractor should not perform this work without consent by the contracting officer. Handling endangered species is prohibited without specific permission by applicable governing agencies, such as NOAA Fisheries or US Fish and Wildlife Service.

Other guidelines and restrictions on dewatering methods may include some of the following:

- In-stream work periods limiting time the stream may be dewatered.
- Restricted work area due to property boundaries or utilities.
- Permits restricting stream channel modification.
- Requirements to capture and preserve aquatic species before and during dewatering
- Requirements to allow slow re-watering of the stream to protect aquatic organisms when the dewatering system is removed.
- Dewatering features should be reliable and able to withstand stream flows and storm events throughout the construction period without failing or causing contaminated water to enter the stream.

Minimize the time the stream is dewatered to lessen impacts on aquatic species. Dewatering can be delayed until excavation is very close to the stream bottom. Footing can be precast; pipes can be preassembled; and bedding, stream simulation rock and backfill can be stockpiled close by. This may reduce stream-dewatering time from months to weeks to days, depending on the structure and contractor ingenuity. Some sites may lend themselves to maintaining stream flow by diverting the stream into developing flood plain channels, by having the room to construct open bottom foundations outside the existing culvert edges, or by dewatering the foundation areas with cofferdams while maintaining stream flow.

Dewatering can be a complex design problem for the contractor to solve in an effective and acceptable manner. It requires capturing stream surface flow, diverting and carrying it away from construction activity, and releasing it downstream. In addition, subsurface water in excavations requires capture, transport, treatment and release. Details of the system may be specified in the contract, but unique site conditions, especially with inter gravel flow, will require adjustments or additions to many designs. Figure 2 shows an example drawing of a dewatering scheme for a stream diverted through the work area. It is usually more convenient for the contractor to divert the flow around the primary work area.

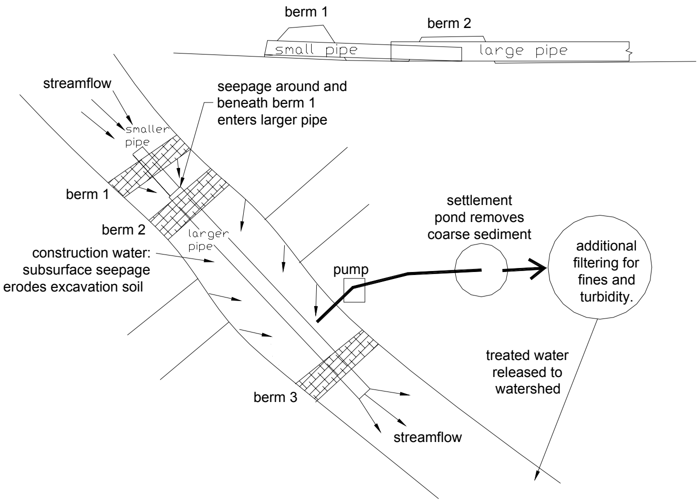


Fig. 2. Conceptual sketch of a complete dewatering system.

Capturing Stream Flow

Surface water is usually collected by constructing a low elevation dam or cofferdam across the streambed. The pooled water is then diverted into a transport pipe or channel. Some regulations require the use of sandbags with clean fill instead of local fill material to construct diversion dams. The pooled water creates increased hydraulic pressure on the surrounding channel and frequently forces some surface water beneath or around the dam. Plastic or membrane lining can be placed on the upstream dam edge and the upstream channel bottom for 10's of feet will help capture surface water and reduce leakage around the dam. A second dam may be placed a short distance downstream to collect water that seeps by the first dam. When a pipe transport system is used, the first dam's pipe may be fed into a larger pipe in the second dam. This leaves an annular opening capable of collecting water behind the second dam. The designer may have specific reasons for designing a detailed dewatering plan instead of asking the contractor for a dewatering plan for approval. Knowledge of good practices combined with experience can help facilitate construction and prevent turbidity problems.

Commercial cofferdams may provide a better solution, especially for larger projects. Water-filled cofferdams are flexible bladders that conform to the ground to form a seal. There are some limitations on their use that can be found on the Internet site www.waterstructures.com/.

Driven pile cofferdams are complex engineered retaining walls that may be suitable in some locations. They have more impact on streams especially when removed. They may also help control groundwater leakage into the project excavation. Pile driving may be prohibited during part or all of the in-stream work period. Useful information may be found at the Internet site www.corusconstruction.com/piling/Cofferdams/.

On small projects that can be constructed very quickly, the entire project dewatering system may simply consist of pumps. If a draw down pool exists upstream or can be constructed, the project may be dewatered easily. Pumps may need to run 24 hours a day and be maintained during that time. A backup pump should be available in case of breakdown. Siphoning may take over if enough flow capacity can be reliably maintained.

Fig. 3. Dewater only part of the stream to maintain aquatic organism passage.

Water Transport

Pipe(s) should be designed to carry expected storm-generated flows during the construction period. Failure to do so can lead to overtopping or failure of the diversion dam. Maintain pipe inlets to prevent plugging by leaf and small wood debris. Water from the diversion can be transported by gravity or by siphoning with pipes placed through the construction area or adjacent to it. Placing the transport pipe away from the excavation can dry work areas and aid work processes. If diversion pipe joints leak, they contribute water to the construction area drainage, adding to the volume of water requiring treatment. If pipes are placed in the fill or on excavation benches, leaks may cause fill instability, endangering workers in the excavation area below. The use of pipes with sealed joints is recommended. Various O-ring, sleeve and strip gaskets are available for this purpose.

Some projects may have an adjacent channel in a floodplain, abandoned channel or one formed with a cofferdam that can be used for water transport. These have the advantage of possibly providing aquatic species passage during construction. Channels may have to be lined to prevent erosion and seepage into the construction site.

Water from pipes or channels is usually released as close to the project as practical to minimize the area of channel area dewatered by the project. The outlet area should be chosen or modified to dissipate any excess energy created by any steeper gradient, or higher outlet flow. Outlet drops should be avoided. A pool area may be available where the outlet can be placed and submerged to dissipate energy.

Construction Water

The construction area for the structure is excavated below the surface of the stream channel. Groundwater is frequently intersected near the channel elevation in perennial and intermittent streams. Subsurface water discharge can vary with weather and can be large, matching or exceeding surface flows especially during storm events. During excavation and pipe removal, sediment mixes with construction area runoff and ground water, elevating suspended sediment to unacceptable levels for release into the stream. Even foot traffic can generate high turbidity levels just by walking though loose soil where water is flowing or standing. The excavation surface can be covered with a geotextile (optional) and a thin layer of clean well-drained crushed rock such as 1/2" – 2" diameter drain rock (see Stream Turbidity section).

Capturing subsurface flow inside the excavation requires care and sometimes artful ditching and piping. Narrow excavations leave little room for constructing ditches outside of footings or embedded pipe edges. Water can be collected in a depression or a natural outlet pond at the downstream end of the excavation. A pumping or siphoning system should always be in place to remove groundwater from the construction and excavation area. Multiple pumps may be required to keep the construction area drained during storm events. A backup pump should be available. Failure to remove water fast enough can cause the excavation to flood. If the downstream dam is overtopped, the resulting damage to downstream habitat and organisms can be severe. Downstream construction water containment dams can leak through channel edges below the dam. The upstream channel and dam edge should be lined with an impermeable membrane or thick plastic to minimize seepage.

All water containing suspended sediment must be treated. Oil-absorbing booms should also be on hand in case of hydraulic hose leaks. Obviously, equipment should be washed thoroughly to remove oil and grease. Equipment may also require washing to remove invasive plants seeds and aquatic diseases.

Stream Turbidity

Subsurface water and construction water should be pumped to a holding pond to settle fines before returning it to the stream (see figure 2). The importance of preventing erosion, and elevated turbidity levels in streams, is due to the negative effects on aquatic organisms and their habitat. Fine sediments generated from a project are detrimental to incubating fish eggs because blockage of interstitial spaces by silt prevents oxygenated water from reaching the eggs, adversely affecting the removal of waste metabolites. Although construction may not occur during these times, sediment may become mobile later, causing damage during critical periods. High silt loads may also inhibit larval, juvenile and adult behavior, migration, or spawning. Siltation, substrate disturbances and increased turbidity also affect the invertebrate food sources of anadromous fishes. Figure 4 illustrates the effect of construction-generated sediment reaching the stream and covering streambed gravels.

Fig. 4. Construction-generated sediment effects on streambed, before and after excavation.

Many major statutes may apply to stream simulation projects and contain language specifying allowable turbidity levels including: Anadromous Fish Conservation Act, Clean Water Act, Endangered Species Act, Fish and Wildlife Coordination Act, Magnuson Fishery Conservation and Management Act, National Environmental Policy Act, and the Rivers and Harbors Act of 1899 (Buck 1995).

It may be wise to attempt to separate clean subsurface water from water with suspended sediment in the construction area to reduce the volume of water to treat. Sand-sized particles can be settled out of suspension by reducing water velocity. Water can be transported to a settling pond, portable water storage pools or by passing through other types of filtration units, vegetated swales, or constructed wetlands. Finally, there are confined areas where treatment of suspended sediment is not possible in the adjacent riparian areas. In these cases water may have to be transported out of the immediate project area to be treated or released into a suitable filter area such as a permanent settlement pond, constructed wetland, or well-vegetated areas. Project permits may limit the upper level of turbidity allowed in the stream. Limits are sometimes set for a specific time period, such as < 50 NTU instantaneously or < 25 NTU for a 10-day average.

Turbidity is expressed in a unit of measurement quantifying the degree to which light traveling through a water column is scattered by the suspended organic (including algae) and inorganic particles. The scattering of light increases with a greater suspended load. Turbidity is commonly measured in Nephelometric Turbidity Units (NTU), but may also be measured in Jackson Turbidity Units (JTU). The velocity of the water resource largely determines the composition of the suspended load. Suspended loads are carried in both the gentle and fast currents of flowing waters. The suspended load usually consists of grains less than 0.5 mm in diameter including sand, silt and clay sediment classes. (Schmitten 1996).

Option - Use of Natural Flocculants for Treatment of Turbidity

Chitosan (pronounced ky-toe-san), a natural polysaccharide derived from crab and shrimp shells, is an effective flocculate to remove suspended sediment by causing particles to settle out of the water column. Chitosan has been tested for effectiveness of sediment removal and fish lethality in the laboratory. It is approved for drinking water treatment and industrial wastewater treatment. There is uncertainly about how it reacts when applied to a natural stream system. Little is known about the fate of the residual product or its effects to stream biota. In addition, little is known about the consequences of settling sediment by flocculation in downstream reaches from in-situ application. (Oregon DOT 2003; McPherson 2002)

Erosion Control of Slopes and Embankments

Provide erosion control at the beginning of the project to protect the stream, riparian areas, wetland and other important areas near the project. The erosion control system should be in place before excavation begins, dewatering systems are constructed, equipment access and traffic bypass roads are constructed, and sufficient erosion controls and measures are provided.

When excavation begins, the protective soil cover of organic debris, roots, and vegetation is removed, exposing it to wind and water erosion. As excavation removes pockets of soil, slopes are temporarily steepened which can lead to collapse of soil pockets that may fall into flowing water. It is generally wise to install the dewatering system before excavation begins to prevent excavation materials from dropping into live streams.

The system used should reflect the soil's vulnerability to erosion. Soil erosion is a function of particle size, gradation, character of the fines, chemistry, moisture content, slope, and erosive force. Sources of erosive force to consider are usually rainfall, wind and gravity. Mass wasting can become problematic if excavations or temporary embankments are over steepened.

The length of time a project takes affects the erosion control methods used. During single season construction projects, brief storms may be the largest risk to site erosion. In some areas of the country, the construction season may occur during periods of very intense rainstorms, with the potential to cause considerable erosion of freshly exposed soil. Increases in surface and subsurface flow may overwhelm dewatering and drainage systems.

Multiple-year projects experience a full cycle of seasons and may include multiple rainstorms, wind, snow, ice and drought. This can make some common erosion control methods unsuitable. Probably the best method to protect multi-year projects is to establish grass or some other dense annual groundcover. In arid areas, a thin layer of aggregate may be sufficient to reduce erosion.

Some projects may consist of removing a culvert and embankment the first year, then letting the stream adjust through the next season before reconstructing the site. Protection of exposed soils should be carefully considered. Stabilization may be undesirable at some sites, but necessary at others to prevent uncontrolled head cutting or destructive bank erosion. It may be possible to use on-site material, such as trees, brush, and large rocks, to provide some stabilizing structures.

Erosion Prevention Methods

Generally, slopes should be protected as excavation or embankment construction is completed. Preventing erosion means preventing soil particles from becoming dislodged. Some products are called erosion control even though they allow some erosion that can be trapped near its source. An example is straw mulch. If it doesn't cover nearly 100 percent of the surface area, some rainfall will fall between pieces of straw and dislodge soil. A 100 percent effective erosion control method would be to cover the vulnerable area with an impermeable membrane or a layer of non-erodable material on a moderate slope, such as a clean, coarse gravel layer. Areas to protect with more reliable methods are long sloping surfaces leading directly to live streams, such as a road embankment. Other critical areas are wetlands, rare and endangered sensitive plant locations, private land, utility corridors and archeological sites.

The type and effectiveness of the product should be based on the vulnerability of the soil in the environment. Steep slopes with loose fine sand may require 100 percent effective methods. Common effective erosion protection materials are straw mulch, hydraulically applied mulch grass seed, and erosion control fabrics. The contract may call for live vegetation, such as willow starts, in various configurations to quickly obtain root strength, shade and cover particularly in riparian zones, wetlands and along banks. Many rural forest projects can be left to "self seed." Native grass is commonly used to provide short-term erosion control until other natural seeding takes place and is established. Planting may have to be delayed until a suitable season arrives for successful germination.

Stockpiles may need to be covered with an impermeable membrane to prevent rainfall and wind erosion. Runoff from covered stockpile areas and larger drainage areas should be gathered and directed toward a suitable release point where it can be dispersed. Large openings may generate large amounts of dust and drainage. Reduce erosion by providing an effective frequent drainage system and a surface cover such as grass, mulch or gravel. Permanent waste areas may require more extensive planting, mulching and sometimes irrigation systems to establish permanent vegetation cover. More extensive landscape plantings are common on urban area highway projects and may include a complete landscape plan with mulch, groundcovers, shrubs and trees.

Excavation style and technique can affect the amount of sediment generated from the project. If the excavated slope angle during fill removal is too steep it may lead to shallow soil failures which fall into the excavation area or slide toward the live stream. Some excavation slopes are vulnerable to erosion and may benefit from a cover when not being worked on. Covering slopes may slow drying of embankments. Erosion of excavated slopes can become the largest source of sediments on some projects. Preventive erosion costs may be less than the costs of providing removal of that same suspended sediment for construction drainage. Loading and hauling excavated materials on the project can leave considerable amounts of fines on the road surface, which may wash into live streams. These areas should either be kept clean or a system of drainage and sediment trapping should be employed to protect the stream.

Sediment Trapping

The purpose of sediment trapping is to capture sediment that has already been dislodged and mobilized by rain or wind or gravity. The conventional methods of sediment trapping consist of silt fence installation around the entire work area. It may extend along some haul routes and surround stockpiles and waste areas. Other mechanical means of sediment trapping include berms, straw bales, wood shaving bundles, brush piles, vegetated swales, and use of vegetated areas with extensive groundcover capable of trapping sediment. Rain-generated sediment may be collected and treated with excavation water or other suitable filter systems.

Sediment collection ponds at the downstream end of the excavation may accumulate enough sediment to require removal to maintain adequate storage capacity. Consideration should be given to maintaining access to the pond during construction. Sediment may have to be loaded and transported to a suitable location for disposal. Since this sediment is usually saturated as well, it may drip from the bucket and risk entering a live stream. Determine how to transport this to a waste site with a suitable method (sealed container) ahead of time. This can be difficult in confined areas.

Clearing

After erosion prevention and sediment trapping systems are in place, clearing and grubbing proceeds. If sediment-trapping systems such as silt fences are damaged during clearing, they should be immediately repaired. When the contract calls for in-stream wood structures, tree removal from embankments may require leaving the stump attached. Other wood debris may be conserved and used as an additional erosion control feature on new embankments or riparian areas when the project is near completion. Clearing should be minimized and care should be taken to retaining vegetation for stream shade. Clearing limits should be outlined in the contract but flagged in the field.

Excavation

If excavation slope angles, bottom width and depth are not specified in the contract, the excavation will tend to be as narrow and steep as possible since this is an area of potential cost savings to the contractor. This can result in inconvenient and unsafe working conditions. Excavation slopes can ravel or fail creating excavation area drainage problems or damage to completed work. Large embankment or excavation slope failures may be capable of entering live stream areas.

Slope angle is a matter of safety and is regulated by the Department of Labor, Occupational Safety and Health Administration (OSHA). OSHA regulates maximum slopes and configurations for trenches and excavations up to 20 feet in depth. A registered professional engineer must design excavations with depths greater than 20 feet. The Department of Labor recognizes excavating as one of the most hazardous construction operations. Revised OSHA Subpart P, *Excavations,* of 29 CFR 1926.650, .651 and .652 make the standard easier to understand, permit the use of performance criteria where possible, and provide construction employers with options when classifying soil and selecting employee protection methods. Contract administrators should be familiar with this document.

The OSHA manual displays common hazards that may be encountered at stream crossing excavations. Inspectors should be aware of these features. OSHA provides maximum excavation slope angles for five categories of soil and various benching and trenching options. The Internet site is: http://www.osha-slc.gov/dts/osta/otm/otm_v/otm_v_2.html. A slope stability specialist should be consulted when unusual conditions arise. Figure 5 illustrates are common slope stability problems associated with excavation from the OSHA Excavation manual.

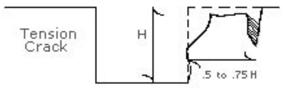
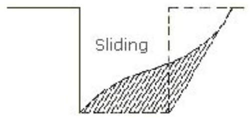
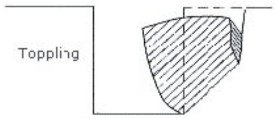
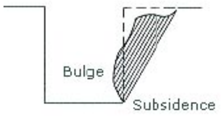
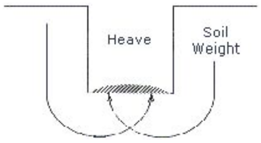
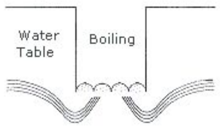
TENSION CRACKS. Tension cracks usually form at a horizontal distance of 0.5 to 0.75 times the depth of the trench, measured from the top of the vertical face of the trench. See the accompanying drawing for additional details.	TENSION CRACK 
SLIDING or sloughing may occur as a result of tension cracks, as illustrated below.	SLIDING 
TOPPLING. In addition to sliding, tension cracks can cause toppling. Toppling occurs when the trench's vertical face shears along the tension crack line and topples into the excavation.	TOPPLING 
SUBSIDENCE AND BULGING. An unsupported excavation can create an unbalanced stress in the soil, which, in turn, causes subsidence at the surface and bulging of the vertical face of the trench. If uncorrected, this condition can cause face failure and entrapment of workers in the trench.	SUBSIDENCE AND BULGING 
HEAVING OR SQUEEZING. Bottom heaving or squeezing is caused by the downward pressure created by the weight of adjoining soil. This pressure causes a bulge in the bottom of the cut, as illustrated in the drawing above. Heaving and squeezing can occur even when shoring or shielding has been properly installed.	HEAVING OR SQUEEZING 
BOILING is evidenced by an upward water flow into the bottom of the cut. A high water table is one of the causes of boiling. Boiling produces a "quick" condition in the bottom of the cut, and can occur even when shoring or trench boxes are used.	BOILING 

Fig. 5. Common slope stability problems associated with excavation from the OSHA Excavation manual.

Conserving Streambed Deposits

Once the existing pipe is removed, the excavation is normally deepened to the new pipe embedment or foundation depth. The excavated material may appear "dirtier" than other streambed material but is often stream sediments covered with fines from excavation. The material should not be substituted for imported streambed simulation rock unless approved by the designer since it may not represent the gradation of other streambed sediments and may lack the armor needed for streambed simulation material. Excavated material is often wet and should be dried to facilitate compaction in the structure. Place this material in a separate stockpile and protect it from contamination from other excavation.

Foundation Area Preparation

The excavation may intercept groundwater as general seepage, piping or "subsurface streams." This can cover the excavation bottom making it difficult to see the foundation bed area. Excavation normally begins downstream of the structure, extending upstream to facilitate subsurface drainage away from the work area and avoid pooling. The foundation area should be kept relatively dry to allow foundation areas to be seen, and shaped. As the bottom of the excavation is reached, a survey check should verify the proper depth has been reached. Measure twice and excavate once. A simple drive probe of rebar or pipe may be useful in prodding for bedrock, or estimating the soil consistency.

When the excavation is ready for foundation work, consideration should be given to covering the bed with either pipe bedding or "drain rock." This will keep excavation drainage much cleaner, improving mobility and working conditions.

Bedrock

When bedrock is encountered where the foundation is to be formed, the bedrock should be removed or the design should be modified to fit. The designer should always be consulted before making field adjustments to foundations since changes can affect streambed simulation, structural integrity and can lead to project failures. The designer and interdisciplinary team must be proactively involved during this phase of construction in case some condition arises which affects the foundation stability, or position. The site should be made to fit the design; otherwise, the designers should determine a new solution for the changed conditions in a timely manner.

Blasting Near Wildlife and Aquatic Species

Blasting may be desired when bedrock is countered. It can be prohibited for various reasons in some areas, or during part of the year. Nesting birds may require protection during specific periods. Time periods and concerns should be listed in project NEPA documents. If a wildlife biologist surveys the specific site and finds no species of concern, it may be possible to blast during normally restricted times. Blasting in or near water may be prohibited to protect aquatic species such as fish. Dewatered sites may be only partially hydraulically disconnected from the adjacent stream due to construction area drainage, or subsurface water in bedrock joints. Fish near blast sites may be injured as a result of swim bladder rupture, tissue and organ damage or internal bleeding. The damage to fish depends on size of charge, distance to fish, depth of water, substrate type and the size and species of fish (US Army Corps of Engineers 1995).

Some suggested blasting mitigation practices include (Golder Associates /Alberta Transportation, unknown):

- Limit the charge size and detonation velocity
- Prohibit explosives capable of producing an instantaneous pressure change greater than 100 kPa (14.5 psi) in the swim bladder of a nearby fish
- Prohibit explosives that produce peak particle velocity greater than 13mm/s in a spawning bed during incubation.

Table 2

Setback distance from detonation center to fish habitat to achieve 100 kPa standard

Weight of explosive charge (Kg)	0.5	1	2	5	10	25	50	100
Setback: Rock (m)	5	7	10	15	20	35	50	70
Frozen Soil (m)	5	6	9	14	20	31	45	62
Ice (m)	5	6	8	13	18	30	40	55
Saturated Soil (m)	4	6	6	12	18	28	40	55
Unsaturated soil (m)	3	4	5	10	12	20	28	40

Table 3
Setback from detonation center to spawning habitat to achieve 13 mm/s standard

Weight of explosive charge (kg)	0.5	1	5	10	25	50	100
Setback Distance (m)	15	20	45	65	100	143	200

Other blasting considerations include:

- Increase the delay between charges to 25 milliseconds or more
- Perform blasting work during non-critical or less sensitive time periods for fish
- Keep fish out of the blast area by electro shocking and surround the area with block nets
- Fill (stem) blast holes flush and consider using blasting mats to minimize blast debris scatter
- Ammonium nitrate-fuel mixture (ANFO) should be prohibited in or near water due to the production of toxic by-products (ammonia)

These specifications should be listed in the contract. Blasting details should be submitted by the contractor and checked for compliance by a knowledgeable blasting engineer.

Foundations

The foundation preparation area extends beneath footings, the area directly beneath pipes and an area to the side of the structure that supports backfill. The width of fill to either side of large multi-span structures can be quite wide and is based on structural considerations of soil/structure interaction. This width should be shown in the contract drawings. The foundation area should be approved by the foundation engineer before proceeding with construction. Concrete foundation may be founded on soil or rock. Metal footings require a bedding material beneath for even support. The AASHTO Soil-Corrugated Metal Structure Interaction System Chapter 12.1.6.3 states: "…It is undesirable to make a metal arch relatively unyielding or fixed compared with the adjacent side fill…Where poor materials are encountered, consideration should be given to removing some or all of the poor material and replacing it with acceptable material." Thus when bedrock is found under part or all of the foundation, it may be desirable to place a soil cushion over the rock to allow more even settlement of the footing and to reduce drag forces from settlement of the adjacent fill material. The structure thickness may be designed to accommodate drag forces and cushioning may not be necessary. Consult the designer before taking any actions not provided for in the contract. It is important to limit settlement to avoid adversely affecting line, grade, and structural shape.

The contract administrator must have a fundamental knowledge of soil types and be able to judge whether a material is suitable. Local experience is invaluable. General advice is to avoid fine-grained soils that are wet and soft to the touch. Wet granular soils may be suitable. Familiarity with the anticipated foundation bearing capacity is also important. A hammer driven probe can be used to find deeper layers of firm material or bedrock and to estimate soil consistency. Commercially available hand-held soil penetrating or shearing devices can be used to test undisturbed soil for shear strength to compare with design assumptions.

Settlement Beneath Foundations

Controlling settlement of the foundation area assures adequate backfill support and helps to maintain the constructed road surface shape. Compaction of this area, the condition of the soil during compaction, and the soil's properties control the potential settlement in this zone. If very soft materials are present, such as wet clay, silt of other soft plastic fine-grained soils, they should be replaced with structural backfill to improve compaction and limit settlement. Structural backfill should be a well-graded, dense material resistant to piping. The area directly beneath the structure should be compacted slightly softer than the embankment backfill to provide slightly more settlement, which will reduce settlement-caused stress on the pipe structure.

Concrete Footings

Constructing forms for concrete footings is a relatively time consuming part of the construction process. Each forming and concrete pouring sequence may take from a few days to a week or more. Massive rectangular footings are often used on smaller projects to speed foundation construction. Contractors may request changing footings from a footing and stem wall to a single rectangular footing of equal height and width. This is generally not a problem. Any foundation changes should be made or checked and approved by the designer or another foundation engineer. Survey accuracy is vital to obtaining parallel, equal elevation footings spaced properly for the arch dimensions. The structure can be attached to the top of the foundation using either a grouted slot or a bolted metal channel connection set at the proper angle. The grouted slot attachment is generally easier to use and more forgiving of minor errors.

The concrete pour is not always a flawless activity. Pump trucks can plug, concrete can spill, forms can be damaged, concrete can arrive early or late, cold joints can form. An experienced concrete contract administrator should always be present during pours. Protect streams from concrete. Concrete and related products that mix with water and enter live streams can kill fish in minutes because of high alkaline pH levels that are corrosive to fish gills.

Special concrete placement methods may be necessary when standing or running water is present in or adjacent to forms. If it is not possible to remove standing water from the form, it can be displaced. If running water is present, it can be plugged with concrete at the source. Regardless of the concrete placement method, when water is present, the concrete should be placed as gently as possible to avoid mixing and dilution with standing or running water. The pump hose should touch existing wet concrete, or with any method, be released as close as possible to existing wet concrete. Assure that water does not pond on the excavation side of forms where it can be forced through concrete joints washing away concrete and exposing reinforcing steel. Figure 6 illustrates the proper technique to pour concrete near flowing water.

Fig. 6. Concrete is being placed to seal off water at upstream end of form first.

Concrete forms can be stripped as soon as the cured concrete can support its own weight. Backfilling should wait until minimum strength is achieved in the concrete. Concrete test cylinders taken during the pour can be tested at intervals to determine when sufficient strength is reached. Accelerating the cure time with additives may be economical for the contractor. With massive footings it may be possible to place streambed simulation rock (interior) and backfill (exterior) on the other side of the footing in simultaneous lifts earlier. The design engineer should be consulted first. With high strength concrete or accelerators, a weekend may be sufficient for curing.

Metal Footings

When metal footings are used for open bottom arches, it may be possible to place some stream simulation material between the footings before full pipe assembly. Take special care to avoid displacing footings, which makes the remaining assembly very difficult.

Bedding

Bedding material and preparation are critical to both pipe performance and service life. Bedding helps maintain proper pipe elevation, eliminate undesirable stresses and ensures good hydraulic performance by minimizing flow around the pipe. Improper bedding beneath pipes can lead to loss of surface flow during periods of low water, preventing passage of aquatic species though the structure.

There are three general methods for placing bedding beneath a pipe. One method is to shape the bedding to conform to the pipe shape before placing the pipe in position. The second method is to carefully tamp a select granular material beneath the haunches to achieve a well-compacted condition (figure 7). Long span structures required intimate contact between invert and underlying soil for proper soil-structure interaction and stability. The third method uses a low strength concrete mix that is poured into position. The pipe must be secure against displacement or flotation prior to placing flowable concrete mixes. Placement of a minor amount of streambed simulation rock in the culvert for this purpose may work, but care must to taken to avoid deformation of the pipe. No machinery should be allowed in the pipe, but material can be placed by bucket or hand. Table 4 shows two sample mix designs for low strength concrete mixes.

Table 4
Examples of low strength concrete mixes

Special Pipe Embedment Material	Flowable Mortar	Controlled Low Strength Material (CLSM)
Cement	100 lbs	50 lbs
Fly ash	300 lbs	250 lbs
Fine Aggregate	2600 lbs	2910 lbs
Water, approximate	70 gallons	60 gallons
Compressive Strength at 28 days	100-200 psi	50 psi

Pipe Assembly

Non-multi-plate pipes require proper joints coupling and waterproofing gaskets to prevent water loss and backfill piping. Water loss during dry conditions can prevent aquatic species passage. Long-span multi-plate structures have special assembly requirements to maintain shape and may require a shape engineer from the manufacturer to guide assembly and backfill operations.

Backfill and Embankments

For embedded pipes, backfilling can begin when bedding is completed and the structure is placed. For open bottom arches with poured in-place footings, backfilling can occur as soon as footings can withstand backfill forces. Backfill should be placed in 6 to 8-inch lifts and brought up at the same rate and time on both footings. Machine compaction is used in wide areas and hand-operated equipment used in confined areas and against the structure. Many existing pipes show some signs of damage from construction handling or backfill operations. Assure that the minimum compacted cover height exists above the pipe before allowing traffic across. Where pipe cover is shallow, construction equipment may require more cover than the finished elevation of the road. A temporary cover may be necessary.

Fig.7. Hand tamping bedding with a pneumatic tamper.

Fig. 8. Placing flowing mortar bedding. Photos courtesy of Contech CPI

Stream Bed Simulation Materials

The most important detail of a stream simulation project is the simulated streambed. It requires the most care to produce a quality product that simulates the stream. It will be home to aquatic organisms traveling through and perhaps even living inside for a period of time. Specifications and drawings should describe the specific bed features.

Streambed Simulation Rock

Streambed simulation rock is the main material used in the structure. It is designed to match the gradation of streambed materials or to be slightly different if the structure requires a different gradient. Using stream simulation design guidelines, a well-graded mix of coarse to fine materials matching the stream is chosen to produce a dense, low permeability, well-interlocked bed. It should be specified in the contract and include details of gradation, placement shape and compaction method. When placed, the bed will have roughness, bed shape characteristics and a variety of hydraulic conditions similar to the natural channels. The bed is shaped to form a low water channel, rising toward the edge of the structure. The slope may flatten before the edge to form a bank line.

Obtaining stream simulation material may take extra effort. Materials often have to be gathered from a variety of material sources of boulders, cobbles, gravels, sands and "soil." Finer sizes of mix, such as 2-inch and smaller, may be available commercially. Table 5 provides a streambed simulation mix for a theoretical cobble and boulder dominated project stream.

Table 5
Project specification

% Passing	**Sieve Size**	**% Within Size Range**
D100	= 750mm	16% from 300mm to 750mm
D84	= 300mm	34% from 120mm to 300mm
D50	= 120mm	34% from 48mm to 120mm
D16	= 48mm	16% from 0mm to 48mm

The contractor and contract administrator should work together to determine a practical way to produce the specified mix as accurately as possible. Table 6 shows a practical recipe to produce the specified mix using locally available material gradations.

Table 6
Project recipe

Material Volume	Size and Source
2 loads of boulders	300mm to 750mm boulders from quarry
4 loads of cobble to boulder	125mm to 300mm shot rock from quarry
4 loads of gravels to cobble	50mm to 150mm mix of landscaping "river rock"
1 load of gravel to sand	50mm minus base rock or "river rock"
1 load of soil	bank soil from project site

Gradation requirements should be achieved and verified by weighing or measuring recipe components carefully. Evenly filled bucket loads are accurate enough. The bed material must be mixed well to provide good interlocking. Mixing may be done on site or remotely. Transport can cause mixed materials to separate some, but the remote mixing and transport may still produce a better product than mixing material on site.

Additional Large Rocks

Large rocks are sometimes added to simulate stream roughness elements or stable channel features found in the adjacent channel. They may be used to simulate stream banks, step-pool steps, and boulder fields. Large rocks may also be used to simulate effects of wood, bedrock, or colluvium. In the contract, the size, number and perhaps shape of the rocks will be specified. Large rocks may be available on site from existing structure riprap, embankment fill, or road maintenance debris storage.

Constructing the Simulated Streambed

The contract drawings should show the streambed in plan and profile views. The details may include:

- A shaped bed with banks and a low water channel
- Reinforced bank areas
- Across-channel steps
- Fields and clusters of large rocks

A study of adjacent streambeds, or the project reference can provide additional visual clues for how rough the surface may look, the orientation of interlocked step-pool steps, orientation of shaped particles and overall channel shape. The shape may appear rougher than the drawing. Drawings simplify the complex shape into representative dimensions for quantity and payment in the contact. Figure 9 shows a sample construction drawing with details for shaping the bed and constructing simple step pools. Specific details should be based on the specific project site, size and depth of streambed materials, and gradient.

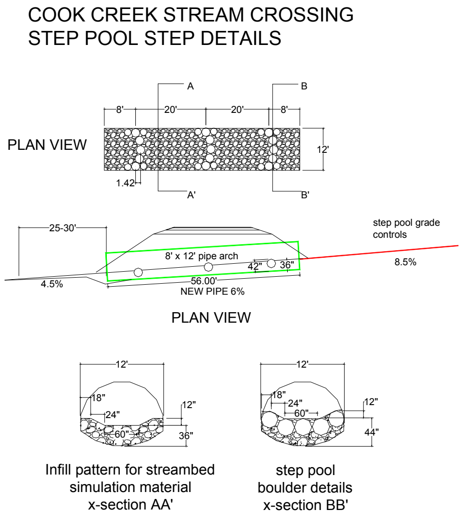


Fig. 9. Step pool and bed shaping details.

Placing Streambed Simulation Materials

Placing streambed materials within an open bottom arch is relatively easy since the material can be placed before the overhead arch is in place. An excavator is usually used to place bed materials. A variety of equipment can be used to compact the bed in thin layers. The backfill and streambed materials should be brought up to the same level at the same time. It is difficult to compact bed materials tightly against a concrete footing with an excavator. Smaller equipment can do more detailed work, but handwork should be used to perform final filling of voids along the footing wall and bed material. This material should be placed, tamped or washed into voids until they are filled before placing the next lift. Washing finer material into the voids with a hose is particularly effective. Proper gradation of bed material and thorough mixing of fines throughout will make this process easier and will take less time and may make it unnecessary. After placing the bed material, the shape of the bed can be made with an excavator bucket, blade, or backhoe. On small projects, hand labor may be any efficient shaping method. Large rock can be incorporated into the upper lifts. Carefully tamp material around large rock features to provide good interlocking and low permeability.

Many embedded pipes are relatively small. Most are non-multi-plate pipes with a maximum span of 12' for round and 14' wide for pipe arch shapes. Small equipment, such as rubber tired loaders (i.e., Bobcat), garden sized tractor-trailers, small dozers run on a cushion of previously placed bed material, or hand labor, can be used to place bed materials. Hand labor is typically underutilized. There is no exhaust to breath. The bed material can be loaded by machine into a two-wheel wheelbarrow, carried downhill and end dumped. As with any embedded pipe filling method, once dumped, the material must be spread by machine or by hand. Machines may be partially used for spreading but can be difficult to use in confined spaces. Hand labor is required to fill void spaces. It is best to place material in lifts and compact with wheels, hand held vibratory compaction equipment or rollers. Fill the voids by hand or by washing between lifts. Placing lifts one at a time through the entire pipe slowly reduces the headroom available. If this is detrimental to construction, the bed can be placed in layers that slope downward toward the inlet (filling end). This may facilitate placing large rocks as well. Figure 10 shows hand labor filling a pipe with a wheelbarrow. Figure 11 shows an excavator placing and mixing streambed material.

Fig. 10. Hand Labor – 1 day to place 45 CY.

Fig. 11. Machine Labor – 4 day to place 600 CY.

Larger multi-plate embedded pipes may allow larger equipment inside to facilitate bed placement. Larger equipment may cause bedding support problems unless bedding is of very high quality. Low strength concrete mixes are suggested if large equipment will be inside the pipe. It is typically not practical to place bed material before assembling the upper half of embedded pipes, though occasionally attempts are made such as cutting a one piece pipe in half, welding flanges to each half, filling, then bolting the two together. The wide flanges allow for some misalignment during connection.

Care should be taken to avoid damage to galvanized coating in steel pipes during bed placement. Pushing material on the metal surface can remove galvanizing, shortening the life of the structure. End dumping is preferred. Rubber tired equipment is strongly recommended. Overfilling of buckets should be avoided and spilled pieces should be removed from the travel path. A cushioning bed of streambed material should be placed in front of a tracked vehicle to avoid metal damage. Regardless of the haul method used, placement of the material is important to achieve density and low permeability. Hand labor is necessary to shape finer bed form details, especially in confined areas. Hand labor is also very useful at plugging voids left during filling between larger pieces of bed or between the bed and the culvert or foundation edge. Finer material, such as ¾"-minus can be packed and tamped into voids to seal the bed. It should be placed between lifts. With large bed material, thick lifts can be difficult to compact as particles lock together without fully seating themselves. The stream will add mobile fines to the bed surface in the future, but this is often not a reliable method of sealing the bed in the first year. When the bed is not sealed, low water flow will diminish or disappear. It can take years to seal the bed unless considerable fine sediments are transported during normal flows. Placing large rocks involves embedding them in smaller bed materials. Machinery is required to move large rocks. Large rocks in step-pool steps, along banks or in clusters should be oriented, fit and packed with finer material by hand for a good fit. This is a qualitative aspect of construction that benefits from natural talent and is difficult to enforce. Figure 12 demonstrates the difference between loose well-interlocked rock placements.

Fig. 12. Views of loose rock on left and tightly fit rock on the right.

Some channel length is usually reconstructed to connect the stream simulation project with the adjacent stream channel. This work requires the same level of concern as the structure including compaction in layers, machine and hand labor to reduce permeability, interlocking, and shaping of the bed material.

It is always beneficial to "kick a few rocks around" to improve the streambed after diverting the stream back through the pipe. The stream will erode fines, shift material around, and may be subsurface in some poorly sealed areas. This work should be part of a special specification in the contract. A few cubic yards of ¾" -

minus hand placed in these zones of vulnerability and tamped into voids can provide good passage conditions faster than if left to nature. Figure 13 shows a finished project with features of wide banks, margins, and a low-water meandering channel, inside an embedded pipe.

Fig. 13. A completed stream simulation project with bed simulation features.

Rewatering

Special attention is required when removing dewatering structures to avoid excess turbidity. In addition, pooled areas both upstream and downstream will have allowed movement of aquatic organisms into areas that may be drained as the diversion is removed. Provide protection by slowly lowering water in pooled areas to encourage movement into new habitat areas. Species may become stranded and need help moving to suitable habitat. Total breaching may be appropriate on some projects. It is normal for some fine sediment to be washed out of the streambed simulation materials during stream rewatering. Normally this will be greatly reduced in less than 24 hours.

Summary

Construction of stream simulation projects requires good design coupled with skilled contract administration and the cooperation of the contractor. Some semi-skilled hand labor is necessary for construction of the streambed features most valuable to the project. Protection of aquatic habitat and species can be a major emphasis and potentially troublesome task during a project. Good communication between designers, contractors, and contract administrators is necessary to make appropriate changes within the scope and objectives of the project. Projects that are not constructed as designed often suffer the consequences. Through the continued open communication of designers, contract administrators and contractors, project designs and contract details can be refined, wisdom can be shared and future project planning can be improved to aid future projects.

Construction Case Examples

The following photos demonstrate some of the problems that can be found during and after construction. All of these may have been prevented with good contract administration and the help of the designer.

Embedded pipe design. Engineer gave permission to County construction crew to eliminate bed material. The assumption was streambed material would be deposited into pipe by the stream. After two winters, pipe has minimal sediment stored, and there is a steep cascade at the pipe entrance, a barrier to many species and life stages of organisms.

- *Predicting sediment transport requires specialized skills.*
- *Sediment that washes into pipe can also easily wash back out.*
- *Recommend placing stream bed in pipe– base on stream reference reach*

Fig. 14. Design/Construction Problem – eliminated streambed material.

Survey error lead to inlet being placed 2' lower than meadow. Head cut traveled upstream draining wet meadow.

- *Sandy loam soil is easily eroded by stream flow.*
- *Channel erodes around wood leaving it stranded.*
- *Pipe invert elevation controls incision depth.*
- *Administration lacked survey quality assurance. Could have been presented.*
- *Site visit by designer during construction may have caught the error before project completion.*

Fig. 15. Administration Problem - Survey error leads to wrong inlet elevation.

Embedded pipe design, 6% gradient, 120% of bank full width structure. Streambed material partially scoured out during a 100-yr storm. Downstream pool area is filled with fine sediment. Water is subsurface my mid summer. Pipe has not refilled after 7 years. Streambed material gradation remaining in pipe is 25% smaller than average cobble/gravel size in upper stream channel.

- *Streambed material scoured because of small size and may have been too thin to develop good interlocking.*
- *Recommend – Construct a new bed based on a stream channel reference reach.*

Fig. 16. Design Problem – Scour resistance of undersized streambed simulation material.

Contract called for "streambed gravel." What went wrong here could happen as a result of: the design or errors in translating into the contract documents, inadequate administration of the contract or misinterpretation by the contractor.

- *Be specific in the contract. Describe streambed material and gradation.*
- *Communicate objective of having the structure streambed look like the channel streambed.*
- *Recommend – Try to remove undersized material and replace with streambed simulation design material.*

Fig. 16. Construction Problem – Supply of incorrect streambed: contract or administration?

Surprise #1:
An extra pipe and wood debris is found beneath existing pipe. It was apparently damaged in a past flood event, smashed and left in place. The pipe and debris extend beneath embankment near inlet. Excavation had to be widened to remove debris. Extra days of work create additional turbidity to treat.

- *Design change*
- *Remove extra debris*

Surprise #2:
Excavation is 6 feet below existing streambed. Multiple past debris slides can be seen in excavation. Abundant groundwater and subsurface streams flood the excavation during summer rainstorms. Dewatering and treatment of turbidity depended on settlement ponds and riparian vegetation filters to remove sediment Filtering capacity was inadequate during storm events. Excavation water should have been transported out of the narrow confined valley to a better filtering area.

- *Design change*
- *Develop and use a better treatment plan*

Surprise #3:
Large boulders were found in the foundation area. This 6' diameter boulder is too heavy to move by the excavator and blasting could dislodge the larger boulder overhead. The foundation design was modified to incorporate the boulder into the concrete footing and stem wall. Holes were drilled into the boulder. Rebar was grouted in holes and connected to foundation steel. Overall dimensions of the footing are massive compared to the boulder.

- *Design change*
- *Modify footing details near boulder*

Fig. 17. Illustrates several "surprises" found during the contract.

Surprise #4

You wake up one morning with a "funny feeling". So you drive out to the project site just because…and you find the contractor got up early too! Give notice of non-compliance!

- *No pumps are running: he is generating very high turbidity levels, water is overtopping the dam, releasing sediment directly into the stream, possible petrochemical pollution.*
- *This is a violation of a basic project objective of protecting aquatic species and habitat.*

Surprise #5

- Pipe lacks any banks or roughness characteristics like it's boulder channel.
- Place materials as shown on drawings.

Fig. 17. (con't) Illustrates several "surprises" found during the contract.

Biological Sketch: David Kim Johansen is a geotechnical engineer and geologist for the Northwest Region of the United State Forest Service. He is a Geotechnical Engineer, Geologist, P.E. who has been with the USDA Forest Service 23 years working in Willamette, Siuslaw, and Gifford Pinchot National Forests. He has been a landscape laborer and foreman 11 years. His primary duties include geotechnical engineering, aquatic organism passage designs, inspections, training, and monitoring.

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FISH PASSAGE AT SELECTED CULVERTS ON THE HOONAH RANGER DISTRICT, TONGRASS NATIONAL FOREST

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Abstract: In the month of July 1997, 38 culverts suspected of blocking upstream passage of juvenile salmonids were inventoried on the Hoonah Ranger District. Attributes measured included species/numbers of fish upstream and downstream of each culvert, in addition to physical characteristics such as outlet barrier height, culvert gradient, and upstream habitat. Thirty culverts exhibited some form of physical impediment (excessive barrier height and/or gradient) to the upstream migration of juvenile salmonids. Of the 30 barrier culverts, the height of the lower lip of the culvert outlet above the streambed ranged from 0cm to 205cm and averaged 36.5cm. The gradient of these structures ranged from –0.5 percent to 14.5 percent and averaged 5.0 percent. Thirteen Class I (anadromous) culverts were sampled, of which nine lacked juvenile coho upstream of the culvert (no juvenile steelhead trout were trapped during the study). Boxplots of number of juvenile salmon trapped upstream of culverts relate a considerable reduction in distribution, median, and mean as compared to downstream. All 13 culverts exhibited an outlet perched above the streambed, with barrier heights ranging from 10cm to 99cm, averaging 38.8cm. Class I culvert gradient ranged from 0.5 percent to 9.5 percent and averaged 3.4 percent. Nineteen culverts were identified as Class II culverts (i.e., culverts in streams providing cutthroat trout and Dolly Varden charr habitat occupied upstream of anadromous habitat) during the survey, of which 17 exhibited some physical form of barrier to juvenile passage. Outlet barrier heights ranged from 0cm to 205cm, averaging 37.2cm. Culvert gradient ranged from 2.0 percent to 9.0 percent and averaged 4.3 percent. Eight of the 19 Class II culverts had resident fish species trapped upstream of the culvert, six of which occurred above culverts exhibiting barrier characteristics such as outlet perch or excessive gradient. Boxplot distribution, median, and mean of height of outlet barrier and culvert gradient tended to be greater at Class I and Class II structures without fish trapped upstream as compared to culverts where fish were trapped upstream. This pattern was repeated for culvert length at Class I crossings, but was reversed for Class II structures. Overall, barrier culverts resulted in a loss of 8.11km (16,534m^2) of fish habitat, comprised of 2.68km (6,408m^2) of Class I and 5.42km (10,126m^2) Class II habitat. Habitat lost per culvert at Class I crossings was 206m (493m^2 by area), and 319m (596m^2 by area) for Class II culverts. Roughly 37% of Class I fish habitat lost (determined by length) was of high-quality Floodplain process group reaches with an additional 47 percent comprised of moderate-quality Moderate Gradient–Mixed Control reaches. Class II habitat lost comprised about 41 percent Mixed-Moderate reaches, followed by 32 percent High Gradient-Contained and 17 percent Alluvial Fan process group reaches, both providing relatively low-quality fish habitat.

Introduction

Recent (Bramblett et al. 2002) and past studies (Skeesick 1970; Cederholm and Scarlett 1981; Peterson 1982; Hartman and Brown 1987; Nickelson et al. 1992) have identified how various juvenile salmonids in the Pacific Northwest migrate upstream into smaller streams seasonally, and during winter or extreme disturbance events (Bustard and Narver 1975; Tschaplinski and Hartman 1983; Swales 1986; Hartman and Brown 1987; Brown and Hartman 1988) to access refugia to avoid injury or death. Anthropomorphic barriers, such as improperly functioning culverts, block such migrations and present a considerable risk to species with such life history strategies. Results from past monitoring reports on what was then the Chatham Area of the Tongass National Forest (TNF; USDA 1995, 1996) identified a need for increased evaluation of fish passage through culverts on the Hoonah Ranger District. In the summer of 1997, Hoonah Ranger District (HRD) personnel, with funding support from the Environmental Protection Agency (EPA) and the Alaska Department of Environmental Conservation (ADEC), conducted a study of culverts along road segments suspected to contain high densities of barrier culverts. The purpose of this specific inventory was to (1) determine if juvenile salmonids were affected by barrier culverts, (2) better understand the physical conditions that comprise barrier culverts and, (3) quantify lost habitat to better prioritize restoration of fish passage for all sites.

Study Area

The Tongass National Forest lies within the Alexander Archipelago of southeast Alaska (fig. 1). One of nine ranger districts and two national monuments, the Hoonah Ranger District encompasses the northern half of Chichagof Island, just south of Glacier Bay National Park. Climatically, maritime currents of the North Pacific moderate landscape temperatures; however, wintertime extremes can result in intervals of stream icing. Southeast Alaska is quite wet, and the study area within northeast Chichagof Island averages 60-100” of precipitation annually, the majority as rainfall in the months of September through November. Geomorphologically, the landscape of the district has been strongly influenced over the last 20,000 years (and earlier) by glacial forces. Valleys exhibit the classic “U-shaped” cross-section associated with glacial action. Stream systems are short and steep compared to other landscapes of the Pacific Northwest. The most common forces of disturbance affecting stream morphology include floods, tree blowdown, and ice. Where possible, roads have been located away from valley bottoms to avoid conflicts with riparian resources, particularly high-value spawning and rearing habitat of salmonids. However, the location of roads too far uphill along valley slopes can lead to other problems, such as erosion and road stability. The collective result has been arterial roads that parallel stream corridors, generally traversing hillslopes at 2 to 8 percent gradient. Providing upstream fish passage through such culverts can be a considerable challenge.

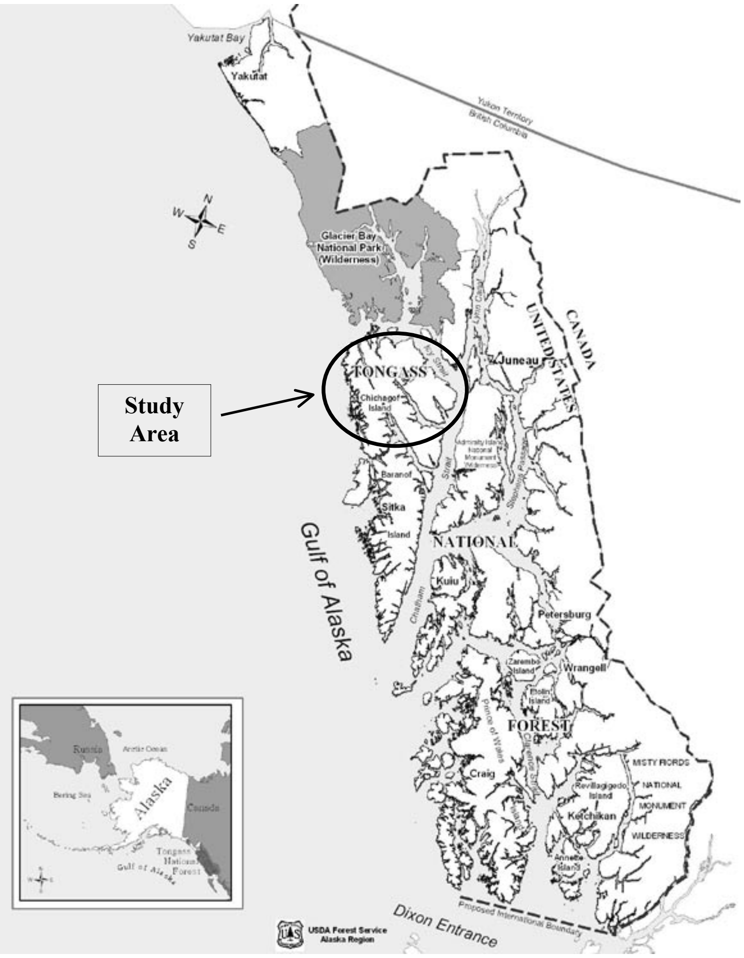

Fig. 1. Map of the study area within the Tongass National Forest, southeast Alaska.

Methods

Road systems of the HRD suspected to harbor high densities of culverts blocking upstream fish passage included segments in the Game Creek (Road #8502 8504), Freshwater Creek (Road #8508), Iyouktug Creek (Road #8534), Suntaheen Creek (Road #8530) and Pavlof River (Road #8513) watersheds. Perched culverts on streams suspected to contain fish were minnow-trapped upstream and downstream of each culvert to enumerate fish species. Two minnow traps baited with borax-treated salmon eggs were each set in unique pools immediately both upstream and downstream of each culvert. All four traps were fished for three hours at each culvert, after which fish trapped were each identified and tallied by species relative to location upstream or downstream of the culvert. Due to an error in sampling, numbers of fish trapped were not tallied at four Class II culverts, although species presence upstream and downstream was recorded.

During the months of June and July 1997, physical attributes such as diameter, length, slope, and barrier height (the elevation of the lower lip of the culvert outlet above the streambed immediately downstream) of each culvert were measured using a fiberglass tape and/or a surveyor's rod and level. Reaches upstream of Class I and Class II culverts were each measured for length of channel, channel type, stream class, mean stream gradient (clinometer), mean channel width, and natural fish barrier attributes to later determine length and area of discrete channel types based on the Tongass National Forest Channel Typing Guide (Paustian 1992). Each change in reach was determined as a result of change in channel type, gradient, stream class, and/or barrier attribute. Natural fish barrier attributes were judged and recorded by the fisheries biologist. Criteria used to determine barriers included height of bedrock falls or other obstacles, or cascades with significant increases in channel gradient, typically greater than 25 percent. A logjam could also qualify as a barrier if it was judged by the fisheries biologist to block upstream passage under high flow conditions and was more than just a transitory structure. Location of culverts were mapped on aerial photos and transferred to blue-line ortho-photo maps with the intention of incorporating this information into the Chatham Area GIS database.

Results

A total of 38 culverts were inventoried during the month of July 1997, of which 35 entailed some degree of blockage to upstream migration of juvenile salmonids at the fish entrance of the culvert. Barrier height between the streambed and lower lip of culverts ranged from 0cm to 205cm and averaged 36.5cm (table 1).

Table 1
Mean physical characteristics of culverts and upstream habitat surveyed, Hoonah Ranger District, July 1997. The asterisk notes that five of six culverts at Class III (non-fish bearing) crossings were perched such that upstream fish passage would be blocked.

Attribute	Class I	Class II	Class III	All fish culverts
Number of culverts sampled	13	19	6	38
Number of culverts blocking juvenile fish passage	13	17	5*	30
Mean height of lower lip of culvert outlet from streambed (cm)	38.8	37.2	23.3	36.5
Mean culvert slope (%)	3.4	4.3	9.0	5.0
Mean culvert diameter (cm)	112	90	107	101
Mean culvert length (m)	12.7	12.7	13.0	12.8
Mean percent of channel constricted by culvert (%)	77.7	87.5	8.3	71.7
Total length of upstream fish habitat blocked (m)	2,683	5,425	NA	8,108
Total area of upstream fish habitat blocked (m^2)	6,408	10,126	NA	16,534
Mean length of upstream habitat blocked per culvert (m)	206	319	NA	270
Mean area of upstream fish habitat blocked per culvert (m^2)	493	596	NA	551

Class I Culverts

Of the thirteen Class I culverts surveyed, ten were previously unmapped, two were mapped as Class I, and one as Class II. All thirteen Class I culverts exhibited an outlet perched above the streambed, with barrier heights ranging from 10cm to 99cm with a mean of 38.8cm. Class I culvert gradient ranged from –0.5 percent to 9.5 percent and averaged 3.4 percent.

Class II Culverts

Nineteen culverts were identified as Class II culverts (i.e., culverts in streams occupied by and/or supporting habitat of cutthroat trout and Dolly Varden charr upstream of anadromous habitat) during the survey, of which 17 exhibited some physical form of barrier to juvenile passage. None of the Class II stream crossings were previously mapped as fish streams. Outlet barrier heights ranged from 0cm to 205cm, averaging 37.2cm. Gradient of Class II culverts ranged from 2.0 percent to 9.0 percent and averaged 4.3 percent.

Class III Culverts

Six culverts were identified as Class III culverts (i.e., culverts in streams not supporting fish, generally a result of natural barriers) during the survey, of which five exhibited some physical form of barrier to juvenile passage, if passage was actually attempted. Outlet barrier heights ranged from 0cm to 40cm, averaging 23.3cm. Gradient of Class III culverts ranged from 3.0 percent to 14.5 percent and averaged 9.0 percent.

Fish Trapping

No juvenile steelhead trout were trapped either upstream or downstream of any culvert surveyed during the entire study. Juvenile coho salmon were trapped from 10 of the 13 Class I streams surveyed. The three remaining Class I culverts were located in streams judged by the author to be Class I as juvenile coho salmon or steelhead trout had been previously observed and/or due to the proximity and accessibility of known Class I habitat. The mean number of fish trapped downstream of all Class I, culverts was more than seven times greater than trapped upstream (fig. 2). Similarly, the box plot distribution and median number of juvenile coho salmon trapped was considerably greater downstream versus upstream of Class I culverts.

Fig. 2. Boxplot of number of individual anadromous/resident fish trapped upstream or downstream of culverts at 10 Class I and 14 Class II culverts on the Hoonah Ranger District, July 1997. The mean number of fish trapped is in parentheses.

Fig. 3. Boxplot of the elevation of the lip of the culvert outlet above the streambed, stratified by Class I or Class II culverts with or without fish upstream on the Hoonah Ranger District, July 1997. Mean barrierheight is in parentheses. Number of culverts inventoried are labelled as "n=" under each category.

Trout and charr were trapped from 18 of the 19 Class II streams surveyed. Due to an error in sampling, the number of fish trapped was not tallied at four of the 18 Class II crossings where fish were trapped. The Class II culvert where no fish were trapped was judged by the author to be Class II habitat due to its proximity and accessibility to known Class II habitat. Similar to the pattern in abundance of juvenile coho salmon downstream versus upstream of Class I crossings, the mean number of trout and charr trapped downstream of Class I and Class II culverts was greater than upstream, although the magnitude of this difference was much less pronounced for these two species, particularly when comparing the median values and the box plot distribution of numbers of fish downstream versus upstream (fig. 2).

Culvert Barrier Height

Juvenile coho salmon were trapped upstream of four Class I culverts. The mean barrier height of Class I culverts where juvenile coho were trapped upstream was 60 percent less than that of Class I culverts where no juvenile coho were trapped upstream (fig. 3). This strong difference in barrier height was also exhibited by the median (~50 percent) and the boxplot distribution. It should also be noted that minnow trapping efforts failed to detect juvenile coho upstream of culverts with barrier heights less than the mean or median height described for culverts where juvenile coho were trapped upstream. Mean barrier height was 10 percent less at Class II culverts with trout or charr trapped upstream than at crossings without fish trapped upstream; this difference would be much greater with the exclusion of the 205cm outlier. At Class I culverts, barrier height was 28 percent less at culverts with trout or charr trapped upstream than at Class II culverts without fish trapped upstream. The median and the boxplot distribution of barrier height at Class II culverts with trout or charr trapped upstream were both considerably less than at Class II culverts without fish trapped upstream, although these differences were only slightly apparent at Class I culverts with trout or charr trapped upstream.

Fig. 3. Boxplot of the elevation of the lip of the culvert outlet above the streambed, stratified by Class I or Class II culverts with or without fish upstream on the Hoonah Ranger District, July 1997. Mean barrier height is in parentheses. Number of culverts inventoried are labelled as “n=” under each category.

Culvert Gradient

Mean gradient of Class I culverts where juvenile coho salmon were trapped upstream was 35 percent less than that of Class I culverts where no juvenile coho were trapped upstream (fig. 4). Comparison of the boxplot distribution of culvert gradient between Class I culverts with and without juvenile coho trapped upstream relate a similar discrepancy; however, comparison between the respective median values shows no real difference, possibly due to the limited number of culverts (4) with juvenile coho trapped upstream. Mean gradient of Class II culverts with trout or charr trapped upstream was slightly less than that of Class II culverts where fish were trapped upstream; whereas, the median was considerably less for Class II culverts with fish upstream. Comparison of the boxplot distribution of Class II culverts with trout or charr upstream is somewhat less than that of Class II culverts without fish upstream. Class I culverts with trout and charr trapped upstream exhibited considerably lower mean, median, and boxplot distribution of gradient than Class II culverts with or without trout or charr upstream.

Fig. 4. Boxplot of culvert gradient stratified by stream class and the presence or absence of fish species upstream of culverts suspected of blocking fish passage, Hoonah Ranger District, July 1997. Mean culvert gradient is in parentheses.

Culvert Length

Mean length of Class I culverts where juvenile coho salmon were trapped upstream was 17 percent less than that of Class I culverts where no juvenile coho were trapped upstream (fig. 5). Comparison of the median and the boxplot distributions of culvert length between Class I culverts with and those without juvenile coho trapped upstream relate a similar considerable difference. The mean length of Class II culverts where trout or charr were not trapped upstream was 27 percent *less* than that of Class II culverts with fish trapped upstream, and 11 percent *less* than that of Class I culverts where trout or charr were trapped upstream. The median and the boxplot distributions of the length of Class II culverts without fish upstream were also considerably less than that of Class I or Class II culverts with trout or charr upstream.

Fig. 5. Boxplot of culvert length stratified by stream class and the presence or absence of fish upstream at stream crossings suspected of blocking fish passage on the Hoonah Ranger District, July 1997. Mean culvert length is in parentheses.

Channel Constriction by Culverts

Figure 6 describes the relationship of culvert diameter graphed as a function of bankfull width for fish culverts surveyed. This graph strongly reflects the tendency of undersized culvert diameter relative to bankfull width of fish streams on the Hoonah Ranger District. Constriction of the channel typically results in increased water velocity and outlet scour during channel-forming (bankfull) flows and greater.

Fig. 6. Culvert diameter as a function of mean bankfull channel width, fish culverts surveyed on the Hoonah Ranger District, July 1997.

Shotgun Culverts

Other observations of culvert condition were also recorded during the survey. "Shotgun" culverts (fig. 7), a term relating how culverts were installed with their outlet extending over and above the streambed at an excessive distance and/or height, were common. Eight of the thirteen Class I culverts were shotgunned, as were 15 of 19 Class II and three of the six Class III culverts surveyed.

Fig. 7. Example of a shotgun culvert. Road #8576, Hoonah Ranger District, 1997.

Fish Habitat Upstream of Barrier Culverts

Fish habitat inventoried upstream of barrier culverts is stratified hierarchically by stream class and process group (Paustian 1992) in table 2. Overall, barrier culverts resulted in a loss of 8.11km (16,534m^2) of fish habitat, comprised of 2.68km (6,408m^2) of Class I and 5.42km (10,126m^2) Class II habitat. Habitat lost per culvert at Class I crossings was 206m (493m^2 by area), and 319m (596m^2 by area) for Class II culverts. Roughly 37 percent of Class I fish habitat lost (by length) was of high-quality floodplain (FP) process group reaches with an additional 47 percent comprised of moderate-quality moderate gradient–mixed control (MM) reaches. Class II habitat lost comprised about 41 percent MM reaches, followed by 32 percent high gradient-contained (HC) and 17 percent alluvial fan (AF) process group reaches, both providing relatively low-quality fish habitat.

Table 2
Number of segments, total length and area, and length and area per segment, stratified by stream class and process group for fish culverts suspected to block upstream passage, Hoonah Ranger District, July 1997.

Stream class	Process Group	Rearing habitat quality	Number of segments	Total length (m)	Length per segment (m)	Total area (m^2)	Area per segment (m^2)
I	FP	High	5	985	197	2,824	565
	MM	Moderate	13	1,260	97	2,753	212
	MC	Moderate	1	382	382	764	764
	AF	Moderate	1	56	56	67	67
Total			20	2,683	134	6,408	320
II	PA	High	1	100	100	1,500	1,500
	MM	Moderate	7	1,352	193	2,090	299
	MC	Moderate	1	252	252	378	378
	AF	Moderate	3	110	37	155	52
	HC	Low	12	732	61	593	49
Total			24	2,546	106	4,716	196
Class II habitat upstream of Class I	FP	High	1	193	193	328	328
	MM	Moderate	9	881	98	1,325	147
	AF	Moderate	17	826	46	1,309	77
	HC	Low	17	978	58	2,448	144
Total			44	2,878	65	5,410	123

Discussion

The physical forces and the mathematical relationships describing the limitations of fish to pass upstream of obstructions such as dams and culverts are fairly well reported (Metsker 1970; Bell 1973; Baker and Votapka 1990; Orsborn and Johnson 1997; USDA Forest Service 1999), although many details, particularly swimming speeds of many salmonid species/life stages, are yet to be determined. Fish culverts surveyed during this study tended to exhibit obvious barrier characteristics, such as elevated outlets and/or excessive gradient. Comparisons of mean, median, and boxplot distributions of number of fish trapped downstream versus upstream of culverts further suggest that all Class I culverts surveyed function as barriers to upstream passage of juvenile coho salmon, and that about 90 percent of Class II culverts surveyed block passage of trout and charr. Comparison of the presence/absence of fish species upstream versus downstream of culverts relative to mean, median, and boxplot distributions of outlet barrier height and culvert gradient lend further credence that improperly designed and/or installed culverts function as barriers to upstream fish passage. Comparison of the presence/absence of juvenile coho salmon upstream versus downstream of culverts suggests that Class I culvert length may be limiting their upstream presence; however, the length of neither Class I or Class II culverts appear to be limiting the upstream presence of cutthroat trout or Dolly Varden charr. Mean length of all culverts (~13m ± 2.5m) appears a function of road prism width.

Results from tagging studies on Prince of Wales Island in southeast Alaska (Bramblett et al. 2002) describe how juvenile coho salmon were abundant in tributaries during all seasons. They also observed the upstream movement of large numbers of juvenile coho from main-stem channels into tributaries during the months of September and October, in addition to lower levels of downstream movement during the same period and during the typical out-migration period of April and May. Bramblett et al. (2002), Bryant (1984), Dolloff (1986) and Bjornn et al. (1991) all reported that juvenile steelhead were absent or rare in tributary channels during summer. Bramblett et al. (2002) described strong upstream movement of tagged steelhead juveniles during the fall, followed by downstream migration of smolt and younger juveniles (re-colonization) in the spring. They also reported that during the months of June and July, juvenile steelhead migrate very minimally, remaining in main-stem channel habitats. Juvenile steelhead trout were not trapped during the course of this inventory, and the results of Bramblett et al. (2002) provide a reasonable explanation for the absence of juvenile steelhead in our traps. Since the focus of this study was on upstream passage of juvenile salmonids, the accuracy of similar inventories in this landscape would benefit if conducted during the fall high-flow season when target species/stages are most inclined to ascend stream crossings.

Compared with juvenile coho salmon, trout and charr were present upstream of culverts with taller outlet barriers and greater gradients. Trout and charr exhibit resident forms located in headwater habitats that express their entire life cycle from reproduction to adult life stages, generally without migrating to sea.
As a result, adult forms of both cutthroat and Dolly Varden grow not only older but also larger than their anadromous cousins in such habitats. Greater body length provides for greater swimming speeds and jumping capabilities, which is one explanation why both species were affected to a lesser degree by barrier height or

culvert gradient than were juvenile coho salmon. Furthermore, culvert length, which reduced the presence of juvenile coho salmon upstream (as would be expected), was actually an advantage to the presence of trout or charr upstream. It may be that other factors such as gradient and or barrier height may have been playing a confounding role at these Class II culverts; however, this possibility was not explored. Continued study to determine life history strategies of resident species, particularly the importance of connectivity to long-term persistence of populations and/or meta-populations, would be crucial to defining how barrier culverts affect fragmentation of resident habitat/populations. Such knowledge would be extremely useful to designing crossing structures without impact to fish passage.

Channel constriction by undersized culverts was evident from this study. Channel constriction results in increased water velocity within and exiting the structure, creating a barrier to upstream fish passage. Where the streambed is not composed of bedrock or properly aproned with riprap, streambed elevation can be reduced. Sometimes this reduction is in the form of a pool and does not alter the ability of fish to enter the culvert. More commonly the culvert outlet becomes “perched” above the lowered streambed, creating a barrier to the upstream migration of smaller, less aggressive swimming fish. The effects of increased water velocity due to channel constriction can also be compounded as a result of excessively high culvert gradient and/or flow augmentation via ditch lines with improper road drainage. Designing and installing road crossing structures that allow bankfull events to flow unimpeded will require larger culverts or alternative structures. Given that channel gradients typically exceed 2 percent, designing structures for the upstream passage of fish will likely require imitating natural roughness inside culverts. Providing for larger structures that mimic natural streambeds requires a greater capital investment, but the return on such an investment will likely be accrued over the long term with reduced maintenance and/or replacement costs. In a landscape where floods and bedload are as dynamic and chronic as southeast Alaska, such a return is certainly worth investigating.

In total, considerable lengths and areas of high- and moderate-quality habitat were lost upstream of barrier culverts surveyed. The length of habitat lost upstream per culvert averaged about 200m, which may not seem considerable until cumulatively assessed across the landscape. Lost habitat certainly results in lost productivity of salmonid species. What this impact is, relative to the long-term persistence of each species, is a task beyond the scope of this study, but certainly worth investigating. Area, as a measure of habitat lost, was usually redundant with length, as most channels in most all process groups averaged about 2m bankfull width, the coefficient multiplied by length to determine area. Describing habitat lost using only length measures simplifies discussion of this subject.

Biographical Sketch: Chris Riley received a B.S. in biochemistry from Oakland University in 1981, and an M.S. in biology from Montana State University in 1996. The title of his thesis is “Evaluation of spawning gravel restoration in a placer-mined Montana stream.” He began his career with the Forest Service as a volunteer in 1988.

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PROTECTION OF AN ENDANGERED FISH *TOR TOR* AND *TOR PUTITORA* POPULATION IMPACTED BY TRANSPORTATION NETWORK IN THE AREA OF TEHRI DAM PROJECT, GARHWAL HIMALAYA, INDIA

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Abstract: Sound ecological practices in development of roads and highways are essential to protect the fragile ecosystem of the Himalayan mountains in northern India. Evidence is growing that the expanding, poorly designed network of roads and trails is a major cause of habitat fragmentation and degradation of both terrestrial and aquatic habitats. These effects have been quantified for two similar species of fish, collectively known as the Mahseer, which comprises *Tor tor* Hamilton and *Tor putitora* Hamilton, in the area of the construction of the Tehri Dam Project, located in the Garhwal Himalaya, India. The Tehri Dam Project will be one of Asia's highest dams (260.5 meters height), and fifth highest in the world. It is being constructed approximately 1.5 kilometers downstream of the confluence of the Bhagirathi and Bhilangana, which together form the Ganges River after meeting the Alaknanda River (30 degrees, 23 minutes N; 78 degrees 29 minutes E). The dam is a multipurpose project which costs more than 8,000 crores of Indian rupees (USD: $1,780 million). It will generate 2,400 M.W. of electricity, and irrigate 2.7 million hectares (6.6 million acres) of land, plus provide municipal drinking water to a large population. New roads have been constructed along the banks and in the riparian zone of the two rivers. This has introduced large amounts of woody debris and sediments into the waterways, resulting in drastic changes in the physico-chemical and biological profile of the aquatic ecosystem. Detrimental effects on transparency, current velocity, conductivity, substrate composition, dissolved oxygen and benthic communities have been documented. Feeding, spawning and migration routes of Mahseer have been degraded or destroyed. Subsequent to road development, standing crop estimates of Mahseer declined from a maximum mean monthly biomass of 0.492 $g.m^{-2}$ (February) to 0.185 $g.m^{-2}$, a 62% decrease, and a minimum monthly mean biomass (July-August) of 0.185 $g.m^{-2}$ to 0.014 $g.m^{-2}$, a 92% decrease. Annual productivity of Mahseer declined from 0.198 $g.m^{-2}.yr^{-1}$ to 0.054 $g.^{m-}2.y^{r-1}$ (73 percent). This decline is believed to have been caused by increase in turbidity, accompanied by a decline in dissolve oxygen, decrease in general benthic productivity, and loss of cover. We have recommended the following measures to restore habitat quality and connectivity for the Mahseer: stream restoration and stream bank stabilization, gravel mining and dredging in the impacted sites, protecting of riparian vegetation, monitoring of water quality, enhancement of fish food reserves, rehabilitation of Mahseer in a hatchery / nursery, ecofriendly techniques for road development and maintenance, and the establishment of strong working partnerships among civil engineers, environmental biologists and the public.

Introduction

The Himalaya is among the highest and youngest mountains of the world, and it is still growing and undergoing structural changes. It is the provider of life support for six countries. Not only does the Himalaya control the climate of Asia, it has also moulded the lifestyles of the people who inhabit the lands in and around the mountain domain. The biodiversity of the Himalaya is extraordinarily high even in the global context. The entire Himalaya has been inaccessible with poor communication. Many development projects, including a network of transportation and river valley projects, have been launched in the Himalayan zone of India during the last three decades to overcome the problems of poor communication. Transportation networks are essential for human mobility and the transportation of materials. The Himalaya is a fragile mountain ecosystem, and it is vulnerable to any change. Transportation networks have caused a large-scale habitat fragmentation, which can lead to species extirpation or extinction. Therefore, it is very important to understand the vital links between aquatic ecosystems and transportation networks in the Himalaya to minimize conflicts between transportation systems and aquatic life and to restore habitat connectivity. Sound ecological practices in the development of roads are essential to protect the fragile ecosystem and the vital living components of the Himalayan mountains in northern India.

Considerable works have been done on the impact of transportation networks on aquatic ecosystems and fish life in America and Europe. However, no sincere effort has been made so far on the protection of fish influenced by the expanding transportation network in India. Therefore, it was felt desirable to asses the impact of transportation networks on two similar species of endangered Himalayan fish, collectively known as Mahseer, which comprises *Tor tor* Hamilton and *Tor putitora* Hamilton in the area of the Tehri Dam Project, located in the Garhwal Himalaya, India.

The Mahseer is an important game and food fish distributed along the Himalaya in India, Pakistan, Bhutan and Bangladesh. The native name *Mahseer* refers to its large scales and heads. The Mahseer is a migratory fish and attains a maximum weight up to 25kg. An 18kg (152cm length) Mahseer has been recorded under the present study. The fish is a column feeder and omnivorous (adult) planktivorous (juvenile). The ecological status of these species of Mahseer has been assigned as endangered by Singh and Sharma (1998), Anon (2001) and Sharma (2003).

Materials and Methods

Physiography of the Study Area

The study area is located in the Garhwal Himalaya, an important zone of the Himalaya and a part of the new state Uttaranchal of India (Latitude: 29 degrees 26 minutes - 31 degrees 28 minutes N; Longitude: 77 degrees 49 minutes - 80 degrees 6 minutes E). It encompasses six districts and covers an area of 30,029km^2. The area is very rich in biodiversity (animals, plants and microbes). The entire region of Garhwal Himalaya is bestowed with the tremendous freshwater resources in terms of major fluvial systems of the Ganges and Yamuna and their tributaries. A total of nine big river valley projects of 978.75 M.W. installed capacity has been completed; eight projects, including Asia's highest project (260-meter height) of 5,174 M.W. installed capacity, are in the process of construction.

Salient Features of the Tehri Dam Project

The Tehri Dam Project is a mega dam costing 8,000 crores of Indian rupees (USD: $1,780 million). It is being constructed by the Tehri Hydro Development Corporation (THDC) with the government of India in collaboration with Russian engineers. The dam site is surrounded by three sides of mountains of 1,000-2,000m above sea level. The dam is being constructed approximately 1.5km downstream, the confluence of Bhagirathi and Bhilangana, which together form the Ganges River after meeting the Alaknanda River. The hydroelectric project will generate 2,400 M.W. and irrigate 6.6 million acres of land plus provide municipal drinking water to a large population. The catchments area of the project is 7,511km^2. The work on the project started in 1979 and is expected to be completed by the end of 2004. Two construction agencies (J.P. Industries Ltd; Thapar Intrafor Co. Ltd) are involved for with the construction of the project. The entire area of the project has a thick network of transportation for human mobility and transportation of materials. A total length of 88km of road network has been constructed in the catchments area of the Tehri Dam Project. Out of this, 39km has been constructed along the bank of Bhagirathi and 14 km along the bank of Bhilangana and in the riparian zone of two rivers. Various road construction activities (rock stripping / bladding / culverts, etc.), frequent land slumps and land slides during heavy precipitation have introduced large amounts of woody debris, soil and sediments into the waterways.

Methodology

Two references sites (S_1), one each on Bhaigirathi and Bhilanagan rivers, and four sites (S_2) at the impacted area, two each on Bhagirathi and Bhilangana, were identified in the project area for collection of water samples and obtaining data related to the aquatic primary production and production of Mahseer (*Tor tor; Tor putitora*). The present study was undertaken for over two decades; however, the data have been taken for a four-year period, November 1997- October 2001, the critical period for drastic impacts on the aquatic environment and Mahseer. For limnological analyses of the degradation of the aquatic environment, standard methods outlined in APHA (1981) and Wetzel and Likens (1991) were followed. Primary production was estimated following the methods of Gardner and Gran (1927) and Rodgers *et al.* (1979). Estimation of the production of aquatic insects (secondary producers) was made following the methods outlined in Downing and Rigler (1984). For the study of density, biomass, and production of the Mahseer (*Tor tor* and *Tor putitora*), the three small seine nets (TSSN) methods of Penczak and O' Hara (1983) were employed. The value for instantaneous growth (G) was estimated, when growth is considered to be exponential.

Where $\overline{W}_1$ and $\overline{W}_2$ = mean weight of the fish at time t_1 and t_2 respectively. To estimate monthly production, mean biomass ($\overline{B}$) was multiplied by the instantaneous growth rate (G): P = $\overline{W}$ G (Chapman, 1978)

The annual production (g.m^{-2}.yr^{-1}) was estimated for Mahseer at all the sites (reference and impacted sites).

Results and Discussion

Manifestation of Environmental Degradation

a. Morphometric Transformation of Fish Habitat

A large-scale morphometric transformations of the habitat of the Mahseer in a large section of Bhagirathi and Bhilangana rivers in the environment of the impacted sites have taken place due to transportation networks in the area of the Tehri Dam Project. As a consequences of these road construction activities, a large stretch of the fluvial system has been transformed into a trench and dammed pools of sluggish currents of water from rapids, cascades part of high water current of riffles. The other section has been converted into narrow turbulent and turbid riffiles from wide and clear water pools as a result of large-scale of disturbances of sand, gravel and stones. The composition of bottom substrates has been drastically altered by the road construction and maintenance activities.

b. Degradation in Physi-Chemical Aquatic Environment

Mean values of physio-chemical parameters of the aquatic environment of Bhagirathi and Bhilangna rivers in the area of the Tehri Dam Project at reference site (S_1), and at the impacted site (S_2) recorded over a four-year period, November 1997-October 2001, have been presented in table 1. Analysis of the data revealed that a slight change in the water temperature at the impacted site (15.09±2.69^{0}C) was noticed based on the reference site (14.43±2.73^{0}C). A drastic change in the hydromedian depth (HMD) was recorded at the influenced site (1.702±1.327m) in comparison with the depth at the reference site (2.514±1.550 m). Conductivity was also influenced from the natural condition (81.70±26.6 µ.mho.cm^{-1}) by the transportation network at the impacted site (83.09±28.18 µ.mho cm^{-1}). The water velocity has been altered to a great extent at the impacted site (1.351±0.809 m.sec^{-1}) versus the water velocity at the reference site (1.475 ± 0.799 m.sec^{-1}). A considerable change in the suspended material in the water at the impacted site (128.73 ± 108.73 NTU) was recorded versus the reference site (115.26 ± 105.37 NTU), leading to a reduction in the visibility (transparency) in the water column. A significant change in the concentration of dissolved oxygen was recorded at the impacted site (8.17±0.69 mg.l^{-1}) versus the reference site (12.78±0.54 mg.l^{-1}). A minor change in other chemical parameters (free CO_2, phosphates, nitrates, sulphates, chlorides and silicates) was also noticed at the impacted site.

c. Trophic Depression in the Aquatic Environment

The biotic profile of the aquatic environment of Bhagirathi and Bhilangana is characterized by periphyton, phytoplankton, and macrophytes at the primary trophic level, and zooplankton and aquatic benthic insects at secondary trophic level. These biotic components act as food for the hillstream fish Mahseer. The natural composition of these organisms was also influenced drastically by the transportation network. The population of aquatic macroinvertebrates reduced drastically. Primary production contributed by aquatic plants was drastically influenced by road construction activities. Annual net primary production (Pn) of aquatic plants was reduced (43%) to 40.94 k.cal.m^{-2} from 72.43 k.cal. m^{-2} during the span of the four-year study (fig.1). The peak in primary production was recorded during November-December (winter months) when transparency of water was recorded to be high.

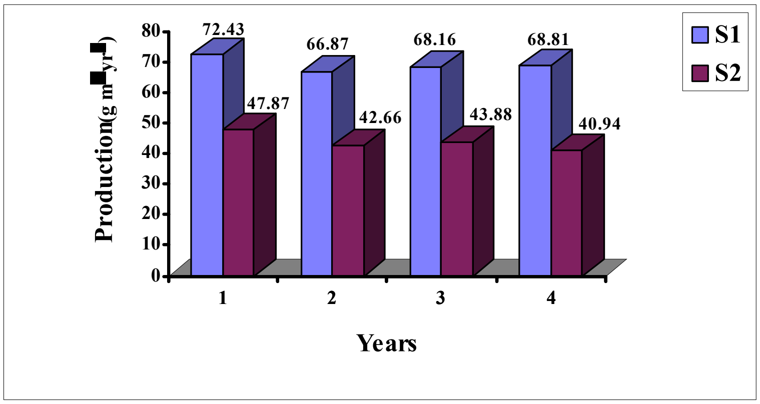

Fig. 1. Annual net primary production (Pn) of aquatic environments influenced by transportation networks in the area of the Tehri Dam Project.

Table 1.
Degradation in physico-chemical aquatic environment caused by the transportation network during a four-year period (November 1997- October 2001).

Parameter	S_1	S_2
	$\bar{X}$ ±SD	$\bar{X}$ ±SD
Air Temperature (^{0}C)	23.58±7.50	23.98±7.54
Water Temperature (^{0}C)	14.43±2.73	15.09±2.69
Hydromedian depth (m)	2.514±1.55	1.702±1.327
Conductivity (μ S cm^{-1})	81.70±26.67	83.09±28.18
Relative humidity (%)	46.27±6.05	42.65±6.26
Water velocity (m sec^{-1})	1.475±0.799	1.351±0.809
Turbidity (NTU)	115.26±105.37	128.73±108.73
Transparency (m)	1.389±0.634	1.201±0.534
Photoperiod (LH day^{-1})	11.78±1.27	11.78±1.27
TDS* (x 10^{2} mg l^{-1})	5.90±5.40	6.40±5.40
pH	7.60±0.07	7.54±0.12
Dissolved oxygen (mg l^{-1})	12.8±4.54	8.17±0.69
Free Carbon dioxide (mg l^{-1})	0.97±0.36	1.03±0.19
Total alkalinity (mg l^{-1})	38.13±6.18	35.52±4.25
Phosphates (mg l^{-1})	0.031±0.013	0.035±0.015
Nitrates (mg l^{-1})	0.025±0.013	0.032±0.013
Silicates (mg l^{-1})	0.040±0.36	0.045±0.031
Sulphates (mg l^{-1})	1.678±0.596	1.535±0.656
Chlorides (mg l^{-1})	3.164±1.124	3.319±0.865

* Total dissolved solids

Annual secondary production of aquatic insects was also drastically influenced by the transportation network. It was reduced from 4.458 g m^{-2}yr^{1} to 1.512 g m^{-2}y^{-1}, a 62% decrease during the span of the four-year study (figure 2).

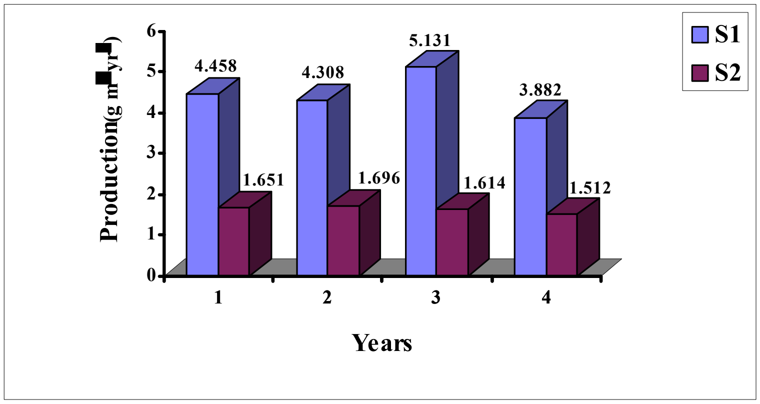

Fig. 2. Annual secondary production of aquatic insects influenced by the transportaion networks

Impact of Transportation Network on the Life of Mahseer (*Tor tor* and *Tor putitora*)

As a consequence of transportation networks in the area of the Tehri Dam Project, the Mahseer, a finest sport and food fish is struggling hard for its survival in the stressed habitats caused by the anthropogenic perturbations. Various life activities of the Mahseer are drastically influenced.

a. Inundation of Spawning and Feeding Grounds of Mahseer

The inundation of spawning and feeding grounds of Mahseer inhabiting Bhagirathi and Bhilangana was observed at the impacted zone of the rivers. As a result of the transportation network, a phenomenal change in the characteristics of substrate composition and drastic changes in turbidity and silting patterns, the failure of spawning or ineffective spawning of endemic Mahseer were observed. The presence of gravel, pebbles, sand and bankside vegetation are prerequisite for Mahseer to build their spawning nests (redds).

b. Choking of Breeding Grounds and Migration Channels
Environmental degradation, brought about by intensified road construction activities at Tehri, has affected adversely the migratory fish species (*Tor tor* and *Tor putitiora*). Due to land slides, slumps, and other construction activities, substantial morphometric transformations have occurred in the fish habitat, which obstruct the movement of Mahseer from the foot hills to upper reaches of the river and tributaries for breeding purposes. Both Mahseer species need clean, stable, well-oxygenated, gravel habitats to spawn in. After the eggs are laid in the gravel, well-oxygenated water must pass over the eggs (Sharma 1984).

c. Impact on Production of Mahseer
Subsequent to road development, standing crop estimates of Mahseer declined from a maximum mean monthly biomass of 0.492 g.m^{-2} (Feburary) to 0.185 g.m^{-2} , a 62% decrease, and a minimum monthly mean biomass (July - August) of 0.185 g.m^{-2} to 0.014 g.m^{-2}, a 92% decrease. Annual prodcutivity of Mahseer declined from 0.198 g.m^{-2}. yr^{-1} to 0.054 g.m^{-2}. yr^{-1}, 73 percent decrease (fig. 3).

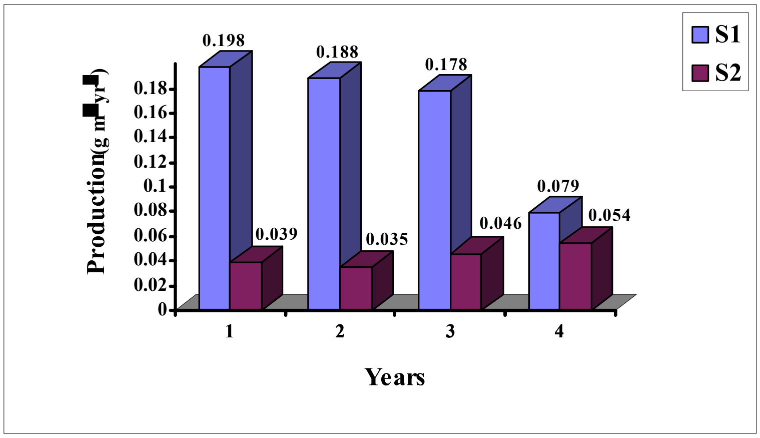

Fig. 3. Impact of transportation network on annual production of Mahseer in an aquatic environment of theTehri Dam Project

Due to road construction activities in the area of the Tehri dam project, large-scale morphometric transformation of the fish habitat resulted. A phenomenal change in the extent of cover (place of shelter) for fish and in the characteristics of substrate composition and degradation of the aquatic environment (high turbidity, total dissolved solids, reduction in access of light and dissolved oxygen) was observed, causing diminution of food resources (primary production and secondary production), inundation of feeding and spawning grounds in addition to blocking of migration channels. Choking of breeding grounds of Mahseer in the Bhagirathi and Bhilangana rivers was also observed at the impacted area affecting their production. Therefore, it makes logic sense to discuss production of Mahseer in the context of these altered environmental variables.

Early work on the influence of inorganic sediment on aquatic life has been reviewed by Cordone and Kelley (1961). The effects of construction of the M11 motorway in Essex, U.K., were studied by Extence (1978). The macro-invertebrate communities above and below the entry of motorway run-off became progressively dissimilar over the study period. Certain groups, such as stone flies, may flies and cased caddis flies, were largely absent at the outset. These studies show that the high suspended solids carried by run-off during civil engineering operations can have a marked effect on the ecology of the received stream. Their long-term effects could, however, prove to be small since, once the works are completed and winter spates have carried the bulk of the material away, recolonisation can occur from upstream. This view finds support in the studies of Barton (1977) who noticed that the reduced fish population (24 to 10 kg.ha^{-1}) immediately below the site of highway construction returned to the original level after the work had been completed. Duvel et al. (1976) reported that "modifications of streams" had a direct deleterious effect on trout populations, as large trout were denied suitable natural hiding places (holes, undercut, banks vegetation). The relationship between fish life and suspended solids was the first to be considered by the European Inland Fisheries Adversary Commission in their Technical Paper Series (EIFAC 1964), and it has since been reviewed by Alabaster (1972) and Alabaster and Lloyd (1980). Trout populations in stream sections affected by high suspended solids had lower densities than in unaffected stretches (Scullion and Edwards 1980)

According to Mann and Penczak (1986), productivity levels of fish are under both biotic and abiotic influences, with the latter being of prime importance. Biotic variables (cover, food, predation) have more influence in stable environments. Zaleswaki and Naiman (1985) demonstrated that abiotic factors (fluvial geomorphology, geology and climate) were of primary importance in many situations. Zaleswki et al. (1985) stressed that growth rates in headwaters (low order streams) are primarily restricted by abiotic factors especially temperature and trophic status. Egglishaw (1970) demonstrated a relationship between fish production, and availability of water flow and feeding sites. According to Power (1973), the presence of cover in the form of boulders and large stones greatly enhances the holding capacity of the river for fish, and hence influences the production level. A deleterious effect of turbidity on fish production was noticed by Starrett and Fritz (1965). According to them, turbidity probably affects the procurement of food by sight-feeding fish. It also affects production of plankton and other food resources of fish.

The production level of fish is also dependent on light access, amount and quality of autochthonous and allochthonous organic matter (Naiman 1983; Minshall et al. 1983) and temperature and its range (Elliot 1976; Edward et al.1976). Thomas (1998) studied the effect of highways on western coldwater fisheries of North America. Highway network activities have an adverse impact on coldwater fish through loss of fish habitat, changes in habitat quality, isolation of populations, reduction, and invertebrate food supplies. Sheehy (2001) reported that roads are the major sources of sediment deposited in streams. This is especially critical when roads are adjacent to streams with sensitive species; and any sediment deposited into streams could have adverse effects.

In the present study on Mahseer production influenced by the transportation network, it seems acceptable that production levela are regulated by abiotic (increased turbidity, total dissolve solids, diminution of feeding and spawning grounds and extensive destruction of cover for fish) and biotic (food resources, primary and secondary production) factors. Thus, the depletion in the production of Mahseer seems understandable as a consequence of the transportation network in the area of the Tehri Dam Project.

Remedial Measures for the Protection of Mahseer

The following measures have been recommended to restore habitat quality and connectivity for the Mahseer (*Tor tor* and *Tor putitora*):

- Stream restoration and stream bank stabilization should be undertaken at the sites of morphometric transformations and fragmentation of the fish habitats.
- Gravel mining and dredging in streams should be undertaken for removing excess sedimentation, soil and woody debris.
- Riparian vegetation should be protected, as it produces cooling water temperature, cover for the fish, and habitat for aquatic insects.
- Efforts should be made for the enhancement of fish food reserves.
- There should be monitoring of the water quality of streams adjacent to the roads in the area of the Tehri Dam Project by the Tehri Hydro Development Corporation (construction agency).
- Natural fish passages (riffle grade controls for sand / gravel bedded, and flow constrictor / step pools for cobble / boulder bedded streams) should be constructed for providing easy passage to the Mahseer for migration.
- THDC should make the necessary efforts for early establishment of a hatchery / nursery for the rehabilitation of Mahseer.
- Ecofriendly techniques for road construction and maintenance should be employed in the area of the Tehri Dam Project
- A strong partnership should be established among civil engineers (road construction agency), environmental biologists, and the public for minimizing the conflicts between the transportation network and the Mahseer.

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Biographical Sketch: Born on January 1st, 1954, in a village of northern India, Dr. Sharma has a distinguished academic career. He passed his graduation with zoology honours and obtained a masters degree in zoology with freshwater fishery biology. He obtained his doctorate (D.Phil.) in environmental biology of fish and doctor of science (D.Sc.) in environmental biology. His wife, Dr. Vineet Ghildial, is a senior faculty at the Department of Humanities (Sanskrit) at H.N.B.Garhwal University. He has two sons (one aged 20 and another 16 years). He has been teaching and undertaking research for almost three decades on environmental monitoring, energetics, limnology, resource management, aquatic biodiversity and transportation and environment in the Himalayas. Several research projects have been completed on these aspects. Sixteen doctoral research students have been conferred to doctoral degrees and five more students are engaged in research under his supervision. He has sufficient professional experience and exposure by way of visiting and working at different research laboratories in India and abroad (USA, Sweden, Poland, Czech Republic and Canada). He has published more than 90 research articles in journals of international repute. He has been awarded many gold medals (NATCON Environment Gold Medal 2001, Zoological Society of India Gold Medal 2002). He is also a fellow of many national and international societies. Currently, he is the Chairman, Department of Environmental Sciences, H.N.B. Garhwal University, Srinagar-Garhwal, Uttaranchal, India.

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SPOONER CREEK RESTORATION AND FISH LADDER

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Abstract

Spooner Creek is a dendritic second order stream located in Erie County, New York, which flows into Cattaraugus Creek, a tributary of Lake Erie. Spooner Creek is identified by the New York State Department of Environmental Conservation (NYSDEC) as a “very significant resource” within Western New York for migratory steelhead trout from Lake Erie.

In the early summer of 1998, a severe storm occurred along the southern portions of Erie County, impacting numerous streams along the Cattaraugus Creek Watershed. One of these impacted steams was Spooner Creek, in the proximity of NY Route 39, in the Town of Concord, Erie County, New York. The current alignment of the existing culvert under Route 39 and the storm event resulted in severe streambed degradation, and erosion to the left and right channel banks. In addition, a large scour hole developed downstream of a grade stabilizing sheet pile wall. The depth of the scour hole combined with the height sheet pile wall created an impassable barrier for the upstream migration of steelhead trout.

To facilitate the migration of steelhead trout beyond the Route 39 structure, the NYSDOT constructed a fish ladder comprising five (5) permanent sheet pile walls, along with the placement of extra heavy stone within the bed of the creek. A series of hydraulic jumps and resting pools were created from the five (5) sheet pile walls, and the placement of the extra heavy stone fill reconstructed a 200-meter section of Spooner Creek with a two percent slope. In addition, a series of twelve (12) baffles were retrofitted within the concrete box culvert to increase water depths during periods of low flow to assist in the migration of fish through the structure. The riparian habitat of Spooner Creek damaged from the 1998 storm event and construction activities were restored and protected through the use of bioengineering and conventional engineering practices.

The Spooner Creek project was completed in the fall of 1999 for a cost of $400,000 utilizing Federal HBRR Funds. Based upon NYSDEC fisheries survey data, graduate studies by SUNY Fredonia, and from general observations, steelhead trout are migrating effortlessly beyond the structure and reproducing successfully in upstream nursery grounds. Bioengineering and conventional engineering methods are protecting the creek slopes from erosive forces, along with providing important habitat for fish and terrestrial fauna.