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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 Houlihan 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 particularly 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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