Stream Simulation

1.1 ECOLOGICAL CONCEPTS

Rivers and streams are more than mere conduits for water and fish. They are long, linear ecosystems made up of the physical environment, communities of organisms, and a variety of ecological processes that shape and maintain these ecosystems over time (figure 1.1). The long-term conservation of important aquatic resources (such as fish) requires the maintenance of healthy and ecologically viable ecosystems. As this chapter will show, road crossings have the potential to undermine the ecological integrity of roaded river and stream systems in a number of ways. To ensure the productivity and viability of river and stream ecosystems, we must protect and restore the quality of the physical environment (habitat), maintain intact communities of aquatic organisms, and take care not to disrupt critical ecological processes.

Figure 1.1—Long-term conservation of aquatic resources requires the maintenance of healthy and ecologically viable ecosystems.

1.1.1 Habitat

To survive, an organism must have access to all habitats it needs for basic life functions. For many species, these needs for access occur throughout an organism's life cycle. Habitat is a combination of physical

and biological characteristics of an area or areas, which are essential for meeting the food and other metabolic needs, shelter, breeding, and overwintering requirements of a particular species. For some species, habitat can be as small as individual rocks or the spaces between pebbles in the streambed. For others, it can include many miles of rivers, streams, **flood plains**, wetlands, and ocean.

The size and distribution of sediment particles and pore spaces within the streambed is particularly important for small and sedentary organisms. Water depth and velocity, as well as the physical and chemical properties of water, are also important elements of habitat for aquatic organisms. Substrate and hydrological characteristics of rivers and streams often vary in predictable ways, depending on whether a particular area is a cascade, riffle, run, pool, **side channel**, **backwater**, or flood plain. The size and complexity of these habitat types affect the abundance and diversity of organisms using those areas. The amount and distribution of habitat types within a river or stream **reach** will, in turn, determine whether the area serves as appropriate habitat for larger and more mobile species. The types, amount, and distribution of habitat types vary, depending on the size and gradient of a river or stream and its association with a significant flood plain (figure 1.2).

Figure 1.2—The complexity of habitat types affects the abundance and diversity of organisms inhabiting the stream as well as the resilience and persistence of animal populations. Photo: Scott Jackson, University of Massachusetts.

At any of these scales—from individual rocks in a streambed to particular habitat types (riffles, pools, cascades) to an entire river system—the particular area's characteristics will determine what species are likely to be present. The tendency of areas to form structurally and functionally distinct portions of the landscape (for example, riffles, pools, runs, flood plains, **headwater streams**, **tidal rivers**) means that organisms that inhabit these areas often form distinct assemblages of species called communities. These communities of organisms and the physical environmental they inhabit are what constitute ecosystems.

1.1.2 Aquatic Communities

Natural communities are more than mere 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 species interdependency. For example, a single stream reach may support a variety of fish species competing with each other for food and appropriate habitat. Diverse communities of invertebrates are essential for providing a food base for fish throughout the year. Disease organisms, parasites, or predators may differentially affect species and thus can affect the balance of competition among these fish.

The presence or absence of fish can affect whether other species are able to use river or stream habitats. Many amphibians, to breed successfully, require aquatic habitats that are fish free. These species may use flood-plain pools or **intermittent** sections of streams as long as fish regularly are not present. On the other hand, numerous species of North American freshwater mussels require specific fish hosts to complete reproduction (figure 1.3). Larval stages (glochidia) of these mussels attach themselves to the gills or fins of host fish (or in one case, host salamanders), a process essential for proper development and dispersal. 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.

Loss of species due to extirpation (extermination) of local populations or the exclusion of species due to migratory barriers (e.g., **anadromous** fish) has the potential to alter and undermine the sustainability of natural communities. Similarly, the presence or introduction of nonnative species can seriously degrade natural communities. Nonnative species may prey upon, compete, or interbreed with native species, and may serve as vectors for disease transmission.

Figure 1.3—A broken-rays mussel uses a mantle-flap lure to attract host darter that it will infect with glochidia. Photo: Chris Barnhart, Missouri State University.

1.1.3 Ecosystem Processes

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 in 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 normally replaced by material transported from farther upstream. **Woody debris** is 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 (figure 1.4).

Figure 1.4—Debris dams can create pools and scour holes, and change patterns of sediment deposition within the stream channel. Photo: Scott Jackson, University of Massachusetts.

Natural disturbances, such as floods, drought, and ice scour can interrupt more regular cycles of stream flow, sediment transport, and the amount and distribution of woody debris. However, not only are these disturbances part of larger patterns of physical and biological change that help define aquatic ecosystems, but they also are generally responsible for defining channel characteristics.

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

1.1.4 Viability and Persistence of Populations

Populations are groups of organisms that regularly interact and interbreed. Animal movements are necessary to maintain continuous populations, and constraints on movement often delineate one population from another. The ability of a population to remain genetically viable and to persist over time is related to both its size and its degree of interaction with other populations of the same species.

An important consideration for maintaining viable populations is maintaining sufficient genetic variability within populations. Small populations are at risk of losing genetic variability due to **genetic drift**, and very small populations may be subject to the negative consequences of **inbreeding depression**. Over the short term—depending on a species' life history characteristics—the minimum population size necessary to maintain genetic diversity ranges from 50 to 200 or more individuals (Franklin 1980; Soulé 1980). For longer-term genetic stability, estimates often range from 500 to 5,000 or more individuals (examples are provided in Lemkuhl 1984; Reiman and Allendorf 2001; Reiman and McIntyre 1993; Fausch et al. 2006).

Fausch et al. (2006) provide an excellent synthesis of the literature on population size, viability, and population isolation for salmonids. Fausch et al. (2006) note that true "viability" (in the sense of sustainability of a population over time) also may require the ability of populations to adapt and evolve to changing environmental conditions. Long-term conservation of species and ecological functions may require greater numbers of individuals and amounts of genetic variability than that required for mere maintenance or "persistence" of small population isolates. Landscape attributes and the range or percentage of life history types present (e.g., migratory versus nonmigratory forms) also appear to strongly influence persistence and viability of salmonids (Neville et al. 2006; Fausch et al. 2006).

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 to 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 extinction can be recolonized by individuals from nearby populations. Stochastic (random) risks such as catastrophic disturbances (landslides, debris flows, toxic spills) even when localized can easily eradicate small isolated populations. Rieman and McIntyre (1993) provide additional background information on stochastic risks to small, isolated populations.

As part of a long-term study of brook trout *(Salvelinus fontinalis)* in western Massachusetts, Letcher et al. (2007) used data on survival and fish movement within the population to model estimated time to extinction under various scenarios. Under one scenario that simulated placement of barriers to upstream movement into two tributaries, local population extinction was predicted in two to six generations. These barriers also increased the probability of network-wide extinction in both tributaries and in a 1-kilometer section of the main stem. Once disconnected from the tributary populations the network-wide population could only be maintained via a large influx of individuals (7 to 46 percent of the total population) immigrating into the population from downstream areas.

Understanding ecosystems: A case study of fragmentation

The lack of population data over long periods of time—whether 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 maintaining both genetic viability and 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).

One recent study provides an excellent illustration of the impact of fragmentation in riverine systems. This 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 unaltered streams. Many of the mountain streams that charr use have been fragmented by small erosion-control dams that 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. However, although charr populations were found in all surveyed undammed sites, charr 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 (compared to populations below dams), including lower genetic diversity, higher morphological asymmetry, and genetically based lower growth rates.

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

The situation of small dams on headwater streams in Japan may be comparable to United States watersheds that contain road crossings with substandard 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, the failure of more and more populations is expected, and the disruption of metapopulation dynamics is likely to keep these areas of suitable habitat unoccupied.

Studies of other riverine species have yielded similar results. Genetic effects correlated with small habitat patches and isolation have been documented for Lahontan cutthroat trout (Neville et al. 2006). Habitat patch size (a surrogate for population size) and isolation have been found to be significantly correlated with the presence or absence of animal populations for bull trout (Dunham and Rieman 1999), cutthroat trout *(Oncorhynchus clarki)* (Dunham et al. 1997; Harig and Fausch 2002), and spring salamanders *(Gyrinophilus porphyriticus)* (Lowe and Bolger 2002). Harig and Fausch (2002) point out that large interconnected stream networks not only are likely to support larger populations of fish, but are likely to provide the complexity of habitat types required by these fish throughout their life cycles.

1.2 ANIMAL MOVEMENT

1.2.1 Importance of Movement for Individual Animals

Animals move through rivers and streams for a variety of reasons. Some movements 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. Examples include juvenile bull trout and Atlantic salmon, American eel, hellbenders, and many other species of stream salamanders. The crayfish *Orconectes virilis* typically moves in the open at night, ranging upstream or downstream as much as 82.5 feet or more before returning to the same daytime area (Hazlett et al. 1974).

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. Flood-plain side-channels and sidewall-channels fed by ground water also provide thermal refuges for fish and other aquatic organisms.

In many stream systems where natural disturbances cause significant habitat variability, access to refuge habitat is especially important. Humans, too, can cause disturbances that require fish to seek refuge habitats. For example, major highways parallel many streams, and toxic spills in streams are not uncommon. When these occur, fish must have the ability to move to unaffected habitats.

Some animal movements are seasonal and therefore 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 fish 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 flood plains 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 (Hall 1972).

The most dramatic examples of breeding movements are the long-range migrations of anadromous fish, including various species of salmon, sea-run trout, shad and other herring species, sturgeons, and other fish. By contrast, the common eel is a catadromous species—living as adults in freshwater and migrating to the ocean to breed.

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 freshwater environments can provide. Other fish species make similar but less dramatic migrations to reach spawning habitats. Pike and pickerel move into vegetated flood plains to spawn. Many "nonmigratory" fish (for example, some species of trout, suckers, and freshwater minnows) use headwater streams as spawning and nursery habitat.

In contrast to fish, many stream salamanders use intermittent headwater streams as adults but deposit their eggs in more perennial areas of the stream. The semiaquatic adults can readily move up into headwaters to exploit the productivity of these areas. The salamanders' less mobile larvae are aquatic, needing areas of more reliable, year-round surface water.

As organisms move through their various life stages, they need access to areas that meet a variety of habitat requirements that may change as the organisms grow and develop. Sometimes spawning habitat doubles as nursery habitat for juvenile fish or larval amphibians. In other cases the survival needs of eggs (for example, cool temperatures, specific substrates, or well-oxygenated water) may greatly differ from those required by juveniles or larvae (appropriate cover, more persistent hydrology, lower flow velocities, or adequate food supplies). Adult fish may require deeper water and larger cover objects. In Wisconsin, brown trout were observed to move more than 9.6 miles downstream to overwintering sites that were too warm for trout during the summer (Meyers et al. 1992).

In dynamic environments like rivers and streams, the location and quality of habitats are everchanging. Large woody debris is an important component of many stream ecosystems. Large logs in the stream can dam up water or create plunge pools on the downstream side of the log. Accumulations of woody debris can change the local hydraulics of the

stream, scouring some areas and depositing the material in other places (figure 1.5). Woody debris that forms jams across the stream can create large and relatively deep pools. These features (woody debris, scour holes, pools, deposited gravel) are important habitat characteristics. However, they are not permanent features; woody debris will eventually break up or move downstream. Flooding, substrate composition, 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. In these dynamic environments movement is critical for aquatic organisms to be able to avoid unfavorable habitat conditions and to find and exploit areas of vacant habitat.

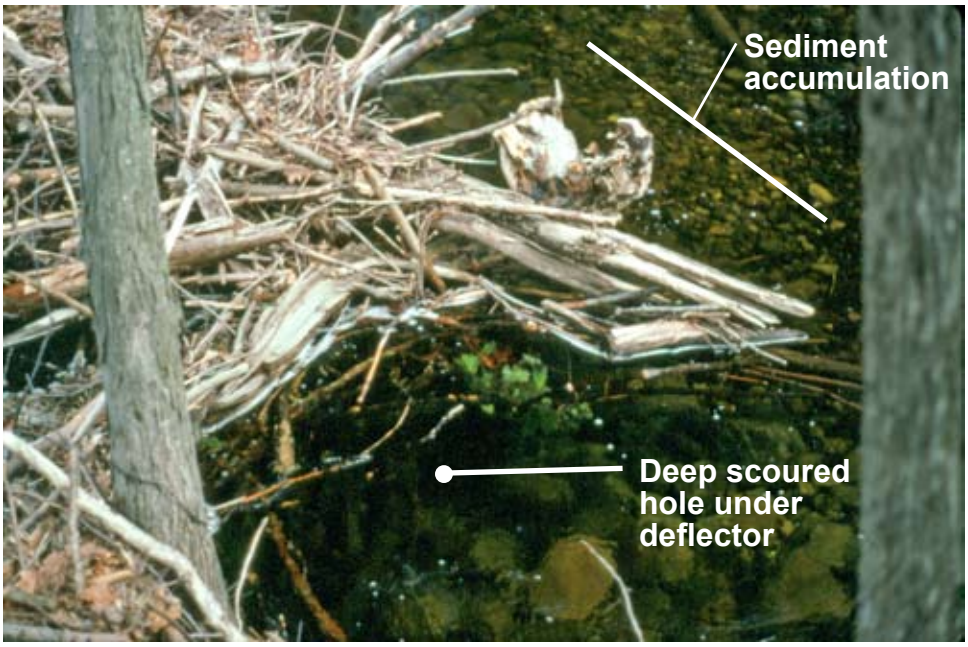


Figure 1.5—Woody debris has altered the local hydraulic conditions in such a way that a deep hole has been scoured out beneath and just upstream of the 'deflector,' with fresh gravel deposited on the downstream side. Photo: Scott Jackson, University of Massachusetts.

In the intermittent Colorado plains streams that provide habitat for the Arkansas darter (figure 1.6), habitat changes seasonally with regular wet and dry cycles. During dry periods, darters rely on ground-water-fed refuge pools. The number, distribution, and quality of these pools change in response to drought, winter conditions (pool freezing), and flooding that occur every few years or decades on average. Occasional flash floods scour out new pools and fill others. To persist in these streams in this ever-changing landscape, Arkansas darters must rely on long-distance movements to locate and colonize pools (Labbe and Fausch 2000).

Figure 1.6—Arkansas darter.Photo: Kurt Fausch, Colorado State University.

For a time, fisheries biologists thought that fish species such as trout generally stayed put, except for specific periods of movement for breeding or avoiding unfavorable conditions. However, we now see that a significant proportion of these fish make regular and remarkably long-range movements (ranging behavior) that allow individuals to locate and exploit favorable habitat within these ever-shifting mosaics (Gowan et al. 1994). For a detailed summary of salmonid fish movement within rivers and streams see Northcote (1997).

1.2.2 Ecological Functions of Movement

Although movement and migration present obvious advantages for individual organisms, these movements are also important for maintenance of populations over time. Animal movement has several important ecological functions responsible for maintaining populations and ecosystems.

Survival of individual animals, facilitation of reproduction, and the maintenance of continuous populations (sufficient to prevent genetic differentiation) are important functions of movement at a population level. Extreme events, such as floods, debris flows, and droughts, may force entire populations to avoid unfavorable conditions by moving. Provided that no barriers prevent the movement of individual animals back into

the areas, populations will reoccupy the habitat once conditions have improved. Among aquatic communities, the movement of animals helps maintain the balance between predators and prey, and facilitates more efficient use of food-based energy within the system.

Dispersal of individuals regulates 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.

Movement is an important ecosystem process for upstream cycling of nutrients and organisms. Within aquatic ecosystems there is a tendency for organisms and nutrients to shift downstream. This tendency has been documented for a number of amphibians, including tailed frogs, boreal toads, and a variety of stream salamanders. The upstream movement of individuals counters this biological displacement and returns nutrients to upstream portions of these systems. When adult salmon migrate upstream and die, they transport essential nutrients to spawning streams, a process that can have an enormous impact on the productivity of those streams (for example, Levy 1997; Wipfli et al. 1999).

Some streams on the Great Plains support a number of minnow species that produce semibuoyant eggs during high-flow conditions. This buoyancy mechanism allows the spawn of adult fish inhabiting perennial upstream areas to drift many miles downstream into intermittently flooded portions of streams running through the plains. With this reproductive strategy, not only is downstream drift important, but unimpeded movement of young fish into more persistent upstream sections is also essential for maintaining minnow populations.

1.2.3 Movement Capabilities of Aquatic and Riparian Organisms

The timing of animal movements varies by species and lifestages. Often this means that, at virtually all times of year, one or more species is moving (figure 1.7). Movements may be between areas of shallow and deeper water or between the water's edge and midstream. Animal movements may be downstream (intentionally or unintentionally) or upstream. For many organisms inhabiting small streams, lateral movements or movements between surface and deeper water within the

stream channel are severely constrained. Under these circumstances, upstream and downstream movements become all the more important for these organisms. Also important are movements between the stream channel and adjacent flood plains, as well as upstream and downstream through flood plains and riparian areas. For rivers with large flood plains, these movements are especially important.

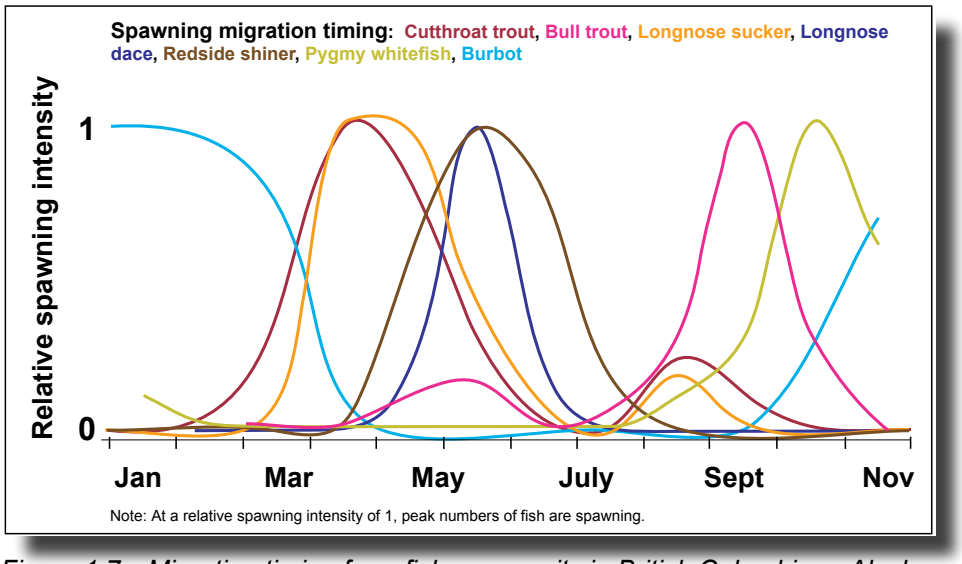


Figure 1.7—Migration timing for a fish community in British Columbia or Alaska. There is virtually no time when migration barriers do not pose a problem for at least one species. Graphic: Brett Roper, Forest Service. Data from Scott and Crossman 1973.

Some organisms are weak swimmers capable of moving only relatively short distances unless displaced by floods or attached to other animals or woody debris. Others 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. While terms related to swimming ability do not have standardized meaning, most researchers use three categories to describe swimming ability (Beamish 1978). These include (1) burst speed (relatively high speeds that can be maintained for only a few seconds), (2) prolonged swimming speed (including the range of speeds between burst and sustained), and (3) sustained speed (speeds that can be maintained for long periods without fatigue). Swimming speeds are significant factors affecting the ability of animals to move through river and stream ecosystems. Burst speed is most

relevant for physical barriers that require jumping or short sections of relatively high water velocity. Prolonged speed is important for crossing longer sections of fast water. Long-distance movements of migratory fish and the ability of fish to maintain position in the stream channel for long periods of time depend on the sustained speed of fish.

There are a number of uncertainties in using data on the swimming abilities of fish for hydraulic design of stream crossings. For several reasons, the available data may not reflect how wild fish behave in real streams:

- Most swim-speed data currently available were developed by forcing fish to swim at a constant speed in a laboratory swimming tunnel. Such conditions are not ideal for developing estimates of a fish's volitional swimming ability.
- Actual swim performance is affected by a host of environmental and physiological factors ranging from water quality (temperature, dissolved oxygen, toxins) to fish condition (disease, spawning status, exercise history, body fat).
- Individual fish of the same species have widely varying swimming capabilities.
- Ordinary swim-performance tests do not include the effects of turbulence.

Most swim-speed data are based on the assumption of a constant relationship between fish swim speed and water velocity. Peake (2004) discovered that free-swimming fish increased their mean ground speed (swimming speed minus water velocity) in response to higher water velocity. Due to their increase in ground speed, small mouth bass actually decreased their passage time as velocity increased.

The fact that swim speed data do not perfectly represent real fish performance in the field does not mean the data are not useful for designing crossing structures. On the contrary, hydraulic design has been used extensively to provide passage for spawning adult trout and salmon, and for other fish for which data exist. It is the best method in many situations, such as retrofits, jacked pipes, and highly altered streams. Nonetheless, we know very little about the majority of fish species, especially small fish (including juveniles). We know even less about the swimming abilities of nonfish species that inhabit rivers and streams.

A number of relatively large aquatic animals that inhabit rivers and streams rarely are considered in terms of barriers to movement (figure 1.7). Much of the United States supports large species of aquatic salamanders (species that rarely or never venture forth on land). Mudpuppies, waterdogs, hellbenders, sirens, and amphiumas are fully aquatic salamanders that range in adult size from about 1 foot to over 3 feet in length (figure 1.8). The Oklahoma salamander and the Pacific giant salamanders of the West Coast are other aquatic salamanders that are vulnerable to movement barriers.

Figure 1.8—Mudpuppy. Photo: Alan Richmond, University of Massachusetts.

Significant portions of the United States support softshell and musk turtles (figure 1.9)—aquatic reptiles that rarely travel overland. Movements of spiny softshell turtles are almost exclusively aquatic, with the exception of nesting and basking. In Arkansas, these turtles moved on 85 percent of the days they were tracked, with average daily movements of 403 to 465 feet per day. Some individuals moved more than 2,970 feet per day. Annual home-range length for these animals averaged between 4,620 and 5,775 feet (Plummer et al. 1997).

Although little is known about the swimming abilities of amphibians and reptiles, they are not believed to be strong swimmers, relative to migratory fish. Many species may rely more on crawling than swimming, yet movement and population continuity are essential to the survival of their populations. When moving upstream, aquatic amphibians and turtles are thought to seek out lower velocity sections of streams and take advantage of boundary layers (low-velocity zones) along the stream bottom and bank

edges. Some salamanders may require relatively continuous cover on the stream bottom, moving from rock to rock to reduce exposure to predators or high velocities (figure 1.10).

Figure 1.9—Spiny softshell turtle. Photo: Gary Stolz, U.S. Fish and Wildlife Service (USFWS) digital image library (http://images.fws.gov/default.cfm)

Figure 1.10—Northern dusky salamander.Photo: Scott Jackson, University of Massachusetts.

Although some crayfish can travel overland, many species are fully aquatic. Some have been documented moving long distances within streams, and all most likely depend on smaller scale movements to

maintain continuous and interconnected populations. Crayfish are dominant components of headwater stream systems of the Ozarks and southern Appalachians, rivaling aquatic insects in importance (figure 1.11). Some headwater populations have been isolated long enough (due to natural conditions) to become separate species. In these United States regions, headwater streams support many rare crayfish with very limited distribution. Further population fragmentation could imperil entire species of crayfish.

Figure 1.11—The Grandfather Mountain crayfish (Cambarus eeseeohensis) is only found in the headwaters of the Linville River, North Carolina, upstream of the Linville River falls. This species does not leave the stream and cannot travel overland around a barrier. Photo: Roger Thoma, Ohio State University.

As a group, the most vulnerable animal species in the United States are freshwater mussels. Over 70 percent of the 297 species native to the United States and Canada are endangered, threatened, or of special concern (Williams et al. 1993). Although adult mussels have a very limited capacity for movement, typically dispersal occurs when larvae (glochidia) attach themselves to host fish or salamanders. Therefore, survival and persistence of freshwater mussel populations depends on the capacity of the host fish or salamander to move through river and stream systems. Many 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 about which we know little except that they appear to have limited capacities for movement. These species 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 cycles of local extinction and colonization in response to changes in habitat conditions. Scour and deposition related to flooding or changes in stream hydraulics (for example, debris dams and deflectors) may destroy habitat in some areas while creating suitable habitat in others. How these organisms move upstream any significant distance is unclear. That some mechanism must exist is a reasonable assumption; otherwise, populations would continually shift downstream as upstream populations are lost to local extinctions. One possible mechanism for such movements is when larger animals transport small organisms or eggs, perhaps in association with adhered sediment or debris.

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. Under natural conditions, the movement of some stream organisms depends on the diversity of channel structure and hydraulics typically found in natural streams. This diversity creates alternate pathways throughout the channel bed and along the bankline; if any point in the channel is a **barrier** (high-velocity or high-turbulence zones) other less strenuous pathways are generally available. Maintenance of unfragmented stream bottom and bank-edge habitats is the best strategy for maintaining continuous and interconnected populations for a variety of weak-swimming species.

In addition to aquatic organisms, riparian wildlife use rivers and streams as travel corridors. These species include semiaquatic animals, such as muskrat, mink, otter, frogs, stream salamanders, turtles, and snakes (figures 1-12 through 14). Within the larger landscape, rivers and streams provide vital links connecting wetland, aquatic, and terrestrial ecosystems. In developed areas, rivers and streams often represent the only available travel corridors for many wildlife species. In arid environments, stream channels and riparian corridors offer wet and humid conditions during extended dry periods, and serve as movement corridors for terrestrial and semiaquatic amphibians.

Figure 1.12—River otters. Photo: Jim Leopold, USFWS digital image library.

Figure 1.13—Muskrat. Photo: R. Town, USFWS digital image library.

Figure 1.14—Snapping turtle. Photo: Scott Jackson, University of Massachusetts.

1.2.4 Barriers to Movement Providing Some Positive Benefit

In some circumstances, barriers to animal movement may serve a useful purpose. When natural barriers have been in place for long periods, isolated populations can become genetically distinct or evolve into separate species. For example, a population of brook trout in western Massachusetts isolated for more than 400 generations (approximately 910 years) above a natural barrier has evolved demographic characteristics distinct from populations in neighboring tributaries (Letcher et al. 2007). Individuals in the isolated population have higher early survival rates and reproduce at smaller sizes, traits that may have been instrumental in the persistence of this isolated population. The loss of the natural barriers could result in the genetic swamping of a distinct population that has not yet fully differentiated into a separate species. Removal of natural barriers can also provide access for organisms that might successfully outcompete rare and geographically restricted species, or allow transmission of parasites and disease from one population to another.

Artificial barriers, such as road crossings, dams, and diversions, also can have positive benefits. Where stocked or introduced strains of fish are genetically different from native populations, movement barriers may protect the native fish from contamination by outside genotypes. Movement barriers also can be important for containing the spread of exotic, invasive species, such as the zebra mussel, Asiatic clam, and rusty crayfish.

Many populations of native trout in the inland West are vulnerable to the negative effects of introduced salmonids. Artificial barriers are viewed as a potential tool for protecting native populations from the negative genetic and population effects of introduced species. However, the use of such barriers comes with risks. Native populations isolated above these barriers may not be large enough to persist. There also may be negative consequences for other, nontarget species. Fausch et al. (2006) offer a well thought-out framework for analyzing the risks and tradeoffs associated with constructing an artificial barrier to isolate a population and protect it from invasive species.

Relying on substandard road-stream crossings to prevent the spread of invasive species is unwise. While such structures may serve to inhibit movement of invasive species, they may not be **complete barriers** to passage. When exclusion of exotic species is the goal, structures should be designed with the specific objective of blocking movement of the target (undesired) organisms.

1.3 POTENTIAL ADVERSE IMPACTS OF ROAD-STREAM CROSSING STRUCTURES

Traditional culverts can impact aquatic animals directly. However, they also can affect aquatic-animal habitats by means of their effects on stream channels and flood plains. These impacts are not universally adverse, but beneficial effects are less common than detrimental ones.

1.3.1 Effects on Channel Processes and Aquatic Habitats

Streams do the vast majority of their habitat construction and valley modification work—mobilizing, **sorting**, and depositing sediments, woody debris, and ice—at a range of higher flows. The highest flows approach or exceed the conveyance capacity of many stream crossings on low-volume roads; therefore, the potential for stream crossings to alter the fundamental processes that create and renew physical geometry and habitat properties of the channel and valley bottom is high.

Aggradation Upstream

Road-stream crossings that are narrower than the incoming channel can cause upstream backwatering during high flows (figure 1.15). In many cases, debris enhances this tendency by plugging the structure. The backwatering usually results in sediment deposition, which can extend a distance of several channel widths upstream of a narrow culvert. These

sediment and debris accumulations at the pipe inlet can constitute fish passage barriers (figure 1.16). The accumulation steepens the local gradient, sometimes accelerating flow at the inlet beyond the velocity against which fish can swim, especially at the upstream end of the journey through the pipe.

Figure 1.15—Many crossing structures are narrower than the stream and block fluvial processes that maintain aquatic habitats. The structures also impede aquatic species passage. Photo: Scott Jackson, University of Massachusetts.

Figure 1.16—Debris and sediment at culvert inlet can be a fish barrier. Photo courtesy of Ross Taylor and Associates, McKinleyville, California.

Aggradation also can be induced by a crossing structure that is skewed with respect to the stream. As a cost-efficiency measure to minimize culvert length, culverts are sometimes installed perpendicular to the road and skewed relative to the stream channel. Where these pipes force flow to turn abruptly at the inlet, they may induce sediment deposition (see skew discussion in section 6.1.1). Skewed-pipe outlets often aim flow at one bank, causing it to erode. A skewed alignment is not always harmful; where the culvert width is nearly as wide as the channel, a mild skew can create an eddy that functions as a resting area for fish.

Degradation Downstream

Because water speeds up inside a culvert, which is usually narrower and smoother than the natural channel, the water flowing out the downstream end surges out as a jet at high flows, scouring (degrading) the streambed (figure 1.17). The degradation usually occurs during the first few years after construction. Scouring can create good habitat; the deepest pool in the affected reach may be the outlet plunge pool. However, it also creates a vertical discontinuity that often stops or impedes passage of aquatic animals. Because the scoured streambed is lower in elevation, the streambanks are taller and may be less stable. Plunge pools caused by local scour at culvert outlets usually do not extend further than 3- to 6-channel widths below the culvert.

Figure 1.17—High-velocity discharge from undersized culverts causes downstream scour. (a) Culvert was placed at grade in 1979. (b) By 1998, undersized culvert had caused over 1 foot of downstream scour.

Plugged Culverts

Debris-plugged inlets often are found to be responsible for crossing and fill failures due to overtopping during floods (Furniss et al. 1998) (figure 1.18). Plugged culverts act as small dams, and overtopping flows can cause partial or complete fill failure. Alternatively, where the road slopes away from the crossing, flow will divert down the road. If the flow then runs across the road onto a hillslope, it may erode a gully that can contribute sediment to the stream (Furniss et al. 1997). The diverted flow may reach another channel, increasing flow there and causing that channel to erode and enlarge.

Figure 1.18—Culvert-crossing failure after flooding, Plumas National Forest, California.

Flood-plain Hydrology

Almost all streams have an adjacent valley bottom of some width. The stream may inundate the valley bottom frequently (every 1 to 3 years) or infrequently (greater than 50-year **recurrence interval**). During floods, water, sediment, and woody debris move down-valley across the flood plain creating new habitats, such as side channels and debris accumulations. Roadfills approaching crossings are often raised above the flood-plain surface, creating a bottleneck at flows higher than bankfull, and locally changing the erosional and depositional processes that maintain the diverse flood-plain habitats. The extent and duration of upstream flood-plain backwatering shown in figure 1.19 are unusual, but the photos demonstrate the concept.

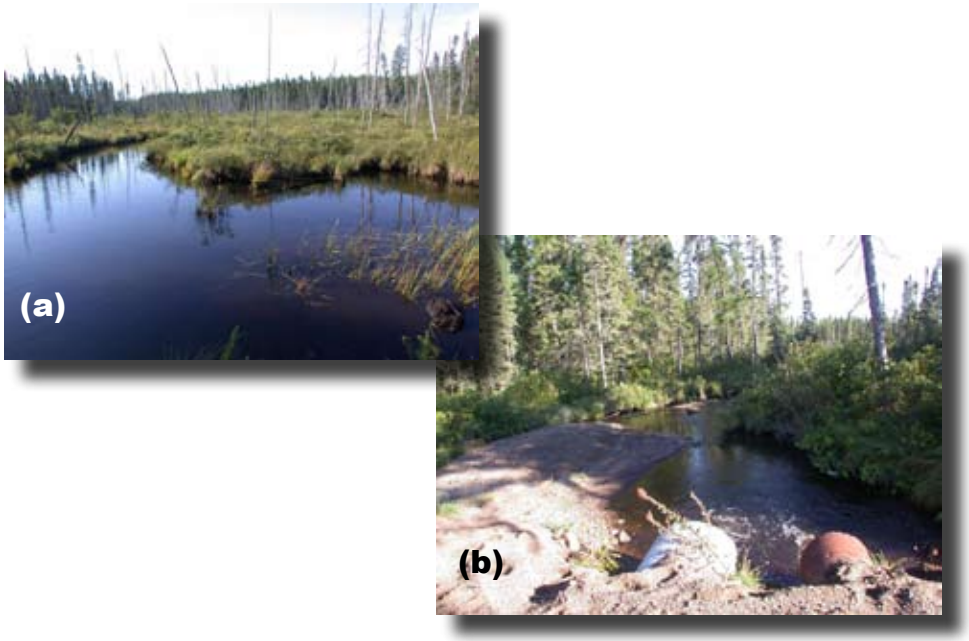


Figure 1.19—Roadfill effects on flood-plain hydrology—Minnesota. (a) Meandering channel with half-mile-wide flood plain remains backwatered for several weeks during snowmelt runoff, and sediment deposition extends for thousands of feet upstream. High water tables have killed the flood-plain trees. (b) Downstream view from same point as (a).

The channel itself can be affected when sediment transport into the downstream reach is reduced, as in figure 1-19. When **overbank flows** are funneled through the culvert, streambed scour tends to occur at the culvert outlet. Bank erosion can occur at both the inlet and outlet.

Direct Habitat Loss and Degradation

Replacing the natural streambed and banks with an artificial crossing structure usually results in direct 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 with substrate that is similar to 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 near the crossing, depending on how much the **ford** alters the streambed, banks, and water-surface elevations (figure 1.20).

Figure 1.20—Elevated concrete-slab ford eliminates aquatic habitat area directly underneath the structure and blocks fish passage at low flows. However, it may not significantly alter the character of aquatic habitats upstream and downstream.

Erosion and sedimentation are two significant impacts of road crossings. They often occur during construction if **BMPs** are not used, but they also can occur even when BMPs are in place. Ongoing erosion of embankments, the road surface, and drainage ways are of more long-term concern. Excess 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.

1.3.2 Effects on Aquatic Organism Passage

There are a variety of ways by which crossing structures can impede or prevent the movement of animals:

Inlet or Outlet Drop

Elevation drops at the inlet or outlet or within a crossing structure can create physical barriers to many animal species. Not all stream-dwelling aquatic species have strong jumping capabilities, and many subadult life stages of strong jumpers are not well enough developed to navigate vertical drops associated with crossing structures. In addition, outlet pools often have insufficient depth to allow fish to jump into structures (figure 1.21).

Figure 1.21—Outlet drop formed by scour at the downstream end of an asphalt apron. Photo: Scott Jackson, University of Massachusetts.

Physical Barriers

Clogged or collapsed culverts and trash racks can block animal movement. Weirs or baffles, which are typically designed to facilitate fish passage by increasing depth or decreasing local velocities within a crossing structure, can be barriers for nontarget weak-swimming or crawling species.

Excessive Water Velocities

Water velocities can be too high to pass fish or other organisms during some or all of the year. As stream-discharge increases, velocities within culverts increase correspondingly. Average velocities can easily exceed 10 feet per second, a speed far greater than the prolonged swim speed of most fish. In addition, culverts usually contain no resting areas for aquatic species attempting to pass through them. The result is that the animal may have to swim the entire length of the structure at burst speeds, and may exhaust itself before reaching the end of the culvert.

In corrugated metal pipes, the corrugations moderate velocities near the culvert wall, and fish use those lower velocity areas. Depending on the flow, culvert average velocities can be much higher than water velocity in the swimming zone inside corrugated metal pipes (Behlke et al. 1991). Average velocity is more likely to represent the swimming zone in smooth-walled concrete box culverts and steep bare-metal pipes.

Absence of Bank-edge Areas

Because certain organisms utilize bank edges for movement in natural stream channels it is possible that the absence of those bank edges may at least inhibit, if not prevent, passage by weak-swimming or crawling organisms (figure 1.22). Constructing a crossing structure that allows for bank-edge areas is often challenging, because of the increased cost associated with the larger structure needed. However, long-term costs to species may justify the additional cost of constructing a structure that provides bank-edge areas.

Figure 1.22—This box culvert has a concrete floor and no shallow edges for crawling-species passage. Photo: Scott Jackson, University of Massachusetts.

Excessive Turbulence

When a culvert creates more turbulence than the natural channel, the associated aeration and chaotic flow pattern can disorient aquatic species, inhibit their swimming ability, and block their passage. Turbulence barriers are common downstream of perched culverts; at some flows fish may not even be able to approach culvert outlets. Baffles, riprap, or other **roughness** elements designed to reduce the water velocity can also create turbulence that blocks movement. Turbulence at culvert inlets can also block 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 (figure 1.23). In streams with highly variable flows, the challenge is constructing a structure capable of passing high flows while still maintaining a defined low-flow channel

similar to the natural streambed. In these systems the most successful structures are often those that provide bank edges and a flood plain within the structure. When designing these types of crossings, project teams need to pay particular attention to the size, location, and spacing of substrate within the structure to emulate the natural streambed as closely as possible.

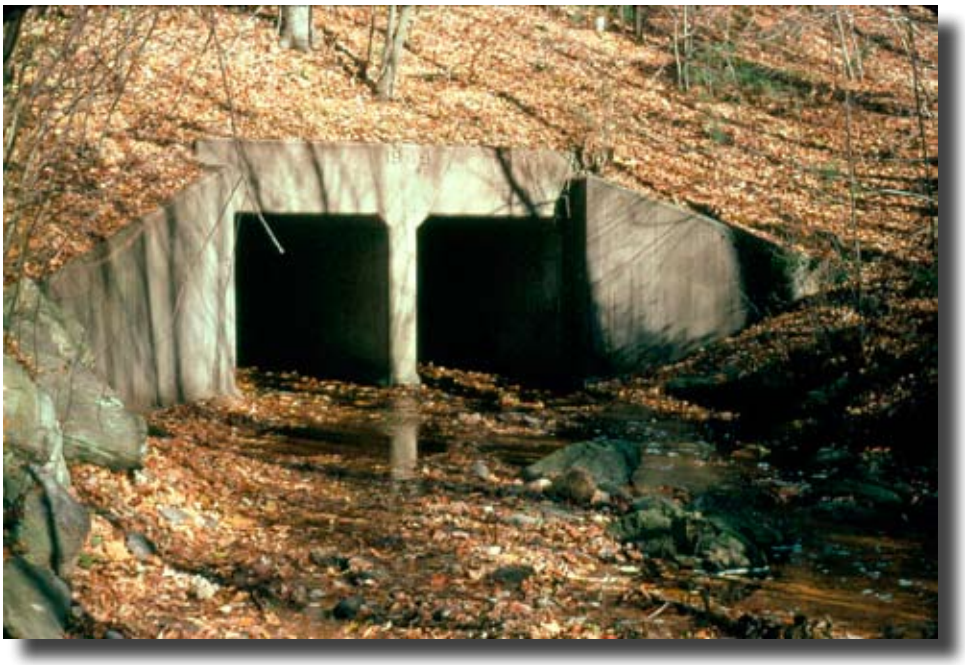


Figure 1.23—Lack of a low-flow channel results in insufficient water depth in these box culverts. Photo: Scott Jackson, University of Massachusetts.

Discontinuity of Channel Substrate

Crossing structures that lack any natural substrate or contain substrates (including riprap, baffles, 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, or over the surface of, appropriate substrates. Hyporheic zones (saturated stream sediments below the surface of the streambed) typically support a host of invertebrate species including copepods, ostracods, amphipods, nematodes, tardigrades, rotifers, oligochaete worms, and early instars of aquatic insects. Fauna in the hyporheic zone are an important contributor to nutrient cycling and food-chain support in river and stream communities.

Much of the movement of benthic organisms is downstream as passive drift. However, rare upstream movements must also occur to compensate for this drift and ensure that upgradient sections of streams do not become depleted over time. The flying adult stage of most aquatic insects provides

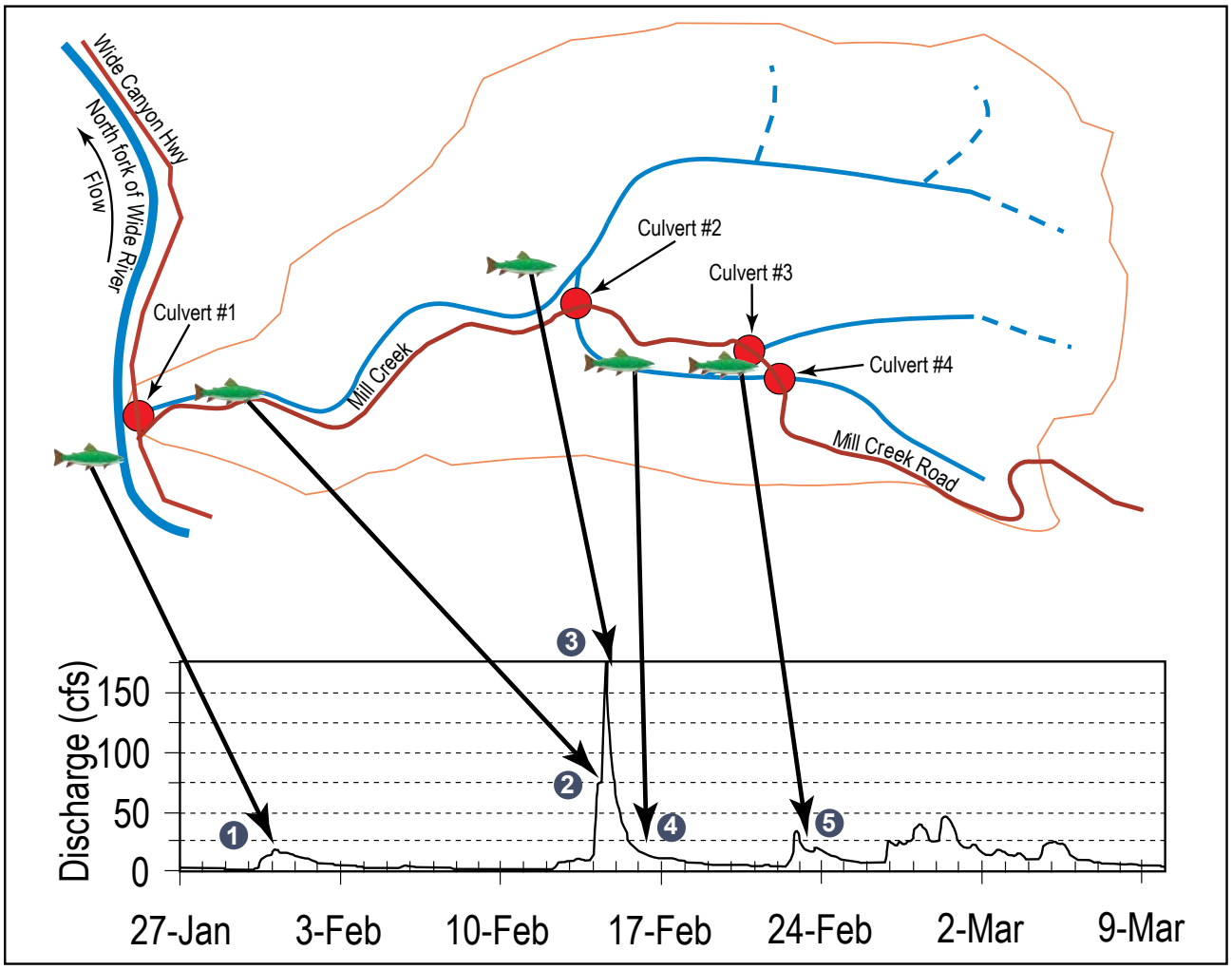
an obvious opportunity for upstream movement. However, noninsect invertebrates most likely require other mechanisms, such as movement through the streambed or attachment to larger organisms for upstream movement. There is some concern that streambed discontinuities caused by crossing structures may disrupt and fragment populations of these benthic organisms. Vaughan (2002) offers a thorough discussion of crossing effects on invertebrates.

Summary: How Crossing Structures Can Impede Movement

- Debris accumulation
- Inlet or outlet drops
- Physical barriers (weirs, collapsed culverts)
- Water velocities exceed swimming ability (too fast for too long)
- Absence of bank-edge areas
- Excessive turbulence
- Insufficient water depth
- Discontinuity of channel substrate

1.3.3 Effects on Individual Animals

If not properly designed, road-stream crossings can block animal movements, delay migration (a process made worse where many crossings exist), and cause physiological stress as animals expend energy passing both natural and artificial obstacles (Fleming 1989) (figure 1.24). Delays in movement also can result in overlap of individuals that typically occupy different stream reaches. For example, culverts often concentrate migrating fish in large pools at their outlets. These pools often provide resident fish habitat, and residents can experience increased predation or competition from migrants when such overlap occurs. Increased susceptibility to fishing pressure and stress associated with overcrowding can also occur when fish movements are delayed at crossings.



1. Fish enters North Fork of Wide River and swims to mouth of Mill Creek. Culvert 1 is low-flow barrier, water too shallow.
2. After 2 weeks of waiting for sufficient water depth, the fish passes through culvert 1 as flow rises.
3. Fish reaches culvert 2 as flow begins to recede. Velocity in culvert too high. Fish repeatedly attempts to swim through culvert.
4. Fish successfully passes through culvert 2 after flow drops. Water depth in upstream channel has become insufficient.
5. After waiting 7 days for flows to rise again, the fish is able to swim upstream to culverts 3 and 4 but oulets are perched too high.
6. Finding no mates, the fish migrates further downstream to spawn, 4 weeks after first arriving at the mouth of Mill Creek.
7. South Fork of Mill Creek remains unseeded, with young-of-the-year concentrated in the lower portion of the watershed.

Figure 1.24—Hypothetical example of the cumulative effects of delaying spawning salmon at a series of culverts. Used by permission of Mike Love, Love and Associates, Eureka, CA.

Riparian wildlife may choose to cross over the road surface rather than pass through a crossing structure that does not have banks or other dry passage. However, if physical barriers, such as fencing or Jersey barriers are present, passage across the roadway may be blocked. Even where passage over the road is not blocked physically, if the road supports high-traffic volumes, individual animals are likely to be killed trying to cross. For some long-lived species with low reproductive rates, such as turtles, roadkill can undermine the viability of populations significantly. Stream-simulation structures generally offer dry passage opportunities for riparian-dependent species, since the structures are wide enough that the channel edges are dry much of the year.

1.3.4 Reduced Access to Vital Habitats

Crossing structures may be complete barriers—essentially blocking passage for all aquatic species—or they selectively may pass some species or lifestages while blocking others. Even for a particular species a partial barrier may allow passage for only the strongest swimming individuals in a population. Partial barriers are sometimes referred to as "filters" because of their selective nature in facilitating passage. Other structures may be barriers at certain times of the year (high-flow or low-flow conditions) but not others. For some species, the timing of movement is critical and temporary or seasonal barriers might seriously impact survival or reproduction within a population.

Crossings that are partial or complete barriers may 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 other seasonal habitats. With restricted access to vital habitats, we would expect populations of affected fish or wildlife to be reduced or lost altogether [figure 1.25 (a) through (c)]. For important fisheries, reduced access to vital habitats can result in a significant reduction in productivity.

1.3.5 Population Fragmentation and Isolation

To the extent that road-stream crossings act as barriers to animal passage, they can fragment and isolate populations [figure 1.26 (a) through (c)]. Smaller and more isolated populations are vulnerable to genetic change and extinction from chance events. Genetic changes may result from **genetic drift** that occurs in small populations, or via **inbreeding depression** in very small populations. Local extinctions can result from demographic chance events (change in sex ratio), natural disturbances, or human impacts. As crossings contribute to population fragmentation and isolation, they undermine the viability of animal populations. (For examples of how this may have impacted riverine species, see: Dunham et al. 1997; Dunham and Rieman 1999; Harig and Fausch 2002; Letcher et al. 2007; Lowe and Bolger 2002; Morita and Yamamoto 2002; Neville et al. 2006).

1.3.6 Disruption of Processes That Maintain Regional Populations

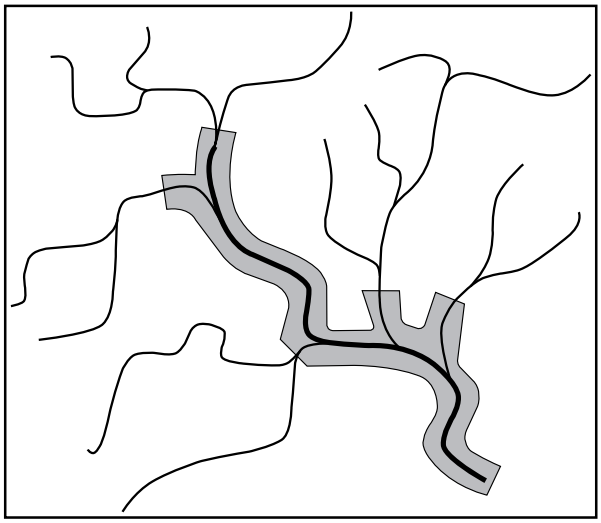
Decreased animal movement can undermine processes that help maintain regional populations over time. Barriers to movement can block the exchange of individuals among populations, eliminating gene flow and disrupting the ability of "source" populations to support declining populations nearby. Barriers to dispersing individuals also eliminate opportunities for recolonizing vacant habitat after local extinction events [figure 1.27 (a) through (f)]. (For examples affecting riverine species see Cooper and Mangel 1999; Dunham and Rieman 1999; Letcher et al. 2007; Lowe and Bolger 2002; Morita and Yamamoto 2002).

1.3.7 Time and Geography

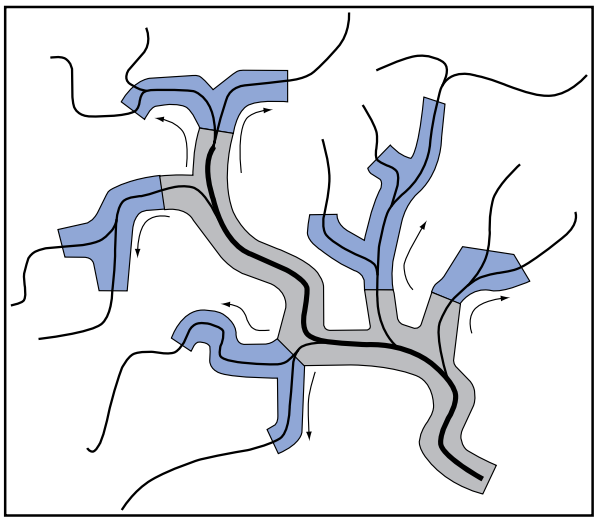
When road-stream crossings result in the loss or degradation of habitat, impacts, such as those caused by erosion and sedimentation, are immediately obvious. Portions of streams may no longer provide habitat for certain species. As a result, the abundance and diversity of aquatic organisms inhabiting 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 from changes in hydrology, sediment transport, or the movement of woody debris within a river or stream, may occur over many years. It may result in gradual changes that, over time, reduce the amount of suitable habitat for aquatic organisms. 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 migratory fish, especially anadromous, adfluvial (lake-dwelling fish that migrate to streams to spawn), and fluvial 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 nonmigratory 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 on whether the species is closely monitored. As changes in habitat or barriers to movement cause populations to become smaller and more isolated, we can expect a gradual and continual loss of species over time. Because mechanisms for the recolonization of habitat made vacant by local extinctions have been disrupted, species loss is a cumulative process that can eventually undermine the stability of ecosystems.



(a) For most of the year a population of brook trout occupies the mainstem of a stream network.



(b) During spawning season, adult fish move into the headwater tributaries to mate and deposit eggs.

(c) Construction of a road with substandard culverts blocks access to some of the spawning areas. With reduced access to these vital habitats, the stream network can support only a fraction of its previous population.

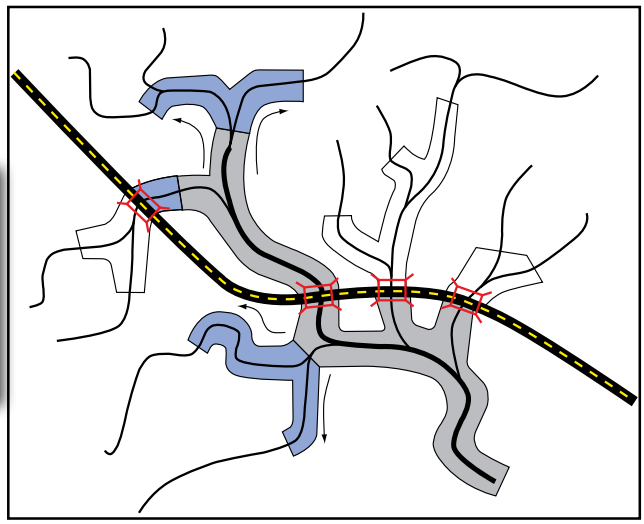
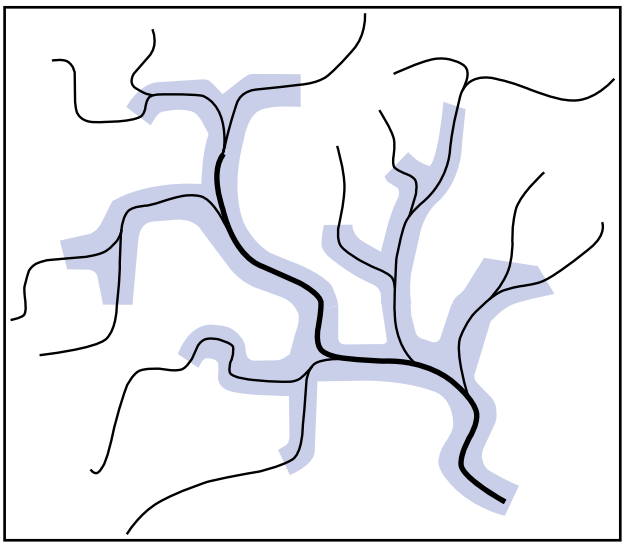
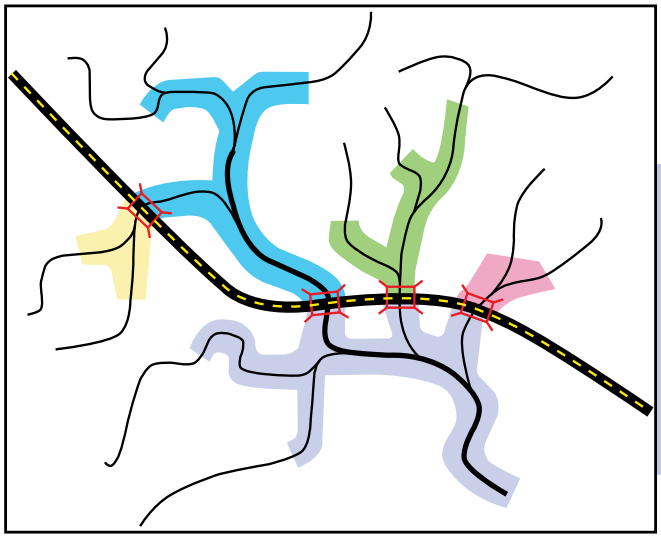


Figure 1.25 (a) through (c)—Hypothetical example of population effects of barrier culverts that reduce access to spawning areas.



(a) This stream network supports a continuous population of Pacific Giant Salamanders, an aquatic species with limited swimming abilities (occupied area illustrated in purple).



(b) After construction of a road with substandard culverts the population is fragmented into five smaller and more isolated populations.

(c) Smaller and more isolated populations are more vulnerable to genetic changes and local extinctions due to chance events. Over time, as these smaller populations fail, the salamander is eliminated from a significant portion of the suitable habitat available in this drainage.

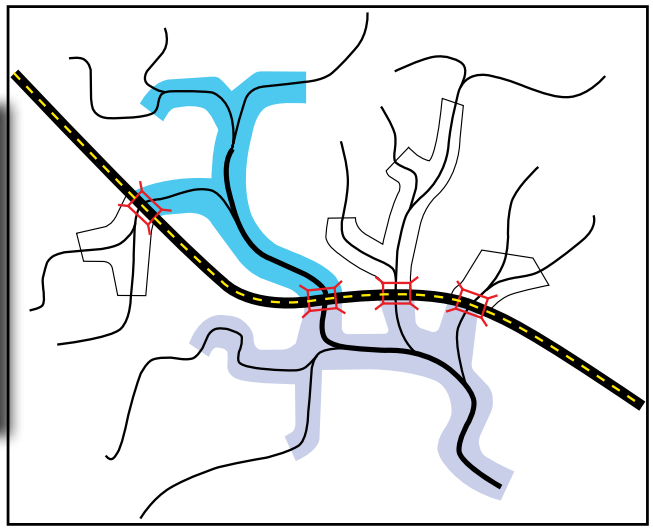
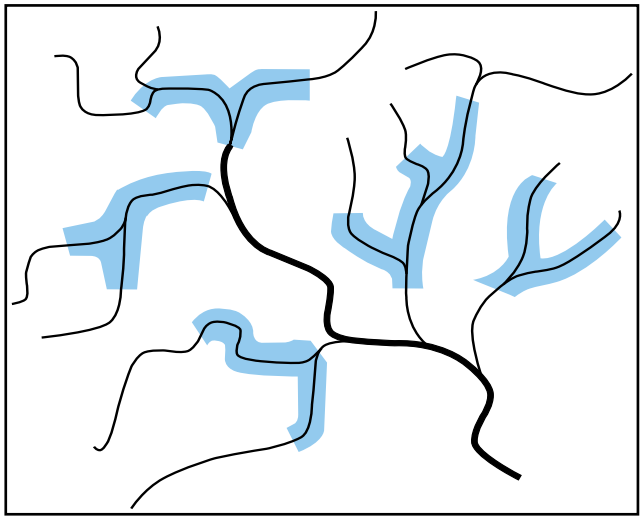
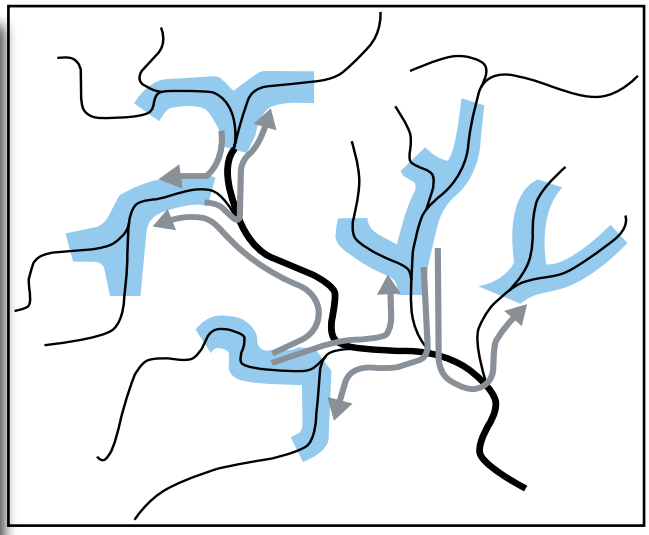


Figure 1.26 (a) through (c)—Hypothetical example of effects of barrier culverts that isolate populations.



(a) The headwaters of this stream network support populations of the Appalachian Brook Crayfish.

(b) Although the mainstem is not suitable as habitat, crayfish are still able to move through the area to occasionally exchange individuals among populations. Such exchanges facilitate gene exchange and can allow source populations to supplement and maintain populations that would otherwise be declining.



(c) In a period of extended drought it would not be unusual to lose one or more of the small crayfish populations. However, dispersal of individuals from populations nearby would recolonize some of the areas.

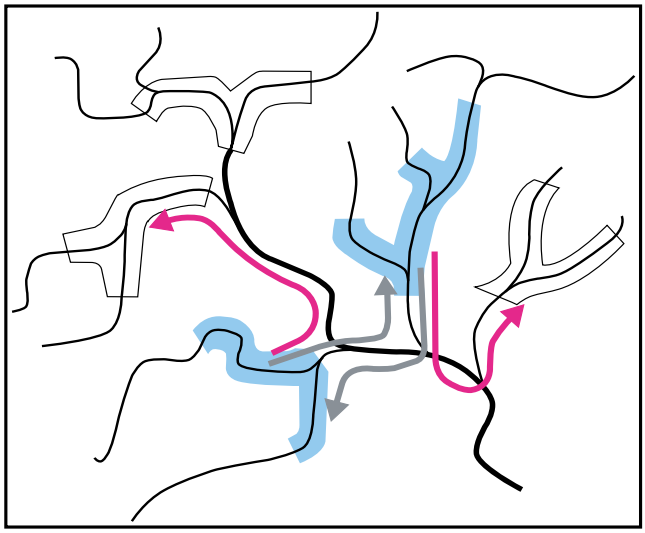
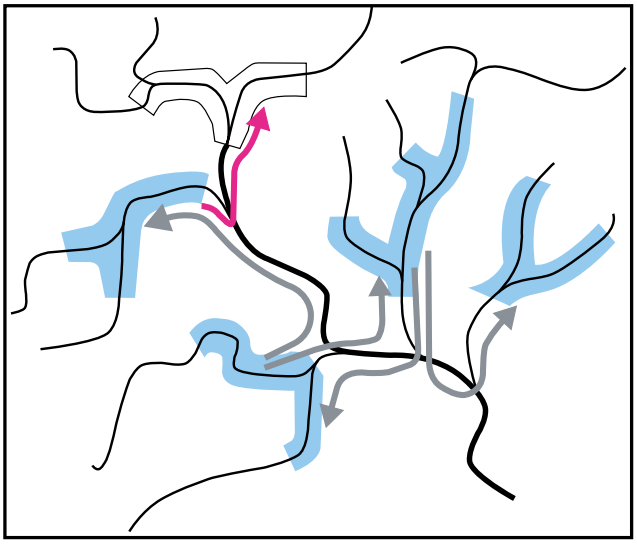
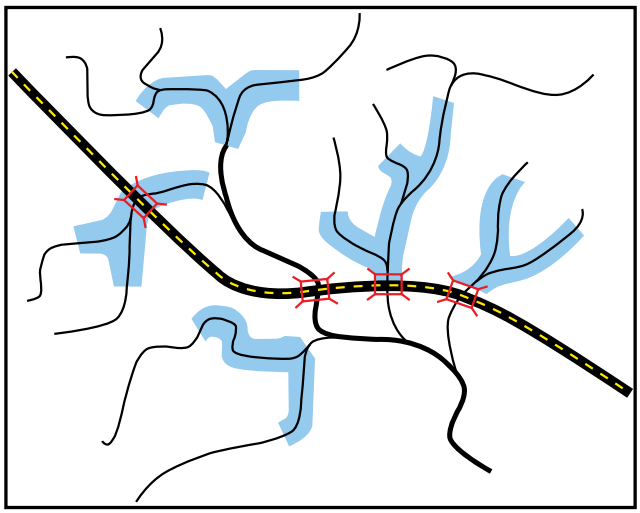


Figure 1.27 (a) through (c)—Hypothetical example of population effects of barrier culverts that prevent recolonization after catastrophic disturbances.



(d) Once these areas are recolonized, they can serve as a base to reestablish a population in the more distant tributary. Maintenance of a regional population structure eventually allows all suitable habitat in the area to be reoccupied after the drought.



(e) The presence of a road with substandard culverts blocks movement of individuals among populations.

(f) Tributaries that had supported populations that failed due to genetic effects of fragmentation or natural disturbance such as drought, can no longer be recolonized by dispersing individuals from nearby populations.

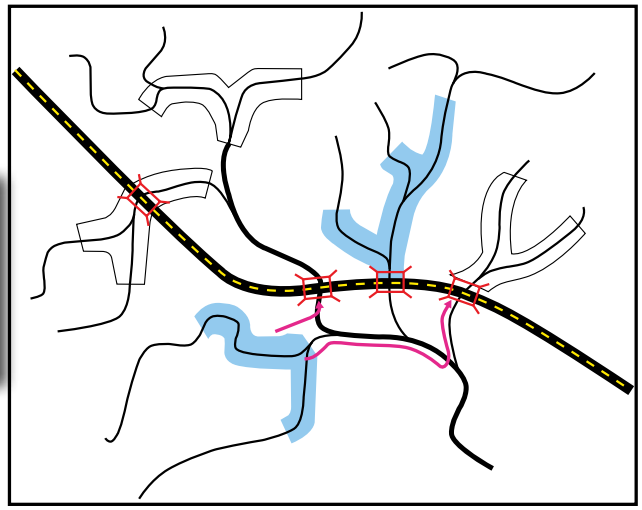


Figure 1.27 (d) through (f)—Hypothetical example of population effects of barrier culverts that prevent recolonization after catastrophic disturbances.

Although the effects of population fragmentation and isolation may take years to occur, these effects are nonetheless 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 1-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, including data of the road network from 1944, revealed an even more significant negative relationship between roads and species richness (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 suggest that, despite taking decades for the ultimate impact of roads to be apparent, the impacts can be quite significant. Thurow et al. (1997) concluded from a study of seven salmonid fish in the Interior Columbia River and portions of the Klamath River and Great Basin that the proportion of areas with healthy populations (strongholds) declined from 0.58 in roadless watersheds to 0.16 in watersheds that exceeded 4 kilometers of road per square kilometer.

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. Typically, little consideration is 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 support species of fish and wildlife that are not found in larger waterways (Meyer et al. 2007). A road network that crosses every tributary of a river could have a large effect on the entire system.

Zero-, first- and second-order streams account for most of the total stream miles within any watershed. They cumulatively provide much more habitat area for aquatic organisms than large rivers. Small streams are also highly productive systems, owing to their relationships with adjacent upland habitats (figure 1.28). These areas of high productivity are often used for spawning and nursery habitat by fish that normally inhabit larger waterways as adults.

Even intermittent and very small **perennial streams** play an important role in transporting invertebrates, detritus, and other organic matter that fuel downstream food webs (Wipfli et al. 2007). One study in Alaska estimated that fishless headwater streams export enough invertebrates downstream to feed 100 to 2,000 young-of-the-year salmonids per kilometer (0.6 mile)

of salmonid habitat (Wipfli and Gregovich 2002). In another study (of Sagehen Creek in California), researchers estimated that 39 to 47 percent of rainbow trout in the population spawn in an intermittent tributary that flows for less than half the year (Erman and Hawthorne 1976). Bryant et al. (2004) emphasized the importance of small, high-gradient streams to fish communities in southeast Alaska.

Figure 1.28—Headwater streams are important habitats for aquatic species. Photo: Scott Jackson, University of Massachusetts.

Small streams provide important summer habitat for cold-water fish that move up into headwater streams to escape unfavorably warm conditions in ponds and rivers. Headwater streams also provide a significant amount of woody debris input to mountainous stream systems.

In addition to providing critical habitat for fish, small streams support many animals that do not occur in larger streams and rivers. These include species of stream salamanders, 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 crossing, project teams should consider the cumulative effect of all barriers to movement, such as crossings, dams, and other significant discontinuities (channelized, intermittent, dewatered, or piped sections) within the watershed (see figure 1.29). 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 crossings. On the other hand, because stream systems are convergent, a passage barrier low in the watershed (close to confluence with an ocean or other important water body) can block migratory fish access to entire stream networks. Setting priorities for limited resources calls for a watershed perspective, evaluating restoration opportunities in terms of both habitat quality and river and stream continuity.

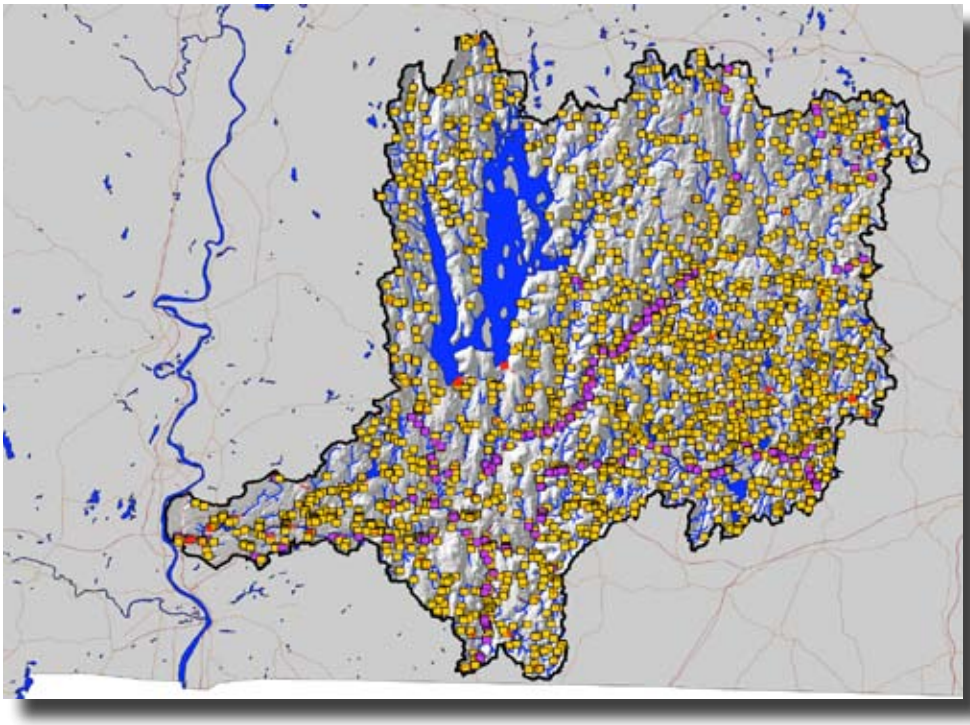


Figure 1.29—Aquatic organism passage barriers in the 721-square mile Chicopee River watershed, Massachusetts, include 195 old small-scale industrial dams and 2,230 rail and road crossings.

1.4 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 fish passage for migratory species. A large amount of time, money, and effort have been expended on the issue of passage barriers for migrating adults. Unfortunately, some efforts to promote upstream passage for adult fish have failed to provide passage for the juvenile stages of the same species. Strategies that focus solely on adult fish but don't address all life stages for a particular species are unlikely to maintain populations over time.

As strategies are adjusted for 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, management strategies that ignore the community and ecosystem context for that species cannot succeed. Conservation strategies that focus only on target species—without careful planning to maintain habitat quality, passage for the variety of aquatic organisms in the stream, and other ecosystem processes—may succeed in the short term, but they undermine long-term prospects for success.

> *"If the biota, in the course of eons, has built something we like but do not understand, then who but a fool would discard seemingly useless parts? To keep every cog and wheel is the first precaution of intelligent tinkering."*
>
> *— Aldo Leopold*

Given the large number of species that make up most river and stream communities and the lack of information about swimming abilities and passage requirements for most organisms, using a species-based design to meet the movement needs of an aquatic community is impractical in many cases. An ecosystems approach is the most practical way of maintaining both the viable populations of organisms that make up aquatic communities and 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.

THREE GUIDING PRINCIPLES FOR THE DESIGN OF ROAD-STREAM CROSSINGS

To preserve or restore all important elements of aquatic ecosystems, crossing structures should be designed following these three principles:

1. **The design should fit both the stream and the road, not just the road.**
   Crossing designs must accommodate the stream—the stream's geomorphic processes and anticipated changes over the life of the structure—not simply road or transportation needs.project teams must factor both systems into the design.
2. **Minimum intervention in the stream process results in the least risk.**
   Crossings should present the least possible obstacle to stream processes. Streams move water, wood, sediment, and organisms. Crossings should be designed, constructed, and maintained to permit movement of these components to the greatest degree possible.
3. **Crossings should present no greater challenge to organism movement than the stream being crossed.**
   Crossings should not fragment aquatic habitats. Avoiding fragmentation means reproducing the natural conditions of the stream being crossed. The key is matching the structure to the stream, both in form and process.

Stream simulation is one approach to road-stream crossings that protects habitats, maintains ecological processes, and sustains aquatic communities. The stream-simulation approach avoids flow constriction during normal conditions by using structures at least as wide as the natural channel. The constructed stream channel within the culvert is designed to insure adequate water depth during low-flow conditions and resist scouring during flood events. Well-designed stream-simulation culverts can maintain the continuity of stream bottom and hydraulic conditions, thereby facilitating passage for aquatic organisms.

Designing culverts to avoid channel constriction and 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) ecosystem processes that maintain habitats and aquatic animal populations. Where passage for riparian and terrestrial wildlife is desired, stream-simulation structures can be adapted for wildlife preferences (see Forman et al. 2003).

Connectivity is key to the successful functioning of both roads and rivers. Ultimately, our goal should be to create a transportation infrastructure that does not fragment or undermine the essential ecological infrastructure of the land.