



# Stream Simulation

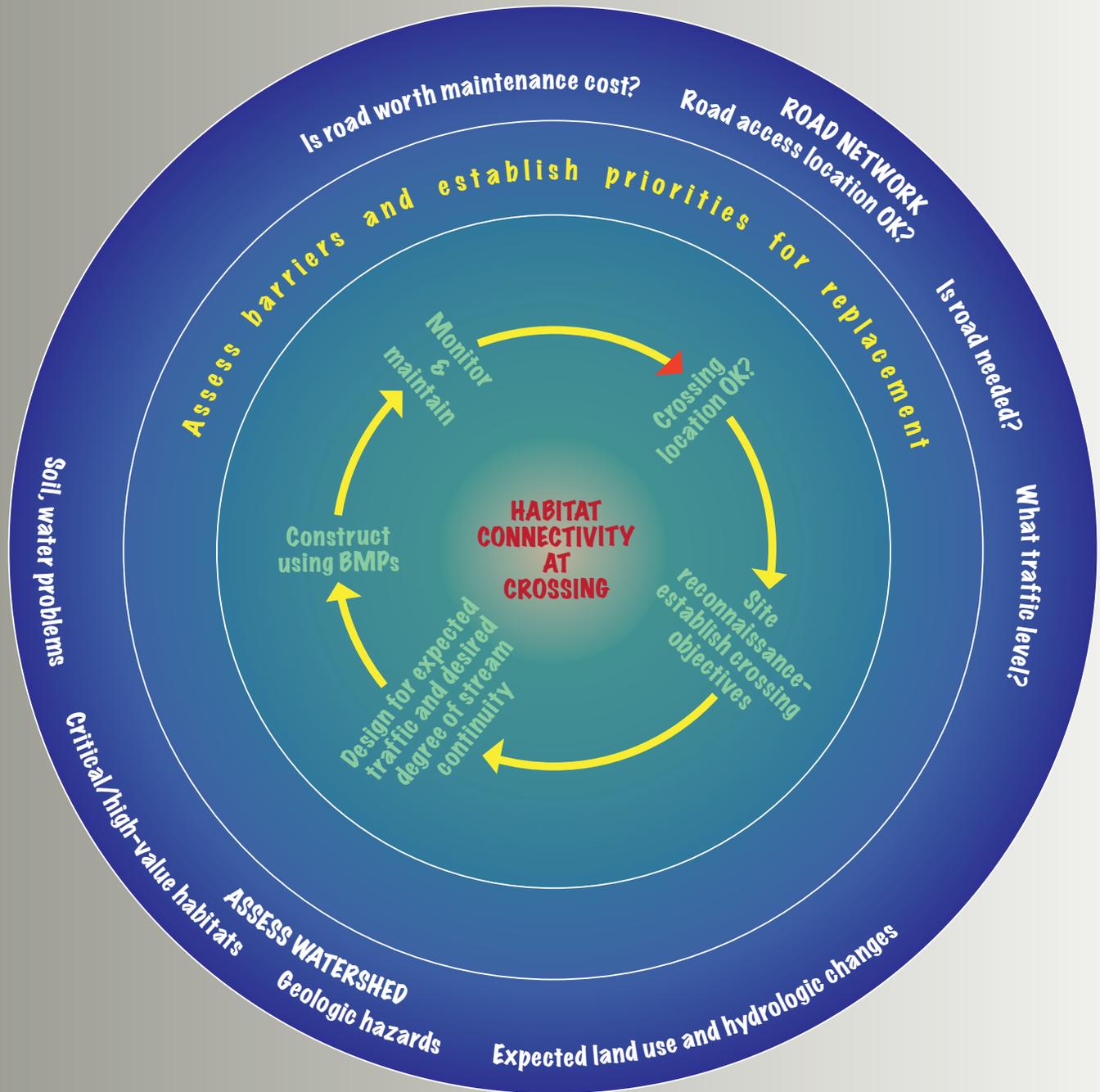


Figure 2.1—General process for providing habitat connectivity at road-stream crossings begins with large-scale assessments and drills down to site-scale design and monitoring.

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Chapter 1 showed that to maintain or restore the long-term viability of stream ecosystems and aquatic populations, roads and road-stream crossings must protect **stream connectivity**. This chapter briefly describes the planning, design, and implementation work needed to provide for stability and continuity in both road and stream networks. The chapter is a summary overview for land managers and decisionmakers among other readers, highlighting actions that protect aquatic habitat. Setting project objectives is emphasized here because it is one of the most important actions that require managers' participation. Chapters 4 and 5 provide more detail about formulating project objectives during the project development process.

Figure 2.1 shows the general sequence of steps required for constructing crossings that maintain or restore stream connectivity—from large-scale transportation system planning to project construction and site monitoring. The feedback loop from monitoring to planning and design is an essential step without which experience cannot improve the technology. Because crossing design is not a perfect science, project teams need to learn quickly from their mistakes if they are to avoid repeating them year after year.

### 2.1 REVIEW THE ROAD NETWORK

Before deciding on the location or design of any particular road or structure, project teams should review the area road network to ensure that it is as efficient and environmentally benign as possible. Creating a road system that is safe, efficient (that is, minimum length to meet access objectives), and protective of the aquatic and terrestrial environment calls for considering a variety of elements from a broad range of disciplines.

For road systems on national forest lands, “Roads Analysis: Informing Decisions About Managing the National Forest Transportation System” (USDA Forest Service 1999) provides a framework for analysis supporting broad-scale, strategic planning. This framework includes a comprehensive set of questions that transportation-planning teams should ask about the areas and facilities they are evaluating. The procedure poses each question in the context of an overall analysis at several scales, citing resources for assistance in determining the relevance of each question. Planning for transportation needs and mitigating environmental effects is often referred to as “access and transportation management”—an application of roads analysis, with the goal of planning the development of the transportation system over a decade or more.

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The roads-analysis process should answer the first question in any road-crossing planning effort: Is the road needed? Before going on to the next step in crossing planning, be sure this question has been answered. Compare the access benefit against the resources and other costs the road incurs, and then ask: Is it worth it? (figure 2.2). The process helps avoid the expensive mistake of retrofitting a crossing for organism passage on a road that may soon undergo decommissioning.

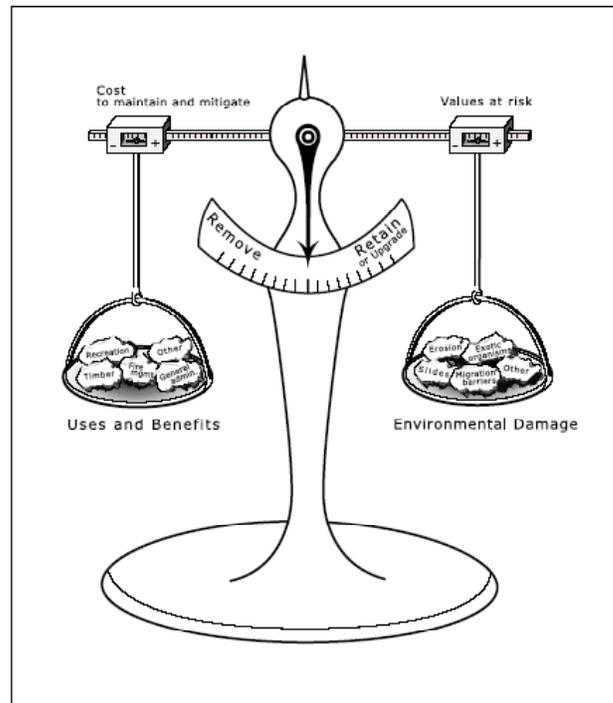


Figure 2.2—Remove or Retain? The cost-risk analysis. From USDA Forest Service 1999.

## 2.2 OPTIMIZE ROAD AND CROSSING LOCATIONS

Many forest roads were originally constructed where access was easiest—in the valley bottom. Despite the damage they may have caused over the years, many of those roads are still maintained. Before doing any upgrade work on a road, check that it is located properly. As all crossings result in some impacts to streams, the first principle is locating roads to avoid stream crossings, wherever doing so is feasible and consistent with transportation and other environmental considerations. All options for locating roads should be explored, because the more roads that are near streams or cross streams, the greater the potential adverse cumulative effects (figure 2.3). Roads that either run along streams or have many crossings, or both, should be considered for relocation or decommissioning. Relocating roads is often the only approach to mitigating the impact of old roads built in streamside areas. Many roads

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have alternative routes that access the same places, and these are good candidates for decommissioning. Where stream crossings are unavoidable, their number should be the bare minimum.

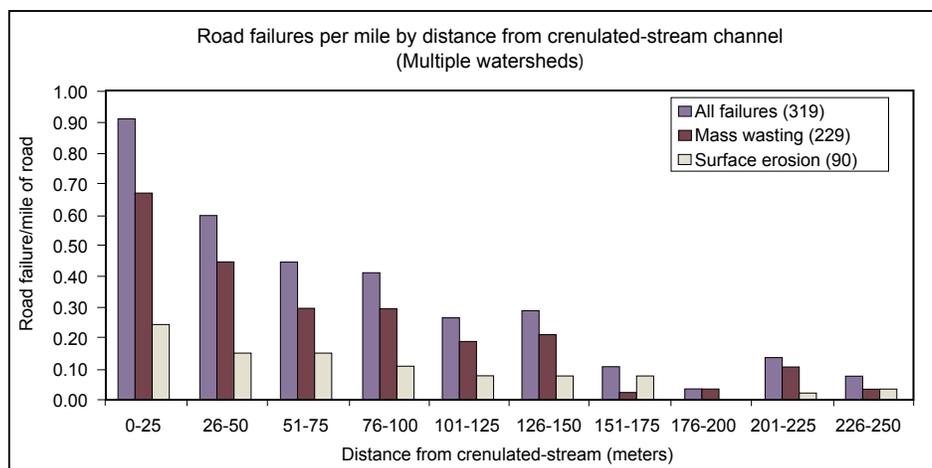


Figure 2.3—Road proximity to streams is usually strongly correlated with road failures, problems, and risks to aquatic ecosystems. From USDA Forest Service 1999.

Conduct a thorough geologic review of areas traversed by the road. If a road is in a high-hazard location, such as steep, wet, or unstable slopes, or streamside areas, consider removing, relocating, or modifying it to reduce its effects (figure 2.4). Also, identify critical or high-value habitats (wetlands, spawning grounds), and avoid them if possible. Road alignment and roadfills should avoid isolating  **flood plains**, constricting or realigning channels, or constraining channel migration, so that riparian and aquatic habitats retain their natural character.



Figure 2.4—Road located on a geologically unstable slope causes massive landslides, Bolivia.

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Try to locate roads away from high-value areas that are sensitive to disturbances created by road users. Roads can provide access for poaching, introduce exotic and invasive organisms, contribute to declines in rare or unique native vertebrate populations, or otherwise increase the potential of damage to important habitats.

As we will see later, crossing location is a critical element in stream-simulation design because location affects the risks associated with processes like shifting stream alignments, flood-plain constriction, and **debris flows**.

### 2.3 INVENTORY BARRIERS AND SET PRIORITIES FOR PASSAGE RESTORATION

There are several systems for evaluating culverts for their impacts on aquatic animal passage and other ecosystem processes (Taylor and Love 2003; Clarkin et al. 2003; Coffman 2005). After these evaluations are done, a process for prioritizing **barrier** crossings for remediation is needed. Priority setting should take into account the habitat quality in the river or stream and surrounding areas, upstream and downstream conditions, as well as the number of barrier crossings and other barriers on and off national forest lands (resource and risk assessments are described in sections 4.2 and 4.3). In some cases, dealing with other problems, such as the impacts of water withdrawals, restoration of in-stream habitat, or control of exotic invasive species, may be a higher priority than upgrading substandard culverts.

To maximize positive outcomes and avoid unintended consequences, using a watershed-scale approach to restoring connectivity is critical. The diversity and complexity of stream ecosystems impede the creation of precise formulas for weighing the various costs, benefits, and other factors that affect decisions about whether and how to replace substandard-crossing structures. Clearly, priorities for restoring connectivity depend in part on biological values in an area. High priority goes to areas with high biological diversity or productivity or with other special values, such as migration-route connectivity. However, because many other social, economic, logistical, and engineering elements go into prioritizing crossing replacement, the project team should weigh and balance them all before recommending priorities.

### 2.4 SET PROJECT OBJECTIVES AND DESIGN TO ACHIEVE THEM

The level of stream and flood-plain connectivity at a site has tremendous implications for transportation efficiency, safety, cost, **fluvial** changes, ecological effects, longevity, maintenance needs, and so on. Again, the most successful approaches to defining the appropriate degree of connectivity involve an active partnership between engineers, **geomorphologists**, hydrologists, and biologists, using an ecosystems approach for each case. At every site, the project team should analyze resource values, ecological risks and consequences, future management constraints, and access needs (see chapter 4). From that analysis, they can recommend what level of stream and valley continuity to aim for.

Federal land managers should be aware of at least three Federal laws when making decisions about the degree of connectivity at a new or replacement crossing:

- The 1973 Endangered Species Act [16 U.S.C. §§ 1531-1544].
- The Clean Water Act, 1977 amendment of the 1972 Federal Water Pollution Control Act Amendments [33 U.S.C. §§ 1251-1387].
- The 1976 National Forest Management Act [16 U.S.C §§ 1600-1616].

All these laws contain provisions that apply at road-stream crossings.

Ecologically speaking, crossing objectives can range from providing for full **flood-plain functioning** and large-animal passage to providing capacity for a certain flood, with no consideration of either animals or woody debris.

A corresponding continuum of design approaches exists (figure 2.5). The degree of stream and habitat connectivity decreases as we move from crossings designed for minimum interference with flood plain and valley processes to those designed simply for passing a flood of a certain frequency. Stream simulation is in the middle of this continuum. The structure types shown on figure 2.5 are not the only ones that correspond to the stated objectives; they simply illustrate the degree of connectivity. In addition to ecological objectives, the design approach will vary according to many criteria, such as traffic volume and type.

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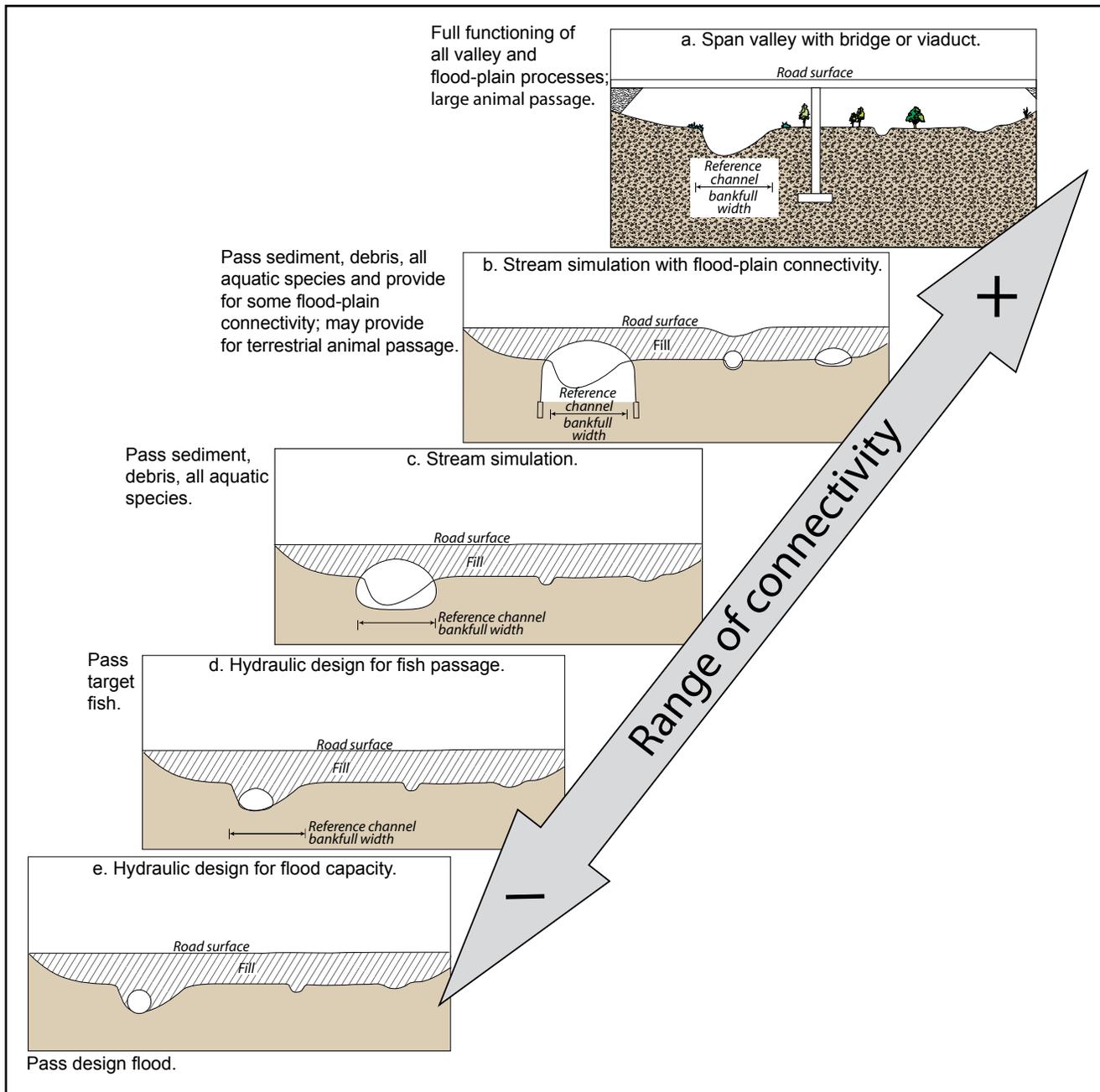


Figure 2.5—Range of crossing ecological objectives and examples of corresponding design approaches.

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Most sites will have a suite of biological, geomorphic, hydraulic, and/or infrastructure objectives. Some of these may conflict. The goal is to balance all the objectives appropriately and design a structure that optimizes achievement of all of them.

The team may have to modify objectives as the assessment and design process progresses. Site and other constraints that limit the degree to which certain objectives can be achieved may become evident as project planning progresses. Site conditions, public safety, land ownership, and cost are some of the many possible constraints. As the team learns more about the site, they are likely to engage in a healthy and challenging discussion about the achievability of objectives, feasibility of structure types, and best design approaches. An open and balanced discussion with due consideration for all aspects of the project is most likely to produce the best overall plan.

Following are examples of some of the ecological objectives and design approaches that a team might recommend for a site. There will be many other objectives related to, for example, local regulations, traffic safety, vehicle types, project footprint, associated infrastructure, etc.

### Full Valley and Flood Plain Functioning

A team might recommend minimal interference with valley and flood plain processes where:

- The stream is shifting rapidly across a wide **valley flat**.
- There are many **side channels** used by juvenile fish or other aquatic species.
- The valley flat is a migration corridor for large mammals and traffic is high on the road.
- The full range of riparian habitat diversity must be sustained as critical habitat.

This objective might guide the project toward a bridge and/or viaduct that spans the valley flat [figure 2.5(a)]. On very low volume roads where traffic interruptions are acceptable, other less expensive ways to maintain a high level of valley and channel connectivity may be appropriate, such as **fords** and dips. In some situations, well-designed fords can help maintain flood plain connectivity by keeping the approach road low across the flood plain. However, maintaining passage for aquatic organisms across fords is challenging, and requires designing the structure to fit the needs of the specific site (Clarkin et al. 2006).

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### Minimal Interference with Flood Plain Habitats and Transport of Water, Sediment, and Debris on Flood Plains

Flood plains are extremely important components of the aquatic system. During floods, water, sediment, and woody debris may move across flood plains, constructing important and unique habitats. Flood-plain stability—and **channel stability**—may depend on deposition of sediment and debris from upstream and on maintenance of the natural flooding regime. Flood-plain continuity is therefore an important value in many locations. Side channels are often important habitats on active flood plains, calling for preservation of aquatic organism passage in these smaller channels, too. In figure 2.5(b), culverts are placed in side channels and swales to achieve this objective. In other situations, such as little-used roads, ephemeral flow, seasonal closure, simple rocked dips may offer adequate passage.

### Terrestrial Animal Passage

Wildlife species primarily associated with stream ecosystems, and others that use riparian areas as movement corridors, may need passage through a crossing structure if the road has a high volume of traffic and/or very high, steep fillslopes. For some species of wildlife, such as muskrat and stream salamanders, maintaining **streambed continuity** (with a stream-simulation structure) may be adequate. Many other species prefer to use banks or dry streambed areas to cross through structures. Figure 2.5(b) shows a structure slightly wider than the **bankfull** channel that offers dry passage for some terrestrial animals.

Larger wildlife species are thought to have minimum requirements for the height of the structure (in many cases minimum requirements are not known). These species may be sensitive to the relative “**openness**” of the structure. [A structure’s openness ratio is defined as the cross-sectional area of the crossing opening divided by the structure’s length, and is usually stated in meters.] A few studies of structure use by deer, for example, indicate that these species need openness ratios of at least 0.6, and that ratios of 1.0 or greater are preferred (Brudin 2003; Reed 1981). The Wildlife Crossing Toolkit ([www.wildlifecrossings.info](http://www.wildlifecrossings.info)) provides information on terrestrial wildlife requirements.

Compared to other crossing structures, bridges are more likely to facilitate the passage of riparian and terrestrial wildlife, because they are more open and shorter in the along-stream direction. When sized properly, open-bottom arches are similar to bridges; the arches maintain the continuity of the streambed, allow unrestricted flow during normal conditions, and

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### Fish and Other Aquatic Organism Passage

typically allow the passage of some woody debris. Project teams may sometimes be tempted to rule out bridges or open-bottom structures in the beginning of the design process because of high cost. However, when the lifetime costs and resource effects are considered together, these structure types may sometimes be the best overall solution.

Ideally, crossing structures should constitute no greater restriction on movement for fish (including juvenile and relatively small resident fish) and other aquatic organisms, such as amphibians, reptiles, and crayfish, than the organisms confront in the stream itself. Unnatural physical barriers, such as inlet or outlet drops, debris racks, weirs, baffles, or other structures that would block movement of aquatic organisms should be avoided if at all possible. Keep in mind, however, that creating passage where there was none originally may be just as undesirable as creating a barrier (see Fausch et al. 2006).

Stream-simulation design is appropriate where passage is desired for all aquatic organisms present in the channel. Structures include open- and closed-bottom structures, but in all cases the streambed is continuous through the structure. [Figures 2.5(b) and (c) show stream-simulation structures; (b) goes further and provides for partial flood-plain connectivity.] Since streambed width, slope, and composition are all similar to the natural channel, stream-simulation structures accommodate the normal movements of aquatic organisms and preserve (or restore) the transport processes that maintain habitats and aquatic animal populations. Weak-swimming and crawling species may need appropriate bank-edge habitat for movement. Again, where passage for riparian and terrestrial wildlife is desired, teams should adapt structures to meet minimum height and openness requirements.

Hydraulic design [figure 2.5(d)] has been used for decades as the primary design tool for fish passage at road crossings all over the world. Hydraulic design optimizes the hydraulic effects of culvert size, slope, material, and length to create water depths and velocities suited to the swimming ability of a target fish. It can be appropriate when designing for a small number of target species with similar requirements, if the hydraulic requirements of those species are known. In current practice, the weakest-swimming species and lifestage of concern is usually selected to set velocity criteria, with the assumption that this also provides for the stronger swimmers. This design method and the uncertainties associated with it are covered in appendix B.

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### Passage of Watershed Products

Streams move water, sediment, and organic materials such as wood and detritus. Maintaining natural channel slope, width, and alignment through crossings is the best way to permit these stream functions to maintain the channel and flood plain downstream. Substantial decreases in slope or channel width will tend to restrict the movement of watershed products and contribute to higher maintenance costs and a risk of crossing failure.

### Minimal Risk of Crossing Failure

Culvert failures usually do much more damage than bridge or ford failures because of the amount of fill that is mobilized within the channel. Teams will find many approaches to minimizing both the probability of failure and its consequences. Stream-simulation design reduces the probability of failure by matching channel width, which generally provides capacity for rare flood flows plus debris and sediment. Carefully designed transitions between structure and stream also minimize the probability of failure. Nonetheless, any crossing can fail, so where the risks and consequences of failure are high, designing for a “soft” failure is a wise strategy. Such a design strategy may mean providing a dip at the crossing to prevent stream diversion, and/or armoring a portion of the fill to sustain overtopping flow.

### Invasive Species Barrier

In a world where exotic species are invading many aquatic habitats, managers sometimes may have to erect or maintain a barrier to protect a population. The value of protecting a population from invasives sometimes outweighs the increased risk to both target populations and other species when habitat is restricted. Fausch et al. 2006 present a framework for evaluating these tradeoffs that may help in making these decisions.

Culvert barriers are often designed hydraulically [figure 2.5(d)] so that they are perched higher than the target fish can jump, or have faster water velocities than the fish can swim. Steep or perched crossing structures not specifically designed as barriers may not reliably block invaders because they may be passable at some flows or to some individual animals.

### Control Stream Bed Elevations on an Incising or Incised Channel

Where a **headcut** is progressing upstream and the existing crossing is protecting the upstream channel from incision, the team may recommend maintaining the **grade control** function. This might happen, for example, where the roadfill backs up water and creates an unusually valuable wetland habitat. A full-bottom culvert or ford can function as a grade control, but to provide for aquatic species passage, the installation may require special measures, such as a specially designed side channel.

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**Channel Restoration** Where a channel has incised downstream of the existing culvert and degraded important habitat, the team may recommend restoring both passage and habitat. This work would involve restoring the channel to an elevation and sinuosity that makes the transition across the road crossing as close to seamless as possible. These projects may be more extensive and expensive than those in which only the crossing is treated.

### 2.4.1 Road Approaches to the Stream Crossing

The effectiveness of any structure depends on how well its design fits the site. Size, alignment, and provision for **overbank flows** and woody debris passage all influence the long-term sustainability and passage effectiveness of structures. Part of the challenge of fitting the structure into the site and minimizing ecological damage is designing the road approaches to the crossing and implementing needed **BMPs**. For example, where the road crosses an active flood plain, the continuity of water, sediment, and debris transport along the flood plain depends on drainage through the roadfill. Side-channel culverts, and culverts or dips on flood-plain swales and other locations across the flood plain might be necessary for maintaining flood-plain habitats and passing aquatic species that use those features.

Other design BMPs act to hydrologically disconnect the road from the stream. Their purpose is to leave no continuous surface flow path from the approach road to the stream during runoff events, so that water quality is protected from road-derived pollutants. These BMPs include:

- Ensuring that drainage ditches discharge muddy storm runoff to a vegetated buffer area or a constructed sediment trap rather than the stream.
- Stabilizing road fills effectively so that sediment production is minimized, not chronically disturbing road fills during road maintenance, and revegetating or rearmoring them for stability where needed.
- Outsloping road surfaces for surface drainage dispersal wherever possible. (Outsloping minimizes needed excavation, hydrologic connectivity, drainage concentration, and maintenance needs. Backup cross-drainage may be necessary where outsloped running surfaces become rutted.) (<http://www.stream.fs.fed.us/water-road/w-r-pdf/surfaceshape.pdf>)
- Armoring road surfaces where necessary to prevent erosion and sediment transport to the stream.

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- Ensuring that stream crossings do not have **diversion potential**. (<http://www.stream.fs.fed.us/water-road/w-r-pdf/diversionpntl.pdf>)
- Anticipating and preventing maintenance problems, and disturbing well-cured roads and trails only when needed for safety or drainage.
- Monitoring roads, trails, and crossings at regular intervals after large storms, and promptly remedying problems.

### 2.5 CONSTRUCT AND MAINTAIN THE CROSSING

The next step is to build the new crossing, ensuring adequate protection of the aquatic ecosystem during construction. This step involves timing and sequencing of installation, appropriate construction methods, and use of BMPs for water quality and aquatic habitat protection.

Timing is important for reducing the environmental impacts of crossing construction. Construction sites may be more vulnerable to erosion—and organisms that inhabit the stream or river may be especially sensitive to impacts—during certain times of the year. For example, many freshwater mussels shed their larvae directly into the water, where the larvae drift downstream until they encounter host fish. These releases occur at specific times of the year, varying according to species. During spawning season, fish may require natural flow conditions to reach **headwater** spawning areas. Likewise, some life stages (eggs, larvae, fry) cannot easily move to avoid unfavorable conditions, such as periods of higher-than-normal turbidity, or dewatering of the stream channel. Before determining the most favorable time for construction, therefore, teams should identify species using the stream or river and understand their specific life cycles and habitat requirements. Except where species are particularly vulnerable during low-flow conditions, timing construction during periods of low flow is usually best. In practice, the ‘work window’ is often specified in the State permit for in-channel work.

The best construction practices are those that reduce the amount of erosion and sedimentation; minimize the extent, abruptness, and duration of streamflow changes; and avoid the creation of physical barriers to animal passage (figure 2.6). Where tradeoffs need to be made among these considerations, knowledge of watershed conditions, the species present, and their ecological needs should guide decisionmaking.

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*Figure 2.6—Isolating the construction area at a bridge reconstruction site in Yellowstone National Park. Photo: Dan Rhodes, National Park Service.*

Water quality, channel integrity, and downstream habitats are always at risk in crossing construction and retrofit projects. Diligent attention to erosion and sedimentation controls and stormwater management during and after construction is essential. Common events such as summer thunderstorms can have important negative effects if teams do not anticipate them when planning for erosion control.

Maintenance and restoration of **riparian vegetation** is another important BMP. Riparian vegetation helps anchor banks, maintains channel form, provides shade and temperature control, contributes nutrients essential for productivity in small streams, provides large woody debris that shapes stream channel environments, and is an important component of habitat for riparian wildlife. (See chapters 7 and 8 for descriptions of construction methods that protect aquatic and riparian resources.)

### 2.6 MONITOR THE CROSSING

Only by monitoring can we know whether our methods meet our objectives. Before beginning, teams must clearly delineate monitoring objectives and determine what data they need to achieve the desired confidence in the results. Several types or levels of monitoring exist:

*Implementation monitoring* occurs during and/or immediately after construction, when the project team checks whether construction BMPs are being implemented and determines whether the structure was installed as designed. Regardless of what further monitoring is planned, as-built surveys or the plans annotated by the contract administrator (with changes made during construction) should be permanently filed, so that future changes can be identified.

*Effectiveness monitoring* answers the question: is the structure performing as intended? It does not need to be complex and time consuming, and can be as simple as the team visiting the site to see whether streambed continuity is being maintained over time. This monitoring can also be incorporated into regularly scheduled road safety checks. In an evolving technology such as stream simulation, this type of monitoring is essential for verifying whether design methods need modification. In some cases, installation problems may reduce a structure's effectiveness, and team members need feedback so that they may correct for past mistakes or poor decisions and continue to improve the process.

*Validation monitoring* (determining how well species can actually move through a structure) is more complex. It should be done as an administrative study, designed and conducted in cooperation with university or other researchers. Much has been learned from past experience, especially from detailed case studies that result from careful validation monitoring (see, for example, Lang et al. 2004). Continued monitoring of crossing structures—with particular attention to innovative designs and a broad range of species—will ensure that we know how well our efforts to protect stream ecosystems are succeeding and how we can improve those efforts.