

Stream Simulation



Figure 3.1—Roaring River crossing site before-and-after culvert replacement in 2007, Boise National Forest, Idaho.

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3.1 WHAT STREAM SIMULATION IS AND WHAT IT ISN'T

Stream simulation is a method of designing crossing structures (usually culverts), with the aim of creating within the structure a channel as similar as possible to the natural channel in both structure and function. The premise is that the **simulated channel** should present no more of an obstacle to aquatic animals than the adjacent natural channel.

Stream simulation developed when people began to realize how important it is to provide passage for the variety of aquatic species and lifestages present in most streams, and how difficult that is to accomplish in a bare or baffled culvert. To solve the passage problem simultaneously for many different species with different movement capabilities and timing needs, stream simulation takes a very different approach from hydraulic design. Stream simulation does not target specific fish or other species for passage, nor does the designer need to match species-specific water velocity, water depth, or crossing length criteria. Instead, a continuous streambed that simulates natural channel width, depth, and slope connects the reaches up- and downstream of the crossing. The simulation creates the diverse water depths and velocities, hiding and resting areas, and moist-edge habitats that different species need for movement (figure 3.1). Given the similar conditions, we can safely presume that the simulated channel inside the crossing presents no more of an obstacle to movement than the adjacent natural channel. Stream simulation crossings are larger than traditional crossings, and therefore less prone to debris plugging. This can benefit the road by reducing any tendency for debris plugging to cause overtopping or flow diversion.

The goal in stream simulation is to set the stage so that the simulated channel adjusts to accommodate a range of flood discharges and sediment/debris inputs, without compromising aquatic organism passage and without having detrimental effects on up- or downstream reaches. For the simulated streambed to maintain itself through a broad range of flows, stream processes that control sediment and debris transport and maintain hydraulic diversity must function similarly to the natural channel. In other words, flows that transport sediment and debris and rework the channel bed should not be constrained or accelerated inside the crossing structure. **Bankfull** flow is widely recognized as a good estimator of the **channel-forming flow** in stable alluvial rivers (Wolman and Miller 1960;

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Andrews 1980; Hey 1997) (see appendix A.4.1). Therefore, as a working criterion, we ensure that the channel inside the structure is at least as wide as bankfull width in the **reference reach**. Although this criterion is by no means the only characteristic of a self-maintaining stream-simulation structure, it is an essential one.

First, the simulated channel is designed. Then the crossing structure—either a bridge or culvert—is fitted over and around it. Its width depends strongly on project objectives, and it may exceed reference reach bankfull width if necessary for achieving objectives such as bed stability or amphibian or terrestrial animal passage.

Simulations are not exact replications of real stream channels. Features we cannot recreate inside crossing structures include:

- Natural light.
- Cohesive soils.
- Channel-spanning or embedded wood.
- Debris jams.
- Bankline vegetation.
- Channel bends.
- **Flood-plain functions.**

Features that provide **roughness** in a stream channel are essential for stabilizing the bed and creating the depth and velocity variations needed for aquatic species passage. Though we cannot duplicate these characteristics, we can simulate some of them with large rock. For example, to simulate natural banklines, we can place immobile rock along the channel margin in various arrangements that mimic the natural streambank. We can also use rock to simulate the grade-stabilizing functions of embedded **debris**.

For these and other reasons, the design is not a perfect simulation of the natural channel. Where to draw the boundaries of “stream simulation” is not always clear. Although stream simulation is most often described in terms of performance (providing passage for all aquatic organisms), since we are unable to verify free mobility for all aquatic organisms at a site, success is likely to remain somewhat subjective.

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Real stream channels are tremendously diverse and complex, with some degree of unpredictability in their response to runoff events and land management. Even using sophisticated quantitative methods for design, we cannot guarantee that a simulated streambed will sustain itself through the full range of flows it may experience. Moreover, our knowledge is continually expanding as we build more structures and as floods test those structures. While this guide synthesizes years of experience to date, the authors have tried throughout to make its limitations clear.

“Always use the best data and methods available at the time.”

—Dr. Charles Behlke

3.2 KEY ELEMENTS AND LIMITATIONS OF STREAM SIMULATION

The reference reach is the key element of a stream-simulation design. A natural stable **reach**, preferably upstream and near the project (see section 5.4), becomes the design template. The reference reach must satisfy the physical conditions of the crossing site, especially the slope, and it must be self-sustainable inside a confined structure. In other words, flows interacting with the bed and the structure walls will dynamically maintain the streambed within the structure. In high flows, although some features of the simulated bed may be immobile, other streambed materials should mobilize and restructure themselves similarly to the natural channel; sediment transported from upstream should replace eroded material.

Setting the stage for self-sustainability in the simulated channel means establishing basic characteristics of the reference reach, such as gradient, cross-section shape, bank configuration, and bed material size and arrangement. The reference reach need not reflect the average conditions in the natural channel; however, the condition should not be extreme. We assume that if we can simulate a reach representative of the natural channel, passage will be as good as in the natural channel. This is a virtual certainty in the many cases where the reference reach is very near the project site and represents the **project reach** as it would be if the crossing had never been constructed.

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The ideal of simulating a stable reference reach inside the crossing structure may not be feasible in certain common situations. These situations include highly unstable channels that are rapidly changing, such as after a major flood, where no stable reference reach exists. Other examples are inherently unstable landforms subject to frequent disturbances, such as alluvial fans (figure 3.2) and **debris torrent**-prone channels. Even stable sites where channel changes occur frequently, such as active meandering streams, are undesirable sites for any rigid structure. The ideal solution is to relocate the crossing and/or the road. Where relocation is not feasible, the project team must predict potential **channel adjustments** for the life of the structure and design for them.



Figure 3.2—Active alluvial fan channel where flows have deposited gravel over the fan surface.

Channels in wide, active **flood plains** present a challenge to stream simulation if the structure has to accommodate a large amount of flow that normally spreads across the flood plain. Funneling flood-plain flows through the structure can exert the sort of pressure on the simulated streambed that a reference reach connected to the flood plain never sees. Chapter 6 (section 6.5.1.1) gives a detailed discussion of design solutions.

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On some occasions the crossing needs to maintain a steeper-than-natural grade. For example, where a long stream reach downstream of the road has incised, the crossing might be retained as a **grade control** to protect the upstream channel. For such sites, the project team may have to search the stream to find a reference reach of the desired (steeper) slope. How far a simulation can diverge from the natural slope of the project reach and still achieve full passage remains uncertain (see section 5.5). The key question is whether the channel immediately upstream of the crossing will be able to supply the size and volume of sediment that the simulated channel needs. Section 6.1.2.3 discusses designing simulations steeper than the natural channel.

Assuming downstream **channel incision** is not ongoing, the ideal way to handle crossings with large elevation drops is channel restoration. Instead of steepening the culvert to tie the upstream and downstream elevations together, the design restores the incised segment to its natural elevation, sinuosity, and diversity. In some cases, to achieve sustainability, restoration of a long reach becomes necessary.

Channel restoration can restore more than aquatic species passage at the crossing; it also can restore aquatic habitat where that habitat has been simplified or destabilized. Section 6.1.2.3 covers the channel restoration option, but details of channel design are beyond the scope of this guide. For more information on channel restoration, see Federal Interagency Stream Restoration Working Group (1998) and Saldi-Caromile et al. (2004).

Many older culverts have caused sediment deposition upstream and local scour downstream (even when the channel has not incised), leaving an elevation difference that the replacement project must deal with. A simple method of handling this situation is to simply reconnect the streambed and allow it to regrade naturally. However, in some cases undesirable ecological effects could result. For example, a small wetland may have developed above the old culvert, and that wetland may now be providing valuable habitat to amphibians. Or an important spawning habitat may exist downstream, where sediment should be minimized. Section 5.3.3 describes some of these considerations.

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What constitutes “stream simulation” in these less straightforward situations is not entirely clear: How far can the characteristics of the constructed channel diverge from the natural channel before some aquatic species is impeded? How much steeper than the surrounding reaches can the simulated bed be? We might find a short, steep natural reach somewhere upstream, and ask: Can we use this reach as a valid reference reach? To answer this, we should keep a couple of basic questions in mind:

- Does the natural reach impede movement of aquatic species?
- Are the local controls on sediment supply, transport, and bed stability similar to the culvert site?

If the reach passes these tests, most practitioners would consider it a valid reference reach.

Where teams can find no reference reach steep enough to achieve site objectives, they can reasonably use a hybrid design procedure for the structure’s streambed. This technique simulates the streambed materials and structure that would be expected in nature at the desired slope. However, the major structural features of the bed are designed to be immobile because, if washed away, they would not be replaced by upstream rock of the same size (see appendix B). The structure may or may not pass all aquatic species at the site; the further the design departs from the characteristics of the natural channel, the less likely it is to pass all aquatic species that are present. To maximize the project’s resource benefits and minimize its natural resources costs, the project team and managers must weigh these compromises and trade-offs that some situations necessitate.

3.3 HOW COMPLEX DOES IT NEED TO BE?

All these factors may make the design method for stream simulation seem complex, but the key is to tailor the level of effort to the complexity of the site. Complicated sites, such as those listed below, require a careful, detailed design process.

CROSSING DESIGN IS MORE CHALLENGING WHEN A CHANNEL IS:

- Unstable (laterally or vertically).
- Undergoing rapid meander shift or bank erosion.
- Severely incised below the crossing.
- Severely **aggraded** above the crossing.
- Subject to debris flows, hillslope erosion events, or other large sediment inputs upstream of the crossing.
- Steeper than 6 percent.
- Made up of intermittent bedrock exposures in the streambed (see section 8.2.10).

Simple sites may not need detailed assessment, and their design is often straightforward. As teams gain experience, they can streamline the process appropriately for each site.

Part of the reason why the stream-simulation process appears complex is that it is inherently multidisciplinary. It requires considerable expertise and experience in diverse disciplines. The project team should include members who understand aquatic wildlife biology and ecology, so that they can identify passage needs, participate in setting project objectives, and protect wildlife during construction. **Fluvial** geomorphology and hydrology are important to understanding the watershed processes that the design must accommodate and the fluvial processes and channel features that must be simulated through the crossing. Civil engineering and hydraulics are essential to designing a fixed structure that will withstand the dynamic stream and valley environment. As no single person can competently cover all these areas of scientific and engineering knowledge, stream-simulation projects always involve a team of people experienced in applying these sciences (figure 3.3). Sometimes other specialists will be needed at especially complicated sites. In all cases, good communications between disciplines is crucial throughout the project.

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Figure 3.3—Multidisciplinary project team on initial reconnaissance of a project site.

3.4 ROADMAP FOR STREAM-SIMULATION DESIGN

Figure 3.4 shows the phases of a stream-simulation project, somewhat modified from phases defined by Jim Doyle (fishery biologist, Mount Baker-Snoqualmie National Forest). Except for stream-simulation design, the phases are essentially the same as for any crossing design project. Figures at the beginning of each of the following chapters will expand figure 3.4 to show details of the actions and considerations pertinent to each phase. It will function throughout the guide as a navigational “road map” to the project development process.

The project phases are identified primarily as a way of organizing this guide. The actual process of stream-simulation design is not linear. The phases overlap, and the team may have to go back and forth between phases when knowledge gained in a particular phase forces reevaluation of earlier conclusions. Often—especially at complex sites—a decision taken in one phase must be revisited in light of new information in later phases. The process starts with a broad view, and focuses down to smaller scales and more detail as the project develops.

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Figure 3.4—Steps in the stream-simulation design and construction process.

3.4.1 Initial Watershed and Reach Review

Unless you are well versed in the field of fluvial geomorphology, read appendix A before plunging into the stream-simulation process. Appendix A introduces geomorphic terms and concepts that are used throughout this guide and that are essential to understanding stream simulation.

In this phase (discussed in chapter 4) the project team reviews the access and travel management plan to verify that the road is both necessary and well located. They collect existing biological and physical watershed-scale information as background for project planning and for helping to interpret observations from the site-assessment phase. Placing the crossing site in the context of the road network and the watershed helps ensure recognition of ‘big picture’ risks, consequences, and opportunities.

Additionally, the team does an initial site walk-through reconnaissance, looking at site-specific risks such as woody debris, sediment accumulation potential, and the elevation drop through the crossing.

Assessment of site risks and suitability for stream simulation begins now, and continues through the site assessment and design phases. If risks are high, the team can plan for a higher level of detail in subsequent phases. This initial review should be done before replacing any crossing structure.

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3.4.2 Site Assessment

The site assessment (chapter 5) is a detailed survey and analysis of the project site, including channel and road longitudinal profiles, cross sections, and channel bed materials. It also includes a survey of the reference reach that will be the template for the simulated stream channel. From the results of the assessment, the project team develops a set of specific design objectives, and provides the information needed to design the **simulated channel**.

3.4.3 Stream-simulation Design

Stream-simulation design (chapter 6) begins with establishing the crossing alignment and the longitudinal profile of the simulated channel. Assuming that stream simulation is feasible, the next steps are to:

- Design the simulated channel based on channel characteristics of the reference reach.
- Size the crossing structure.
- Verify bed mobility and stability, where necessary.

At the end of this phase, the simulated stream-channel design is complete, and we know the area and depth the structure will have to cover. Although the focus in this guide is primarily on culverts, the same principles apply to bridges, and the team does not have to make a final choice of structure type until phase 4, final design.

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3.4.4 Final Design and Contract Preparation

In this phase, final design and contract preparation (chapter 7), the engineer-designer completes the structural design and details of the overall installation. Contract drawings and specifications are prepared, including stream simulation bed construction details, as well as water quality, wildlife, and other environmental protections. The level of engineering expertise necessary in this phase of the project depends on site conditions and risk, but in all cases the engineer-designer is part of the project team. Working through the details, the engineer-designer may discover that certain design objectives cannot be met or that changes in the preliminary design are needed. In this case, he or she should communicate with other team members, who may be able to suggest alternate solutions and should review any changes. Communication with the **Contracting Officer's Representative (COR)** is also crucial for predicting and solving problems that may arise during construction.

At this point, if not before, the COR should become a member of the project team. The COR should review the design during contract preparation, to become familiar with the critical design elements and to comment on the practicality of contract specifications and special requirements. As he or she will have to deal with any contract changes or unforeseen site conditions, the COR should understand earlier design decisions thoroughly. Good communication and mutual trust among team members make it much easier to handle sudden challenges during the construction process.

3.4.5 Construction

Contracting officers, CORs, and inspectors take the lead in phase 5 (construction, chapter 8), which begins when the solicitation is advertised. Again, to help manage changes in project design or unexpected conditions as they arise, the COR should keep other team members informed about progress, and make them aware of construction issues. For example, the biologist may need to be involved in trapping and moving the aquatic organisms at the site before construction and dewatering begin. The fluvial geomorphology specialist who participated in the design may also be able to advise on channel construction. Specialists' continued involvement will help assure the design objectives are accomplished as intended.

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3.4.6 Maintenance and Monitoring

Road-maintenance personnel need to be informed about critical design elements that may not be obvious—especially any grade controls, bank stabilization, or sediment control measures that may require occasional maintenance. Over time, road maintenance staff may be not only the caretakers but also the most regular monitors of crossing condition.

Stream simulations are expected to have lower maintenance needs, since their larger size decreases the probability of them plugging and overtopping. Nonetheless, some maintenance needs will undoubtedly arise. Unforeseen watershed or climatic events and channel adjustments may occur, perhaps changing the simulated streambed in ways that impair passage. Floods exceeding the structure's capacity certainly will cause a need for maintenance. All stream-simulation projects should prepare for maintenance and emphasize both monitoring and sharing monitoring results as a way of improving these design methods as rapidly as possible.

This guide covers maintenance and monitoring only briefly (section 8.3.2), despite their importance. Maintenance, continued monitoring observations over time, and documentation are essential to further development of stream-simulation technology. Early stream-simulation design replacement structures should be monitored intensely to improve our understanding and knowledge of the stream-simulation assessment, design, and construction process. Such monitoring will ensure that (1) mistakes are not repeated on future installations and (2) knowledge gained on techniques and interpretations is applied on future installations.