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Low-Water Crossings: Geomorphic, Biological, and Engineering Design Considerations

Low-Water Crossings: Geomorphic, Biological, and Engineering Design Considerations

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Foreword

Low-water crossings are road-stream crossing structures designed to be overtopped by high flows or by debris- or ice-laden flows. They can be desirable alternatives to culverts and bridges on very low-volume roads and trails, and they can offer substantial environmental advantages in some stream environments. They are useful, for example, where streamflow is highly variable and large amounts of woody debris pose a risk to crossing structures. This publication reviews both the advantages and disadvantages of different low-water crossing structures in various stream environments and illustrates situations in which low-water crossings may be the optimal choice of crossing structure. The publication aims to provide multidisciplinary teams planning and designing road-stream crossing structures with answers to questions about where and how to best use overtoppable crossing structures.

The publication's four objectives are as follows:

(1) To address how low-water crossing structures affect stream functions and stability in various environments.

(2) To provide guidance for selecting low-water crossing structures that minimize disruption of channel processes and habitats.

(3) To summarize basic design parameters and requirements.

(4) To examine a wide range of field examples that illustrate the performance, problems, and advantages of different types of low-water crossings.

This publication is unique because it specifically deals with providing for aquatic organism passage and minimizing damage to channel stability and habitats. It focuses on the geomorphic and road management conditions that favor using low-water crossings as a means of minimizing negative effects to structures, stream channels, and aquatic habitats. It provides guidance on locating, selecting, and designing low-water crossings to fit the channel so they are less likely to obstruct stream functions, damage the aquatic system, and sustain structural damage during floods.

Meeting road management objectives while fulfilling site-specific biological and geomorphic goals requires a true interdisciplinary approach in which a biologist and hydrogeomorphologist work with the design engineer. Biologists and hydrologists do not usually have backgrounds in structural requirements for roads, traffic safety, road alignment issues, and the like. Engineers are not generally familiar with the swimming abilities and passage needs of fish or with fluvial geomorphology or sediment transport issues. A successful structure must integrate the engineering requirements with hydrologic and biological factors. No one person or discipline has all this knowledge and range of experience. Many crossings that later failed were built by individuals who either had limited knowledge about these structures or did not consider all the relevant factors. Thus an interdisciplinary planning and design approach is critical to the overall success of a low-water crossing structure.

The publication is organized into five chapters.

Chapter 1 defines and introduces the various types of low-water crossings and explains in general terms where and when they can be useful.

Chapter 2 addresses key questions necessary for evaluating roads and sites in the larger context of the watershed and transportation system. This evaluation is critical in successfully launching a crossing replacement or construction project.

Chapter 3 describes the process of selecting the best structure for a site. For example, if the structure should be a low-water crossing, then what type of low-water crossing should be used? What considerations go into these decisions?

Chapter 4 brings together the basic tools and procedures for engineering design of low-water crossings, and shows how applying these tools and procedures can achieve various objectives.

Chapter 5 summarizes the authors' observations and recommendations about the benefits and risks of 10 types of low-water crossings.

Appendix A contains 21 case studies, some with plans and drawings from the actual construction contracts. Appendix A also lists the names of forest staff employees and others who provided the information and sometimes the photos for each case study. In addition, several case studies include information on similar structures in other locations.

Appendix B contains the Hydraulic Structure-Site Examination Form. Purpose and uses of the form are described in Chapter 4, section 4.2.

The authors trust this publication will help managers recognize—and develop designs for— sites where low-water crossings are likely to benefit the aquatic system. The publication also serves as a useful warning about unintended detrimental effects that low-water crossings can have on streams and aquatic species.

Acknowledgments

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1.1 What Are Low-Water Crossings?

Words shown in bold throughout this document are defined in the glossary

Three main types of crossing structures are designed to be submerged at some flows: (1) **unvented (simple) fords**, (2) **vented fords**, and (3) **low-water bridges**. Because basic designs require tailoring to individual site requirements and locally available materials, many variations of each of these basic types of low-water crossing structures were developed over time. Figure 1.1 shows the basic low-water crossings types.

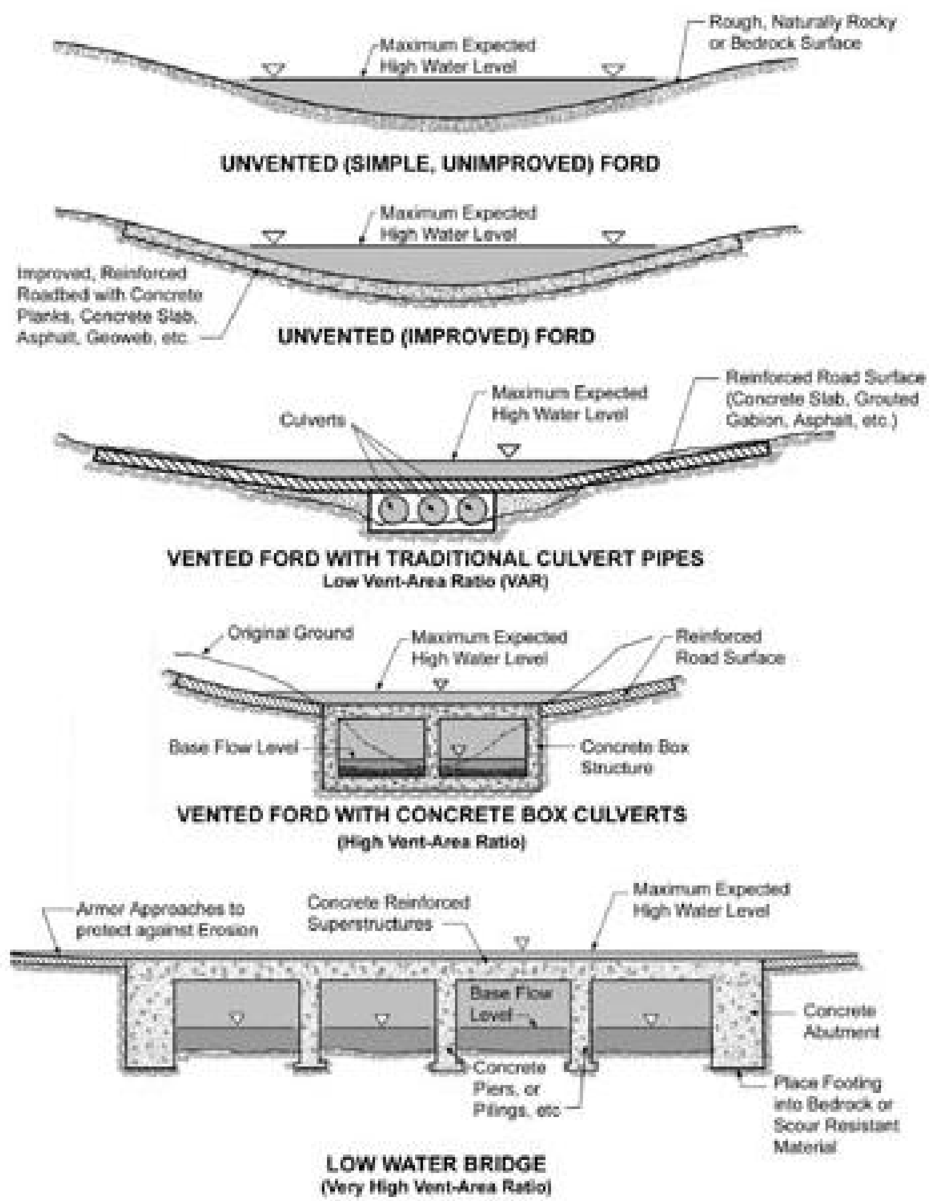


Figure 1.1—Basic low-water crossing types.

Unvented or simple fords cross streams at or slightly above the elevation of the streambed without pipes (vents). Unvented fords fall into two categories—unimproved and improved.

Unimproved fords are simply natural crossings. Figure 1.2 shows an example of an unimproved ford.

Figure 1.2—Unimproved ford on the Fishlake National Forest, Utah.

Improved fords have a stable driving surface of rock, concrete, asphalt, concrete blocks, concrete planks, **gabions**, **geocells**, or a combination of materials (fig. 1.3). Sometimes a small channel or slot is included at the structure's low point to pass very low flows and aquatic animals. The downstream roadway edge may be stabilized and defined with logs, riprap, gabions, or **Jersey barriers**.

Vented fords have a driving surface elevated some distance above the streambed with culverts (vents) that enable low flows to pass beneath the roadbed. The vents can be one or more pipes, box culverts, or open-bottom arches. In streams carrying large amounts of debris, the driving surface over the vent may be removable, permitting debris to be cleared after a large flow event.

Figure 1.3—Improved ford on an ephemeral tributary of the Agua Fria River, Arizona.

Vented fords fall into two categories—low **vent-area ratio** (VAR) and high VAR—each of which affects stream channels differently (fig. 1.4).

Vented fords with culverts that are small relative to the **bankfull** channel area have a low VAR.

A vent opening that approximates or exceeds the size of the bankfull channel has a high VAR.

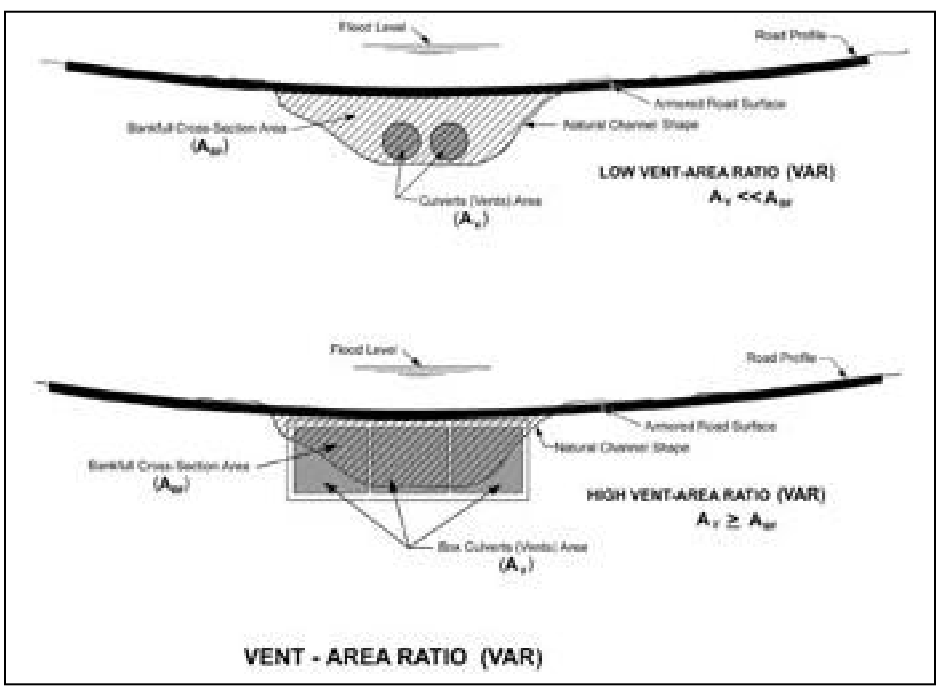


Figure 1.4—VAR-ratio definition sketch.

Bankfull is the flow that just overtops the streambanks and begins to flow out over the **flood plain** (fig. 1.5) (Leopold et al. 1964, Leopold 1994). In many areas of the United States, flow approaches or exceeds bankfull on average once every 1 to 2 years. Generally this frequent high flow is considered to do much of the work of rearranging streambeds and maintaining aquatic habitats by transporting and depositing sediment and woody debris.

For information on identifying bankfull, see the two-DVD set *Identifying Bankfull Stage in the Eastern and Western United States*. It is available on the USDA Forest Service Stream Systems Technology Center Web site.

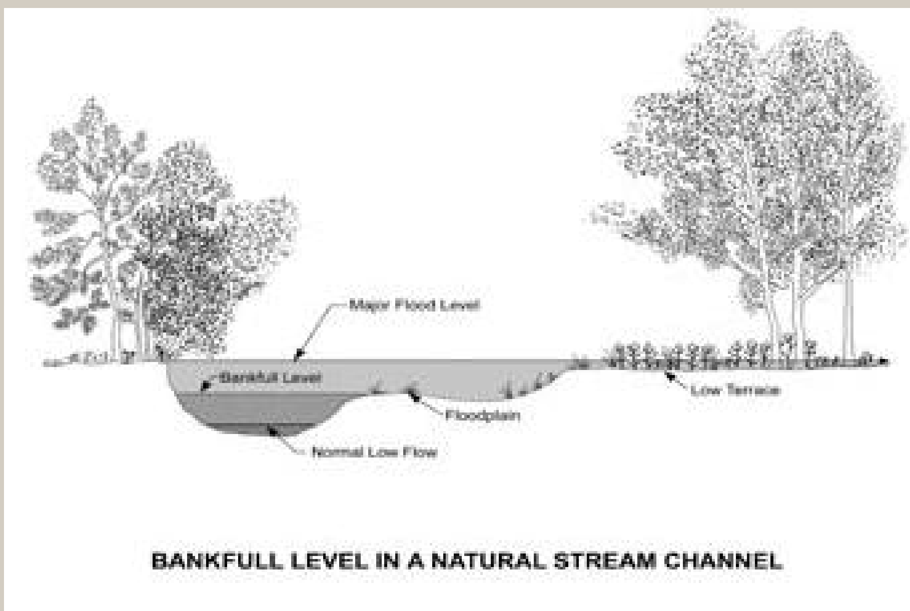


Figure 1.5—Bankfull level in a natural stream channel.

Figure 1.6 illustrates the difference between high- and low-VAR fords. The California example (fig. 1.6A) is an old structure that mostly blocks the bankfull cross section area. The Arkansas vented ford (fig. 1.6B) was constructed in 2004 with the express goal of allowing fish and sediment passage.

Figure 1.6—(A) Low-VAR ford on the Eldorado National Forest, Northern Sierra Nevada, California. (B) High-VAR ford on the Ouachita National Forest, Arkansas. Note that this site is on a curve and needs safety warning signs.

A common type of high-VAR ford is a series of box culverts that approaches or matches stream width and bankfull depth (figs. 1.6B and 1.7). These structures typically look like bridges and, where the bottoms are embedded, can be mistaken for bridges. High-VAR fords may not significantly obstruct flow until the water surface rises to the top of the structure.

Figure 1.7—High-VAR ford composed of three box culverts, Mark Twain National Forest, Missouri.

In this publication, we define *low-water bridges* as open-bottom structures with elevated decks and a total span of at least 20 feet (fig. 1.8). They may be designed with one or several piers. Low-water bridges generally have greater capacity and are able to pass higher flows underneath the driving surface than most vented and unvented fords. As with fords, however, low-water bridges are designed and installed with the expectation they will be under water at higher flows. *Forest Service Manual* (FSM) 7720 (Transportation System Development) requires all structures receive specific hydrologic, hydraulic, structural, and foundation design in accordance with the American Association of State Highway Transportation Officials (**AASHTO**) *Standard Specifications for Highway Bridges.* A qualified engineer must design the low-water bridge and review the completed structure.

Figure 1.8—Low-water bridge at Boiling Springs, Big Piney River, Missouri.

1.2 Potential Benefits of Low-Water Crossings

Choosing the type of structure for any crossing is highly site-dependent. Depending on the site, the main advantages of low-water crossings over culverts and bridges may include the following:

- Lower construction and maintenance costs.
- Less channel and flood plain blockage.
- Adaptability.
- Stormproofing.

Cost

Low-water crossings are generally less expensive to construct. More often than not, designs are less complicated, construction is quicker, and fewer materials are involved. Although the initial cost of more complex low-water crossings may exceed those of simple culvert installations, the lower long-term maintenance and repair costs may still make selecting a low-water crossing more economical.

Low-water crossings may also make sense when there is little funding for structure condition monitoring and maintenance, especially on roads with yearlong or seasonal closures. Unvented fords are more reliable in passing peak flows than culverts (which can plug with debris), and usually require less maintenance than other structure types (Doyle, personal communication; Warhol 1994; Warhol and Pyles 1989). Economic evaluation should take into consideration all lifecycle costs including maintenance, repairs, user costs, and the cost of environmental impacts.

Channel and Flood Plain Blockage

When streamflow approaches the design capacity of a crossing structure, water tends to pond upstream of the inlet, causing sediment deposition and often bank erosion. The less a crossing structure blocks the channel during sediment-transporting flows, the more it can avoid these effects. Unimproved at-grade fords and low-water bridges generally have the least potential for impeding flow and sediment transport through a crossing.

On broad flood plains, road approaches must **ramp up** to a high-profile bridge or large culvert, damming the flood plain to some degree. The roadfill obstructs the downstream transport of water, wood, and sediment across the flood plain during large floods, reducing the erosional and depositional processes that create diverse flood plain habitats. Road approaches to low-water crossings can be low across the flood plain and generally dip down toward the stream, minimizing any impairment of flood plain processes.

Low-Water Crossings

Adaptability

Simple low-water crossings like unvented fords are useful in naturally unstable channels such as alluvial fans and braided streams, or in channels with extreme flow variations. Because they obstruct flows less than most culverts, they are less likely to cause flow diversions or accelerations both of which can exacerbate a channel's inherent tendency toward instability. They can also be inexpensive to reconstruct in a new location if the channel does move.

Stormproofing

At ordinary culvert crossings, streamflow can back up when the culvert plugs or when its capacity is exceeded during a flood. If this happens where the road surface or ditch slopes away from the crossing, water can run down the road or ditch before breaking over the roadfill, and it can cause major erosion on receiving slopes and channels (Flanagan and Furniss 1997). Because fords are shaped as dips in the road profile, water is likely to stay in the channel rather than diverting down the road or ditch. Well-designed overtoppable structures avoid the roadfill failures that occur during large floods when deep roadfills over culverts are breached. The types of structures appropriate for these incised channel locations are, however, limited (case study 16).

For the same reasons, low-water crossings are very useful in watersheds that have experienced severe disturbances and where substantial mobilization of rock and woody debris is expected.

Other Possible Functions

Like other crossing structure types, low-water crossings can be designed to do the following:

- Enable passage of **aquatic organisms**.
- Protect endemic species from invasive competitors.
- Provide a **grade control** in an incised stream system for protection or restoration of upstream reaches.

Many low-water crossings and culverts create passage problems for aquatic organisms. For this reason, the current trend is designing both culverts and low-water crossings to provide passage for as many of the local species as possible (section 4.3).

Conversely, the survival of a native population may depend on preventing an exotic species from invading new habitats. Although exclusion was usually an unintentional effect of existing road crossings, crossings can be designed as barriers. This choice, however, requires careful consideration

(Fausch et al 2006). Exclusion can also prevent nontarget species from accessing their habitats, possibly putting their populations at risk over the long term.

Like culverts, low-water crossings can function as grade-control structures in situations where a **headcut** is moving upstream. In these situations, it may be necessary to provide alternative passage for aquatic organisms. For more information on headcuts and channel **degradation**, see Castro (2003). Case study 15 is a good example of a vented ford with a fish ladder used as a grade control.

The following list summarizes the general advantages and disadvantages of low-water crossings. Individual structures may or may not exhibit these characteristics depending on how well they are designed to fit their sites.

Advantages of low-water crossings are as follows:

- Structures designed for overtopping.
- Less likely than culverts to be damaged by debris or vegetation plugging.
- Typically less expensive structures than large culverts or bridges.
- Less susceptible than other structures to failing during flows higher than the design flow.
- Good for "stormproofing" roads where large amounts of sediment and debris are expected, like after a large storm event or forest fire.

Disadvantages of low-water crossings are as follows:

- Have periodic or occasional traffic delays during high-flow periods.
- Are not well-suited to deeply incised drainages.
- Are typically not desirable for high use or high-speed roads.
- Can be difficult to design for aquatic organism passage.
- Can be dangerous to traffic during high-flow periods.

USDA Forest Service road management decisions are based on Transportation Analysis Process (TAP) (USDA Forest Service 1999) results. Transportation Analysis (previously known as Road Analysis) is an integrated ecological, social, and economic approach to transportation planning, covering both existing and future road and trail systems. Ideally, the TAP should be conducted along with watershed Hydrologic Condition Assessment (Watershed Analysis). The two analyses together create a long-term, large-scale view of both watershed conditions and the transportation system. These extensive results enable road system planning which takes into consideration the context of current watershed conditions and predicted future trends, as well as the location and objectives of individual crossings.

2.1 Evaluate the Whole Road

Large-scale road or trail management objectives should be formulated before locating a new crossing or deciding to fix or replace an existing one. Formulating such objectives requires analyzing the entire road or trail location and asking the following questions:

- Is the road needed?
- Is the road being used?
- What future development is likely to occur, and where?
- How is traffic type likely to change?
- How is traffic volume likely to change?
- Are there alternative access routes with less risk to other resources?
- Is the road located and designed to fit the topography, minimizing resource and maintenance problems?
- Are there recurrent road surface drainage, slope stability, stream stability, or water quality problems?
- What road relocation possibilities exist?
- Are there opportunities to decrease the number of stream crossings?

Many roads were originally constructed where access was easy or traditional, such as through meadows or in riparian corridors with multiple stream crossings. Costs to soil, water, and other resources were not necessarily considered. With new timber harvest technologies, changing management emphasis, and a more developed road network, the road itself may no longer be needed and decommissioning may be a reasonable management choice. Alternatively, a different location may better fit the landscape.

Certainly in some places, topography, private land, or archeological sites can limit relocation possibilities. Nevertheless, road relocation often solves both resource and long-term maintenance problems. Road relocation, therefore, merits serious consideration even when upfront costs are larger than simple replacement. A truly inclusive value analysis that considers both resource and road-related benefits and costs might lead to a decision to relocate the road away from the stream, minimizing their interactions.

2.2 Evaluate the Crossing Site in its Watershed Context

In addition to the large-scale road or road system evaluation, the site should be evaluated in its watershed context. The entire watershed is linked via its drainage network and upstream and downstream changes can seriously affect a site. Although this is not an exhaustive list, the following questions will help identify essential ecological processes that should be factored into decisions about crossing location and design. (Refer to the site survey and assessment recommendations in section 4.2.)

1. Is the crossing on or just downstream from unstable landforms (e.g., alluvial fans, landslides)? Is it located in a depositional area?

Landslides and earthflows can intermittently produce large amounts of sediment that may cause downstream culvert structures to plug and fail. Alluvial fans and other depositional areas are located where valley gradient flattens or where a confined stream enters a wider valley. Crossing structures in these locations are subject to plugging. In addition, when deposition happens rapidly, such as during a large flood, the channel may shift to another location, leaving the structure isolated.

2. Is the channel stable at the watershed scale? Is there a headcut working upstream that could affect the site in the future? What changes from planned watershed development could affect channel stability upstream or downstream of the site and, therefore the site itself?

A stream is a dynamic continuum. Changes in watershed and channel conditions occurring upstream or downstream can affect any point on the stream. For example, streams continuously adjust in response to floods, changes in sediment loads, or changes in riparian conditions that control bank stability. **Channel incision** initiated by, for example, gravel mining or channel straightening can migrate upstream, affecting the entire system's bank and bed stability. An existing or planned dam in the river system will change the channel sediment load and can affect streambed elevations. See Rosgen (1996) for information about how and why natural stream channels change over time. Castro (2003) has good information about channel incision mechanisms and effects.

3. What types of flows are expected from the watershed? Are ***base flows*** *steady, or is the watershed "flashy" with brief, high peak flows? Are most flows clear water or do high flows carry a lot of sediment and debris?*

4. What hydrologic changes are likely to occur due to any planned watershed development? How might the current streamflow regime (i.e., flow quantity, timing, and duration) change over the structure lifetime?

Changes in land cover, such as road and housing development, fires, or timber harvests, can change the proportion of precipitation that runs off quickly in floods. Because the road network connects directly to the stream system through ditches and crossings, runoff is delivered to the stream system more quickly, increasing peak discharge and stream power. The increase in the erosive capabilities of the stream can lead to the undermining and outflanking of a structure. If major development is foreseen, consider selecting structures with larger capacities, and upgrading or rearmoring existing structures.

The same changes that increase peak flows may also decrease baseflows, because a greater proportion of precipitation runs off rather than infiltrating into the soil mantle for storage and slow release later in the season. If such decreases are foreseen, consider changing the crossing structure design to ensure low-flow passage for aquatic organisms.

5. What aquatic biota are present? What are their passage needs?

Is it necessary to design for passage of aquatic organisms or a specific target species/lifestage? [See the sidebar in section 4.3.] Is a barrier needed to exclude an exotic species from progressing upstream?

6. What are the constraints on crossing location, (e.g., nearby archeological sites, private land, location of threatened, endangered, or sensitive (TES) plants, special use permits)?

*7. How is the current crossing affecting the stream? Is it causing sediment deposition (**aggradation**) upstream and/or incision (**degradation**) downstream? Is it causing bank erosion?*

8. Is there an active flood plain, or is the channel entrenched (see box Entrenchment Ratio)?

Wide active flood plains that are frequently inundated often have high ecological value as groundwater reservoirs and as specialized habitats for wildlife. In addition to economical and other objectives, crossing objectives at sites like this might include minimizing the degree to which the road and crossing obstruct flows on the flood plain.

Slightly entrenched streams (see box) in broad flood plains are often highly sinuous and, because the outer banks on bends erode, channel location may shift across the flood plain. If this shifting is rapid enough to affect the structure, it will need to be considered in crossing design.

Entrenchment Ratio

Rosgen (1996) defined the entrenchment ratio as flow width when the stream is at "floodprone elevation" (i.e., when the water surface elevation is twice the maximum bankfull depth) divided by bankfull width (fig. 2.1).

Where a channel is incised deeply enough that high flows do not overflow the valley floor, the channel is entrenched (fig. 2.1A). Another type of entrenched channel is one where steep valley walls border the channel. In these channels, when the water surface elevation rises to twice maximum bankfull depth, flow width is no more than 40-percent wider than bankfull.

A slightly entrenched channel is only slightly incised below the valley floor, and when flows exceed bankfull (fig. 2.1D), flow widens out over the flood plain. When flow depth in a slightly entrenched channel reaches two times maximum bankfull depth, flow width exceeds 2.2 times bankfull width. Moderately entrenched channels are intermediate between entrenched and slightly entrenched.

Exactly quantifying the entrenchment ratio is not important for our purposes. We use the degree of entrenchment to describe vertical containment of the channel, which is an important factor in low-water crossing feasibility because it affects:

- How steep the road approaches will need to be.
- How sharp the vertical curve will be.

- How well the stream can be protected from sediment produced from the road surface and ditches.

The main limitations for low-water structures in entrenched channels are difficulties designing a mild vertical curve and stabilizing and draining a steep approach road (table 3-3). Potential limitations for low-water crossings in slightly entrenched channels are that flow obstructions in the main channel may cause aggradation and bank erosion. The stream may even shift location in some cases.

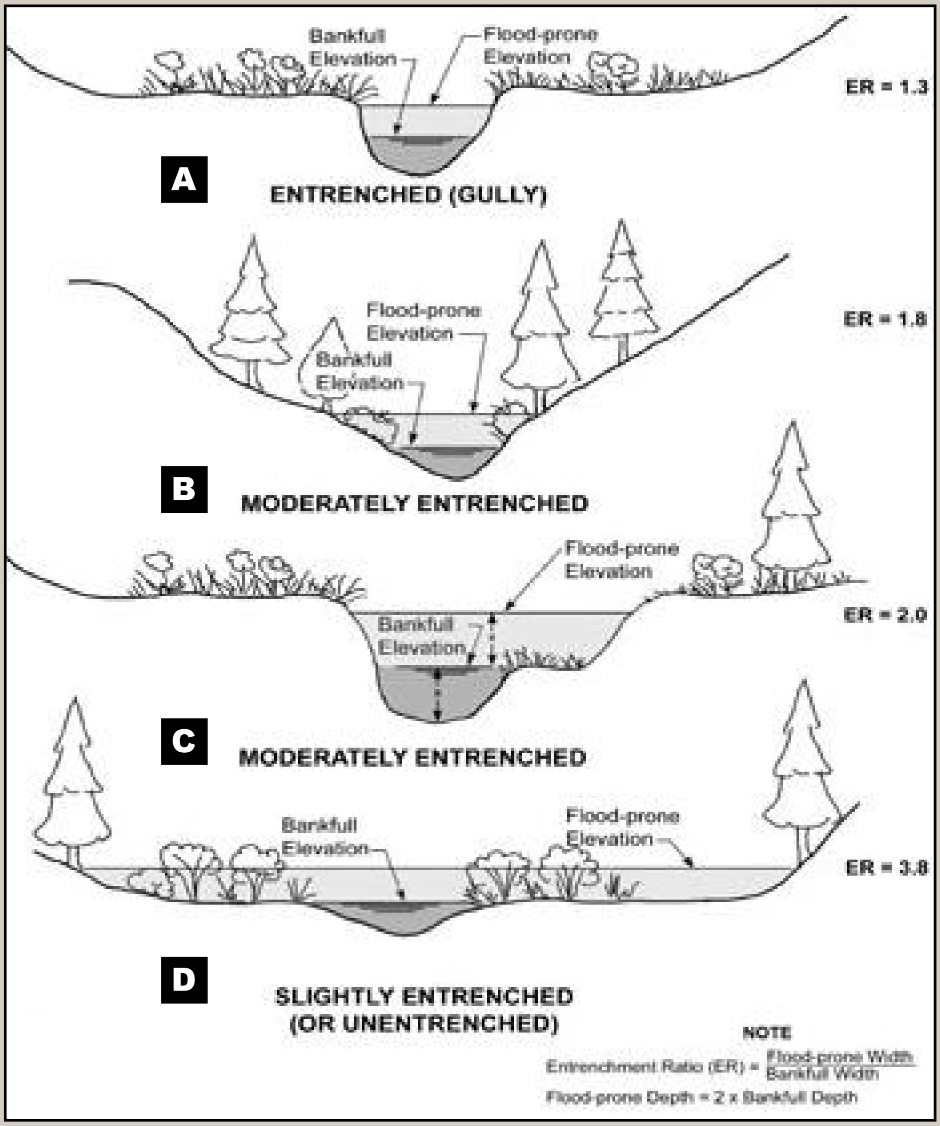


Figure 2.1—Channels with different entrenchment ratios.

9. Is the channel stable (local scale)?

Both lateral and vertical channel stability should be assessed. If the channel is located on an alluvial fan or where a steep tributary meets the valley edge, sediment deposition is likely during floods, and the channel may be—or become—either laterally or vertically unstable, or both. In arid areas, riparian vegetation may not stabilize streambanks and the channel may shift location dramatically during floods. A relatively cheap and easily reconstructed at-grade structure could be desirable there.

A useful method for evaluating channel stability near road-stream crossings is *Rapid Assessment of Channel Stability in the Vicinity of Road Crossings* by Johnson et al. (1999). The method can help identify specific stability risks the design should cover.

Naturally, stable sites are ideal locations for all types of crossings. At less ideal locations, low-water crossings are sometimes a better choice than ordinary culverts or bridges (see table 3.3.). Nonetheless, when given a choice, always select the best possible crossing site for long-term stability rather than living with a poor site that may continue to require maintenance regardless of the structure type. Given local channel and valley characteristics, consider which location is the best one. From the stream perspective, the "best" location would be:

- Where the crossing least interferes with the movement of water, sediment, debris, and aquatic organisms along both channel and flood plain.
- Where rock and/or dense, deeply rooted bank vegetation make the bed and banks resistant to any flow acceleration the structure may cause.

Low-Water Crossing Structure Selection Process

When deciding whether to use a low-water crossing and which low-water crossing type to select, it is important to evaluate the following: the site, costs, streamflow patterns, channel characteristics, and aquatic organism passage (AOP) needs. The various factors can be complicated and interrelated, but the selection process is simplified by a two-step process. First, evaluate whether a low-water crossing structure is appropriate and preferable to a culvert or bridge. Second, decide on the appropriate type of low-water crossing based upon the site characteristics and AOP needs. Each decision can be reached by considering these basic questions:

Questions To Consider in Choosing Whether To Use a Culvert, Bridge, or Low-Water Crossing

- Is the road a noncritical route or does it have alternative access to the area?
- Is the traffic use low and are occasional traffic delays acceptable?
- Is the channel ephemeral or does it have relatively low baseflow?
- Does the watershed have large flow fluctuations or a "flashy" response?
- Does the channel carry a large amount of debris?
- Is the channel unentrenched to moderately entrenched (broad and shallow)?
- Is a low-water crossing the most cost effective or inexpensive structure?

If the answer to most or all of these questions is **YES**, then the site is likely a good candidate for a ford or low-water crossing.

Questions To Consider in Choosing The Type of Low-Water Crossing

- Is road use low and is the stream ephemeral, or does it have a low baseflow and high peak "flashy" flows?

If **YES**, first consider a simple (at-grade), unimproved ford.

- Are the channel bottom and streambank materials soft or erodable?

If **YES**, consider an improved ford with a hardened driving surface.

- Is AOP or maintaining stream function important issues in this crossing?

If **YES**, consider (1) an unimproved ford with a natural bottom; (2) an improved at-grade ford with a roughened driving surface, (3) a low-water bridge, or (4) a high-VAR ford.

- Is driving through water frequently prohibited or are long traffic delays unacceptable?

If **YES**, consider only the vented structures and low-water bridges with an elevated driving surface.

- Is the channel incised or entrenched?

If **YES**, consider a vented structure with boxes that match the channel's shape.

- Is the channel very broad or does it carry a considerable baseflow with high peak flows?

If **YES**, consider a relatively long span low-water bridge.

- Does the channel carry a lot of large woody debris?

If **YES**, consider an unimproved or improved unvented ford.

- Does the drainage pass periodic debris torrents through an incised channel?

If **YES**, consider rock-fill fords. Alternatively, massive concrete vented fords have been used with trash racks to pass the debris over the structure.

- Is a barrier needed to exclude exotic species?

If **YES**, consider an improved, unvented ford with a raised platform or a raised vented ford with a perched outlet (consider, however, potential adverse channel effects).

- Is a grade control structure needed?

If **YES** to promote aggradation, first consider an improved unvented ford with a raised platform (a low dam). A vented ford with perched vents may also work.

If **YES** to stop headcutting, consider using a structure with a solid, stable bottom and downstream cutoff wall.

This chapter will help determine (a) whether an overtoppable structure is appropriate at a given site and, if so, (b) which type is most appropriate.

First determine whether a low-water crossing should be considered at all. Section 3.1 outlines considerations that help distinguish sites conducive to low-water crossings from those where an overtoppable structure would be undesirable. If conditions are conducive to a low-water crossing, then consider what *type* of low-water crossing structure would best achieve the multiple objectives of resource protection, traffic access, and safety (section 3.2).

3.1 Is a Low-Water Crossing Appropriate?

Low-water crossings have substantial limitations and are most suited for roads with low traffic volumes, and trails. The foremost constraint is public safety. According to a review of National Weather Service reports from 1969 to 1981 (French et al. 1983), nearly half the flood-related deaths in the United States each year were occurring in vehicles. Many of these deaths occurred when people drove into flooded crossings. Drivers may underestimate how fast small streams can rise in some parts of the country during a flood, and they may ignore the possibility the crossing has already eroded. Even 2 feet of water can float and wash away an ordinary car or truck (fig. 3.1).

More recent confirmation of the ongoing risks of low-water crossings can be found at http://www.floodsafety.com, managed by the nonprofit Flood Safety Education Project.

Another safety concern is winter ice on the roadway, a condition hazardous even to slow-moving traffic and especially likely on fords at the low point of the dip. Low-water crossings with steep approaches, particularly unvented fords, may not be good choices for icy roads in winter. Table 3.1 lists the traffic and environmental conditions most and least conducive to selecting a low-water crossing structure.

Access priority/alternative route

Low-water crossings are not appropriate on roads that access essential public facilities or that serve as the only public route to an area. Many States restrict construction of low-water crossings on school bus routes and on roads required for national defense. Typically, low-water crossings are not desirable for accessing an area with permanent residences. Even alternate routes to isolated towns may qualify as priority access.

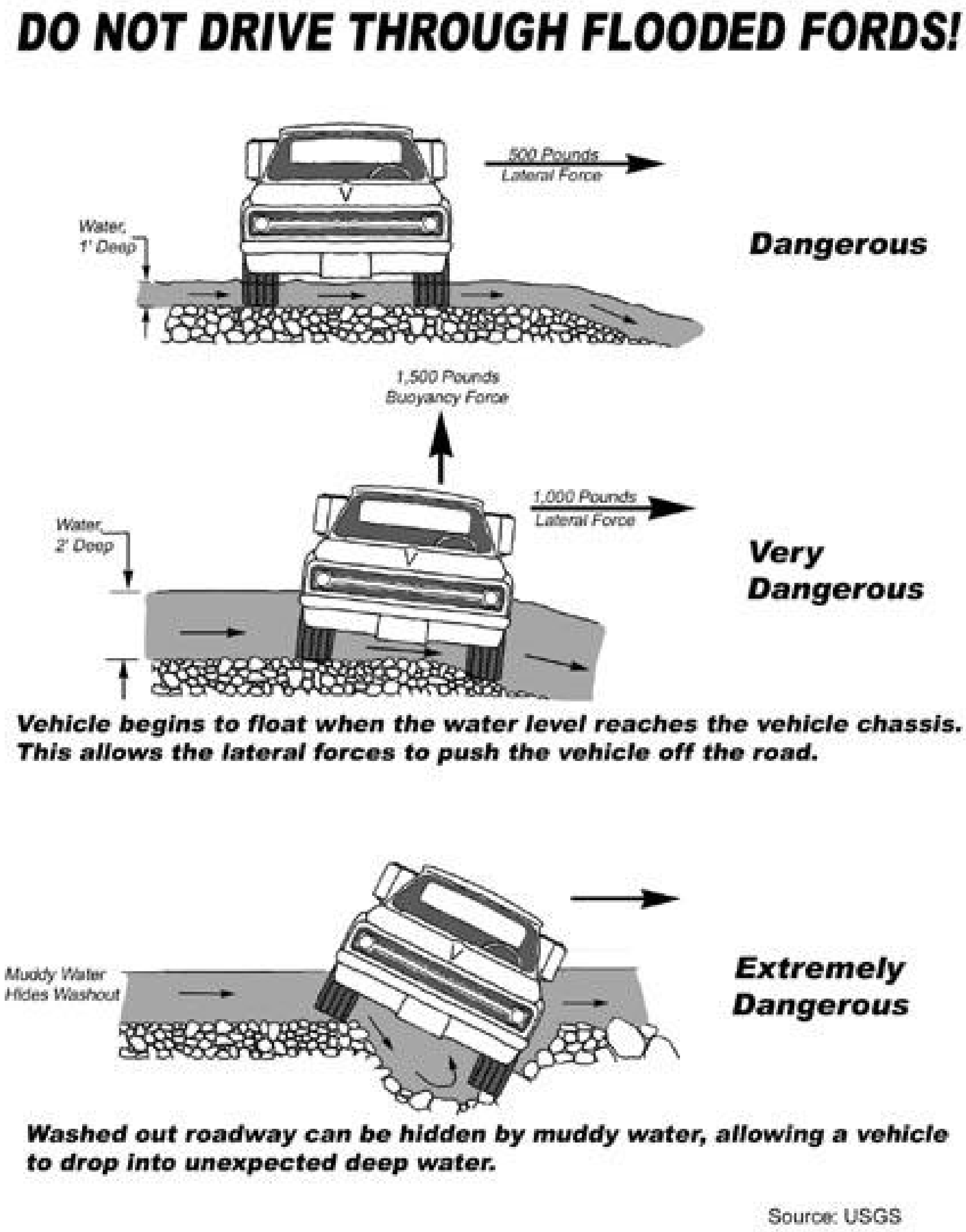


Figure 3.1—Do not drive through floodwaters. Redrawn from USGS Fact Sheet 024-00, March 2000.

Table 3.1—General selection factors for low-water crossings

	Most conducive	Least conducive
Access priority	Low	High
Alternative route	Available	Not available
Traffic speed	Low	High
Average daily traffic	Low	High
Flow variability	High	Low
High-flow duration	Short (hours)	Long (days)
High-flow frequency	Seldom (rare closure)	Often (frequent closure)
Debris loading	High	Low
Channel entrenchment	Shallow	Dee

Traffic speed

Low-water crossings are most suited for rural roads with low-to-moderate traffic speeds. Unimproved fords may only be driven over at low speeds, less than 10 to 20 miles per hour. Vented fords with a broad, smooth dip and gentle transitions may be suitable for speeds up to 30 to 50 miles per hour. If high-speed traffic is anticipated, then low-water crossings are likely unsuitable for that road.

Average daily traffic during season of use

The lower the traffic volume on a road, the more suitable a low-water crossing is likely to be. With only a few vehicles per day, the consequences of periodic delays are minimal. With increasing traffic volume, the impacts of periodic or occasional delays become more important. Many times, short access roads (i.e., less than half mile of road) see little traffic, making a low-water crossing a desirable option.

Flow variability

Low-water crossings are commonly used in areas with highly variable flows, such as desert streams subject to flash floods and thunderstorm-prone areas. High, short-duration peaks followed by long intervals of very low or no flow are most conducive to low-water crossings as long as traffic interruptions during floods are tolerable. Because standard crossings need to be very large to convey such high flows together with their debris loads, they may not be economically feasible for many low-volume roads. Streams with highly variable flows may also be less stable than streams in which steady baseflows support vigorous riparian vegetation. Putting a large expensive structure on a channel that may shift within the structure's lifetime is even less desirable. Chapter 4, section 4.5 contains information about hydrologic data useful for evaluating flow variability.

High-flow duration

The duration of an overtopping flow controls how long a crossing will be closed. Although weather patterns are the greatest influence (e.g., intense summer short-duration storms), watershed attributes also play a large role. Characteristics of 'flashy' watersheds (where flows rise and fall rapidly) can include the following:

- Steep, short drainage basin (high basin relief).
- Small basin area.
- High drainage density (miles stream/basin area).
- Thin and/or impermeable soils.
- Little or no flood plain.
- Low vegetative cover.

High-flow frequency

The peak-flow frequency during the season that the road or trail is used is another variable affecting the probability of traffic interruptions and safety problems. Look for long-term stream gauge records. Alternatively, road maintenance records, local newspaper archives, or interviews with area residents can indicate the historical frequency of and damage sustained from large runoff events and flooding.

Debris loading

Channels in areas prone to landslides and/or debris flows may be good candidates for low-profile crossings that allow debris to pass over the road.

Channel entrenchment

Channels deeply incised below the adjacent ground surface and channels closely bounded by steep slopes (**confined**) are generally difficult locations for low-water crossings (fig. 2.1). In both cases, the soil disturbance necessary to construct approaches creates the potential for sediment to impair water quality and aquatic habitat. Although some low-water crossings are successful in such locations (case study 6), mitigating potential erosion problems requires special measures, such as paving the approaches and rocking the ditches. Shallow channels on wide flood plains may be good candidates for low-profile crossing structures because the road approaches do not need to ramp up to cross a high culvert or bridge.

Table 3.2 provides more quantitative—although still subjective—selection criteria from a survey of transportation engineers from several different states (Motayed 1982). Although these numbers may not be applicable to all USDA Forest Service locations, they are a starting point for forests to develop their own criteria.

Table 3.2—Quantitative selection criteria for low-water crossings (Motayed et al. 1982).

Criteria	Most favorable for LWC	Least favorable for LWC
Average daily traffic (ADT)	Fewer than 5 vehicles	200 vehicles
Average annual flooding	Less than 2 times	10 times
Average duration of traffic interruption per occurrence	Less than 24 hours	3 days
Extra travel time for alternate route	Less than 1 hour	2 hours
Possibility of danger to human life	Less than 1 in 1 billion (with excellent warning systems)	1 in 100,000
Property damage, dollars	None	1 million
Frequency of use as an emergency route	None	Occasional-frequent

3.2 What Type of Low-Water Crossing Best Fits the Site?

If site and traffic conditions are conducive for a low-water crossing, decide what structure type is best suited to the specific field situation. Table 3.3 lists key site, road management, and resource protection factors affecting the choice of structure type. It points out pros and cons of each general structure type for each factor. Keep in mind, however, functionality depends strongly on specific features designed to tailor the structure to the individual site. Chapter 4 contains information on these design considerations.

Low-VAR fords are undesirable in virtually all situations. Table 3.3 mentions them only to warn practitioners about specific effects they can have (see sidebar low-VAR fords).

Why are low-VAR fords not recommended?

In very stable streams, low-VAR fords may not have severe detrimental effects on channel stability. It is common, however, to see at least a fair amount of channel instability associated with these structures. When flow begins to exceed the vents' capacity, low-VAR fords begin to function like low dams. They backwater flow upstream of the structure, and where the stream is carrying a substantial bed sediment load, deposition reduces channel capacity and elevates the streambed. This frequently leads to bank erosion and channel widening. Sometimes, the aggraded stream may also shift its location across the valley floor when it seeks lower ground or a steeper grade (fig. 3.2). In channels that are already laterally unstable, low-VAR structures exacerbate the tendency for bank erosion and channel shift.

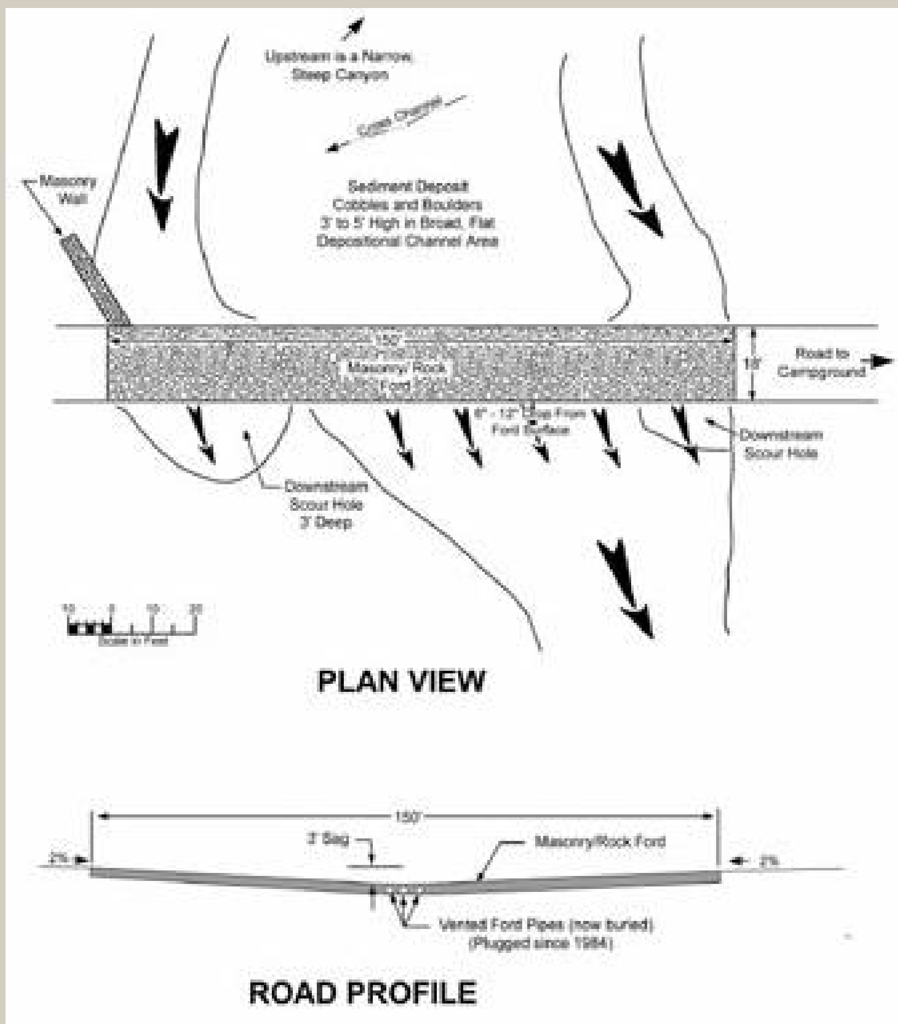


Figure 3.2—Sediment deposition and channel widening caused by the "damming" effect of a low-VAR ford. Tonto National Forest, Arizona.

Compared to high-VAR fords, these dam-like structures overtop relatively frequently, so scour protection is critical to avoid bed erosion downstream. Even with adequate scour protection, streambed composition can become coarser when the fines are winnowed away, which happens in channels downstream of dams that impound sediment. Also, depending on how well the ford matches channel shape, the backwatered pool upstream may flow out around the structure's edges. When flow reenters the channel downstream, it can erode both the flood plain and streambanks.

Because the vents or pipes in low-VAR fords are small compared to the stream, they plug easily and tend to require frequent maintenance. In addition to being small, they may or may not be installed at stream grade and they are usually at least partial barriers to AOP.

For all these reasons, the authors' recommend high-VAR fords be used when a vented ford is desired. Low-VAR fords are not included in table 3.3, which deals with considerations for selecting the type of structure best suited to a site.

Table 3.3 occasionally makes reference to Rosgen's channel types. For reference, appendix C includes two figures illustrating the classification system. Readers unfamiliar with this classification system should refer to either Rosgen's paper (Rosgen 1994) or book (Rosgen 1996).

Table 3.3—Considerations for low-water crossing structure type selection.

Type of Factor	Factor	Unvented Fords	Vented Fords (High-VAR)	Low-Water Bridges
Site	**Baseflow** Baseflow is the component of streamflow derived from ground water. It is relatively constant. Flood flows, which are derived from surface or near-surface runoff, vary much more than baseflow. Ephemeral stream channels are above the ground water table, and therefore have no baseflow. Intermittent channels intercept ground water only when the water table is high after a runoff event. Perennial channel beds are below the ground water table year round. Normal low flows are generally baseflows.	Appropriate for ephemeral streams and intermittent streams where the road is closed during the flow season. Where baseflows are high and steady, vehicles must drive through water that will probably be a habitat for aquatic species. In some parts of the country, unvented fords are still common on perennial streams where traffic volumes are low, but they are likely causing at least some damage to aquatic organisms and their habitats.	Appropriate for intermittent and perennial streams. Consider the need to provide aquatic organism passage.	Appropriate for all flow regimes.
Site	**High-flow duration during season of use** See discussion in section 3.1	Most useful where high flows are short (so that traffic is only briefly interrupted). Commonly used in flashy desert streams.	These structures usually convey a relatively large volume of flow under the deck, so they are useful where high flows last longer. Where the structure will be submerged for long periods of time, an alternate route should be available	
Site	**Woody debris and ice blockage hazard** Structures designed for overtopping reduce the risk of crossing failure and stream diversion where ice or debris may plug culverts. See case studies 16, 17, 18, 19.	The open cross section presents least risk of debris- or ice-blockage. Traction can be a severe problem for winter traffic when the ford surface is icy.	Consider high-VAR fords where ice or debris may plug a culvert. However, even fords with large openings can plug and be maintenance headaches if the channel carries a lot of large woody debris and tree trunks. Can be designed with removable driving surface (e.g., cattleguards) for easy clean-out. Removable metal grates, can be more slippery than gravel or paved surfaces when icy.	Consider low-water bridges where debris loads are very high and traffic volume does not justify construction of a bridge high enough to avoid debris jams. The hazard of debris- or ice-jamming is higher than for ordinary bridges because of the lower clearance. Traction issues are similar to those encountered with conventional bridges.

Table 3.3—Considerations for low-water crossing structure type selection—*continued*

Type of Factor	Factor	Unvented Fords	Vented Fords (High-VAR)	Low-Water Bridges
Site	**Slightly entrenched** (Rosgen E, DA, stable C) See case studies 18, 19, 20. Overbank flood plain flows are fairly frequent on these streams, and can be of long duration. Road approaches are often raised above the flood plain surface, backwatering overbank flows upstream of the road, and altering scour and deposition processes that maintain flood plain habitats and ground water tables. Unentrenched channels in wide flood plains are often highly sinuous and may shift their location on the flood plain over time.	Appropriate where channel width is much greater than depth, so that a ford matching channel shape has a vertical curve adequate for passage of the design vehicle. Many channels in wide flood plains have steep, densely vegetated streambanks (even though they may be low). Approaches to unvented fords cut through the banks and widen the high-flow cross section, inducing sediment deposition. Additionally, many meadow soils are soft and compressible, qualities that contribute to this problem if approaches are not adequately reinforced or hardened (case study 7).	Good options if potential problems with outflanking during high flows can be avoided. Overbank flows that go around the structure can cause bed and bank erosion downstream. Road approaches should be kept low across the flood plain, or should span it to avoid interrupting flood flows and sediment and debris transport on the flood plain. (See case study 20 for an example of a very low profile low-water bridge in a flat E channel in Florida.) Even stable meandering streams experience meander shift. At bends, erosion on the outer bank and deposition on the inner bank cause the channel to change location over time. This process often modifies the channel's angle of approach to a crossing. An acute angle of approach can cause sediment and debris deposition above the structure. Culverts can plug and bank erosion can become severe. Designers should consider spanning the entire meander belt (the zone of active meander shift), or they might plan for regular monitoring and maintenance.	
Site	**Moderately entrenched** (Rosgen B) See case studies 4, 8, 9, 12, 17.	Because these streams have relatively mild approach grades and are moderately wide relative to their depth, unvented fords can be appropriate.	Good options. Bank erosion is less of an issue than for slightly entrenched streams because the channel is more constrained and less able to shift location.	
Site	**Entrenched** (Rosgen F, A, G) See case studies 3, 5, 6, 16. Entrenched channels are either incised between high banks (Rosgen F) or are closely bounded by valley walls (A or G). Approaches to the low-water crossing have to slope steeply into the channel, creating the risk of sediment introduction from road surface and ditch. Be careful to carry channel protection from scour high enough in these channels, since the water surface does not spread very much (but rises vertically) as flow increases.	Generally not appropriate at deeply entrenched channels where the approaches require cutting through the adjacent slopes to achieve a drivable grade. Approaches may also require extraordinary stabilization measures, such as paving and rocking ditches. There may be no room for ditch relief or a sediment trap. If aquatic animal passage is not an issue, rockfill fords (e.g., case study 3) can be appropriate in entrenched channels.	Application limited to small entrenched channels where the driving platform can be raised high enough to have a suitable road alignment and entail minimal earthwork. Useful in steep channels that are subject to frequent debris flows (case study 16). Successful vented fords are large concrete structures that allow debris to ride over the driving surface and have removable tops for cleaning out	Suitable for spanning small channels. A bridge crossing a wide entrenched channel would likely be a standard high-clearance structure.

Table 3.3—Considerations for low-water crossing structure type selection—*continued*

Type of Factor	Factor	Unvented Fords	Vented Fords (High-VAR)	Low-Water Bridges
Site	**Laterally unstable** (especially Rosgen D, unstable C) In depositional channels such as braided or alluvial fan channels, or in streams undergoing rapid bank erosion, the channel may shift abruptly or progressively. If at all possible, avoid locating a crossing in such a spot. If you cannot avoid it, then low-profile or flood plain-spanning structures are less likely to obstruct flow and exacerbate lateral shift. Laterally unstable channels frequently have high sediment loads. If a crossing structure obstructs sediment transport—especially if it plugs—it can induce even more channel erosion. See case studies 2, 21.	Unimproved at-grade rock or native material fords are the cheapest and easiest structures to replace when the channel shifts location, and are common in desert braided stream environments. Improved fords in these environments are usually paved or concrete dips. Where the approach roadfill concentrates dispersed floodplain flows through the ford, the added erosive power puts the channel downstream of the road at risk of local degradation.	Generally would not be used because of the risk that the channel would move away from the structure. If used, VAR should be high and road approaches should be low to minimize obstruction of flow and sediment transport.	Where traffic interruptions are not acceptable (i.e. where an unvented ford is not an option), bridges are advantageous because they are less likely to exacerbate channel shifting by obstructing flow or sediment transport. Nonetheless, the potential for the channel to shift and isolate the bridge should be considered. A long structure may be needed to span the flood plain.
Site	**Vertically unstable** (aggrading or incising) If at all possible, avoid crossing any unstable stream. In aggrading channels at valley margins or on alluvial fans, obstructing sediment transport can lead to plugging or channel shift. An incising channel can cause any crossing structure with a floor to become perched, thereby either undermining the structure or causing the structure to become a grade control (i.e., a structure that controls upstream channel elevation and grade). If a grade control is desired, predict the depth of future downcutting and provide downstream cutoff walls to protect the structure (section 4.7).	In an aggrading reach, unvented fords have the benefit of not plugging, and they have no roadfill to fail in a flood event. Given the potential for lateral shift in this setting, consider using an unimproved ford to minimize the investment in the structure. In a degrading reach, like other crossing structures, unvented fords may be undermined when an advancing headcut reaches them. If the structure is well protected from undermining, it will inadvertently become a grade control, preventing the headcut from migrating upstream. See case study 10.	Appropriate at depositional sites such as where a tributary enters the valley floor (case study 13). Use removable tops to facilitate debris removal. Can be designed to function as grade controls in incising channels (case study 15).	Considerations for aggrading channel sites are the same as for laterally unstable channels; i.e., the channel may shift away from the bridge. For incising channels, the risk of scour undermining the piers would be a major site limitation. Designers can minimize this risk by avoiding mid-channel piers and using long spans to keep abutments out of the channel.

Table 3.3—Considerations for low-water crossing structure type selection—*continued*

Type of Factor	Factor	Unvented Fords	Vented Fords (High-VAR)	Low-Water Bridges
Road Management	**Acceptable traffic delay** Acceptable depends on traffic volume, traffic type, and the availability of alternative routes. Where no traffic counts exist, maintenance level can be used as a rough surrogate for traffic volume and type for the purpose of selecting the appropriate structure type. Actual delay times depend on the flood frequencies and runoff patterns of the watershed (section 4.5).	Usually limited to those locations where delays may occur without endangering the public. The lower the traffic volume and the shorter the high flow duration, the more likely a ford is acceptable.	Appropriate for higher traffic volume roads (roughly **maintenance level** 2-3 roads). Flows pass through the vents most of the time, minimizing safety hazards and traffic delays.	Because bridges usually provide the most open area under the deck, they are appropriate for higher traffic volume roads and where traffic interruption is least acceptable (roughly, maintenance level 2-4).
Road Management	**Vehicle type** Ground clearance affects the depth of water a vehicle can be driven through. Wheel-base length affects the allowable vertical curve through a crossing.	Unimproved fords may be appropriate for roads that are closed or managed for high-clearance vehicles or off-highway vehicles only (trails and maintenance level 1 and 2 roads). If the channel is narrow and deep, an unvented ford may have a sharp vertical curve that can snag trailer hitches and cause long wheel-base vehicles to drag.	Raised driving platforms generally minimize the depth of water driven through and flatten out the roadway sag “vertical curve.” Feasibility for various vehicle types depends on approach grades and the resulting vertical curve.	Low water bridges accommodate the widest range of vehicle types. Weight limitations may be a design consideration.
Road Management	**Traction** Wet or icy surfaces are a safety hazard.	Traction can be a severe problem for winter traffic when the surface is icy.	Some vented fords have removable metal grates, which can be more slippery than gravel or paved surfaces.	Traction issues are the same as those encountered with conventional bridges.
	Maintenance access and commitment All structures require inspecting and sometimes cleaning, maintenance or repairs after high flows.	A good choice on closed roads where access for inspection and maintenance will be difficult. They usually require minimal maintenance, depending on the structure type and the quality of its installation. Maintenance needs typically arise after a flood; they include removing sediment and debris, regrading approaches, and replacing surfacing materials.	Vented fords in streams that carry large woody debris often require cleaning and can be a maintenance headache. Removable tops are good design features for streams with large debris loads. The tops can be removed before a large storm or a seasonal road closure.	Generally the only maintenance required is after large floods, when debris trapped on the structure needs to be removed and any channel or bank erosion around the structure is repaired.

Table 3.3—Considerations for low-water crossing structure type selection—*continued*

Type of Factor	Factor	Unvented Fords	Vented Fords (High-VAR)	Low-Water Bridges
Economic	**Cost** Costs associated with crossing structures include installation, maintenance, replacement, and (sometimes) road user costs. Total life-cycle costs also include the damage to stream channels, flood plains, and aquatic habitats caused by obstruction of natural transport processes or by structure failure.	Generally cost much less to install than other structures (Warhol 1994) and, when properly constructed, they require little maintenance. Construction and maintenance costs may be higher where special efforts for water quality or habitat concerns are necessary; in such cases, another structure type may be preferable anyway (see appendix D).	High-VAR fords are likely to have installation costs similar to those of ordinary culverts. Since vented fords are designed to sustain overtopping flows, replacement costs should be lower, especially where plugging makes ordinary culvert failures frequent.	Likely to be somewhat cheaper than standard bridges, because they do not need to be as high above the water surface. Although the risk of debris blockage is higher for low-water bridges, they are not likely to fail because of it. Costs associated with maintenance may be higher in areas with large debris loads. In broad, valleys where debris plugging could cause channel shift away from the bridge in a major flood, channel rehabilitation could add to the lifetime cost.
Resource Protection	**Aquatic Organism Passage** Unobstructed passage for all aquatic animals is presumed to exist when the streambed is continuous throughout the crossing. When channel width, depth, and structure (e.g., steps, pools, riffles) in the crossing are similar to those of the natural channel, the crossing should be nearly indiscernible to aquatic species. Designing for swimmable velocities and depths at selected flows can also allow some fish passage (see section 4.3).	Due to the potential for habitat disturbance, fish injury, and the water quality impacts of vehicles passing through water, unvented fords are not generally recommended for locations with fish passage concerns. However, fords may be a good choice where • traffic volume is low • aquatic habitat is limited • aquatic habitat is poor quality • the channel is prone to shifting In such cases, the resource or access benefits might not justify the cost of a culvert or bridge that would provide fish passage. Good design is critical for fords where aquatic organism passage is desired (see section 4.3) Most fords provide at least partial passage when they are backwatered or submerged.	Can provide passage by matching channel width and maintaining streambed continuity through the structure (case studies 17, 18, 19). Usually, these structures are box culverts that allow the crossing structure to be short in the along-stream direction. Some concrete fords include a slot to concentrate low flows and provide partial fish passage (case studies 9, 10). This type of ford should generally be a last resort in most fish-bearing streams; it is unlikely to provide more than partial passage for a target species and may provide no passage at all for other aquatic species.	Assuming they are wide enough, low-water bridges are the ideal structure type because the streambed remains continuous throughout.

Table 3.3—Considerations for low-water crossing structure type selection—*continued*

Type of Factor	Factor	Unvented Fords	Vented Fords (High-VAR)	Low-Water Bridges
Resource Protection	**Water quality** (See also appendix D: Low-water crossing effects on water quality.) The importance of protecting water quality at a site affects the choice of structure type because structure type determines how frequently vehicles drive through water, and the feasibility of diverting sediment-laden road surface runoff before it reaches the stream.	Construction may affect water quality temporarily depending on site stability, excavation requirements, and flows during construction. Traffic through water is most likely to deliver pollutants to waterways and cause some channel erosion, although significant effects have not been demonstrated. Because they directly connect some portion of the road to the stream, unvented fords have the highest potential for sediment delivery of any structure type. However, since there is no fill to fail, they do not produce the large volumes of sediment that culvert plugging sometimes produces during catastrophic floods.	Construction can affect water quality temporarily if excavation and fill are not isolated from flowing water. Traffic over these structures is likely to have little or no effect on water quality, especially if best management practices are implemented to isolate road surface runoff from the stream.	
Resource Protection	**Noxious weeds** Vehicles may carry invasive aquatic and other weeds (seeds and plant parts) and deliver them to waterways.	Most likely to permit weed introduction to new waterways.	Where the driving surface has gaps (e.g., cattle guards), weed seeds could fall off vehicles into the channel. We have found no information about how significant this risk might be.	

Chapter 4—Design Elements, Considerations, and Tools

Good low-water crossing design is a challenge because the objectives are to produce a structure that meets traffic needs, maintains the natural channel function, passes aquatic species, and is both safe and cost effective. Although each objective may be easy to achieve independently, some objectives can conflict, making it difficult to achieve all objectives at the same time. Poor site selection or choosing an inappropriate structure for a given site can exacerbate the problem. Like most hydraulic structures, low-water crossings require attention to both design detail, and compatibility with the hydrologic and natural setting into which the structure will go.

Acknowledging Risk

Low-water crossings inevitably involve some risk in several aspects of the selection and design process because they may allow people to drive through water, and because sites are commonly in rural areas with limited site and hydrologic information. The following risk factors must be taken into consideration when using low-water crossings:

- Danger when people choose to drive through flooded fords.
- Occasional traffic delays during flooding making road use more restricted than anticipated.
- Exceeding the design flow, although fords are less sensitive to this factor than culverts or bridges.
- Possibility of damage to—and failure of—a structure, depending upon the type of structure selected, the scour protection used, riprap size chosen, etc.
- Environmental damage if the structure does not perform well.

Although difficult to quantify, each risk can be kept at an acceptable level by applying thorough engineering design and good judgment, using good and suitable materials, and using an interdisciplinary process. Examining existing or current structures that are (or are not) performing well and taking a broad view of the stream and its function can significantly improve project judgment and help reduce the risk of problems. Low-water crossings can be very cost effective structures when the attendant risks are controlled and minimized.

If safety risks are determined to be unacceptably high, choose a different type of structure, such as a large culvert or bridge. On low-volume roads, the advantages of low-water crossings can outweigh their risks because traffic is low, speeds are slow, and a failed ford will likely cause less damage and cost less to replace than a failed culvert or bridge.

4.1 Overview of Key Engineering Design Elements

Key design elements of a low-water crossing, as identified in figures 4.1A and 4.1B, include the following:

- Accommodating traffic and passing the design vehicle safely.
- Planning for acceptable traffic delays with selection of appropriate low-flow and high-flow values.
- Ensuring the structure conforms to the site's shape, is as low as possible, and minimizes site disturbance and channel blockage.
- Ensuring passage for aquatic organisms, when appropriate, by considering potential obstacles from structure height, changes in flow depth, or accelerated flow velocities.
- Maintaining the stability of the channel and banks by preventing scour around and beneath the structure, or by preventing bank erosion, sediment deposition, and potential changes in bedload size and quantity (i.e., maintaining channel form and function).
- Providing structure stability, including driving surface, drop structures, footings, approaches, and necessary armoring which prevents damage and minimizes maintenance.
- Armoring the structure's entire wetted perimeter, plus **freeboard**.
- Providing for traffic safety with warning signs, depth and **object markers**, curbs, etc.
- Disconnecting the road from the stream with appropriate surface drainage and roadway stabilization measures.

Poor structure design and site incompatibility can cause a variety of problems, including the following:

- Causing unreasonable traffic delays or difficulty turning around during flooding.
- Narrowing the channel, with resultant increase in flow velocity and scour.
- Damming the channel. (A relatively high structure can cause upstream sediment deposition and downstream scour or degradation, thereby changing the channel's shape).
- Restricting or blocking passage of fish or other aquatic organisms, as a result of high velocities and excessively high waterfalls.

- Interrupting floodwater access to the flood plain adjacent to the active stream channel.
- Causing premature structure failure.
- Accidents and injury.

The USDA Forest Service and other agencies have built many low-water crossings over the past 40 years. Many have worked and many have failed. Most have required some maintenance or improvement to become the functioning structures seen today (see appendix A, case studies). Although functioning from an engineering and road-use standpoint, many low-water crossings are creating stream channel changes, accelerated maintenance needs, and fish barriers. The aquatic, geomorphic, and design perspectives that follow will help interdisciplinary teams design structures to serve road-user needs, minimize long-term costs, and protect the stream environment. Because many sites require considerable experience and judgment for proper structure selection and design, all information in this chapter is based on both standard engineering road design practices and the experience and judgment of the authors.

To accomplish the design objectives of a low-water crossing and have the crossing function well, it is important to evaluate and incorporate several fundamental elements involving channel, hydrologic, hydraulic, fisheries, and engineering considerations. Subsequent sections address these elements in detail. Table 4.1 summarizes these elements and their associated issues, as outlined below:

- Structure-Site Compatibility.
- Fish and Aquatic Organism Passage.
- Roadway and Site Geometry.
- Site Hydrology.
- Hydraulic Design.
- Scour, Bank Protection, and Preventing Channel Changes.
- Structural Design of the Driving Surface.
- Traffic Control and Safety.
- Materials Selection.
- Best Management Practices for Erosion Control and Water Quality Protection.

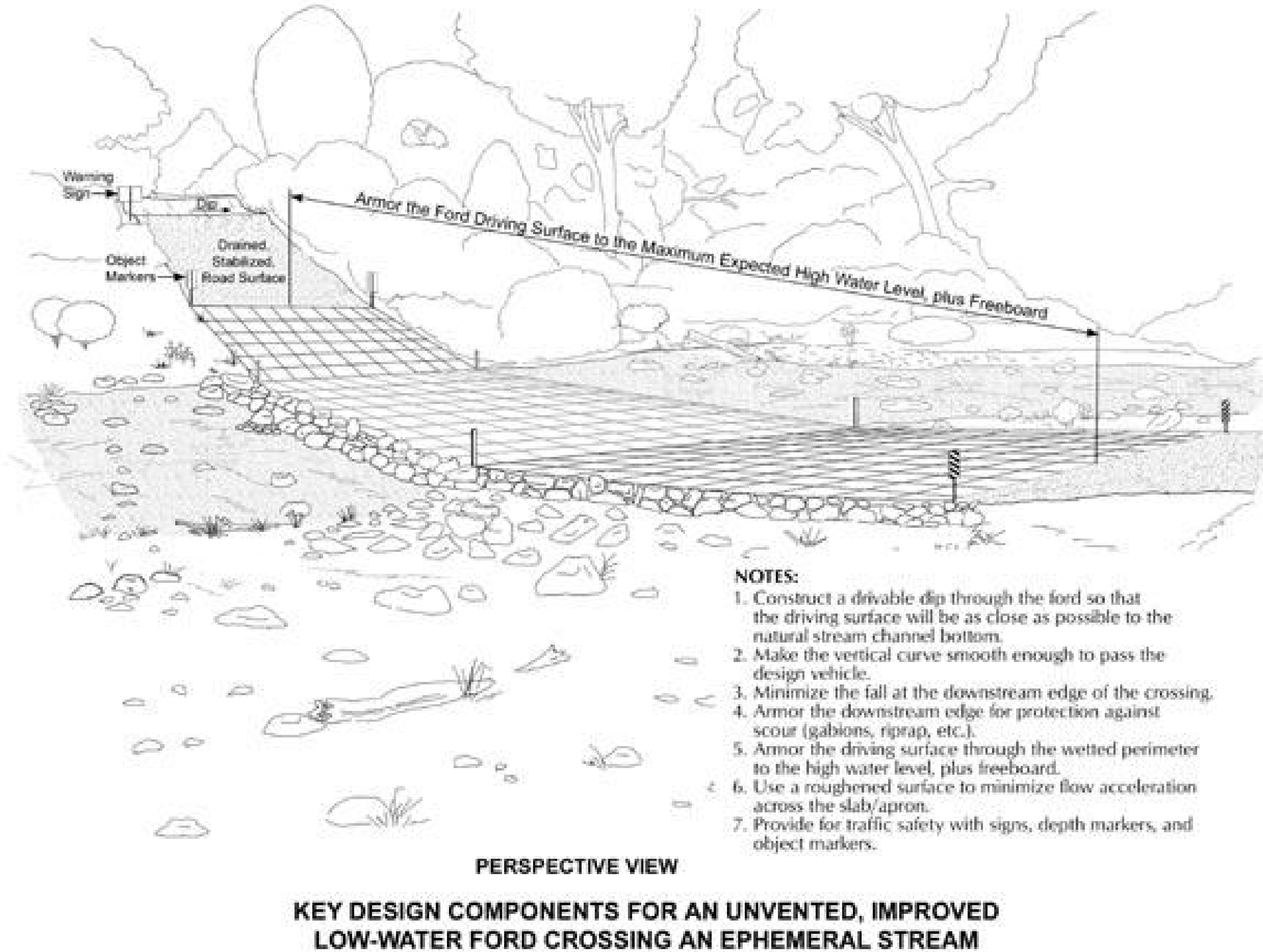


Figure 4.1A—Perspective view of key design components for an unvented, improved low-water ford.

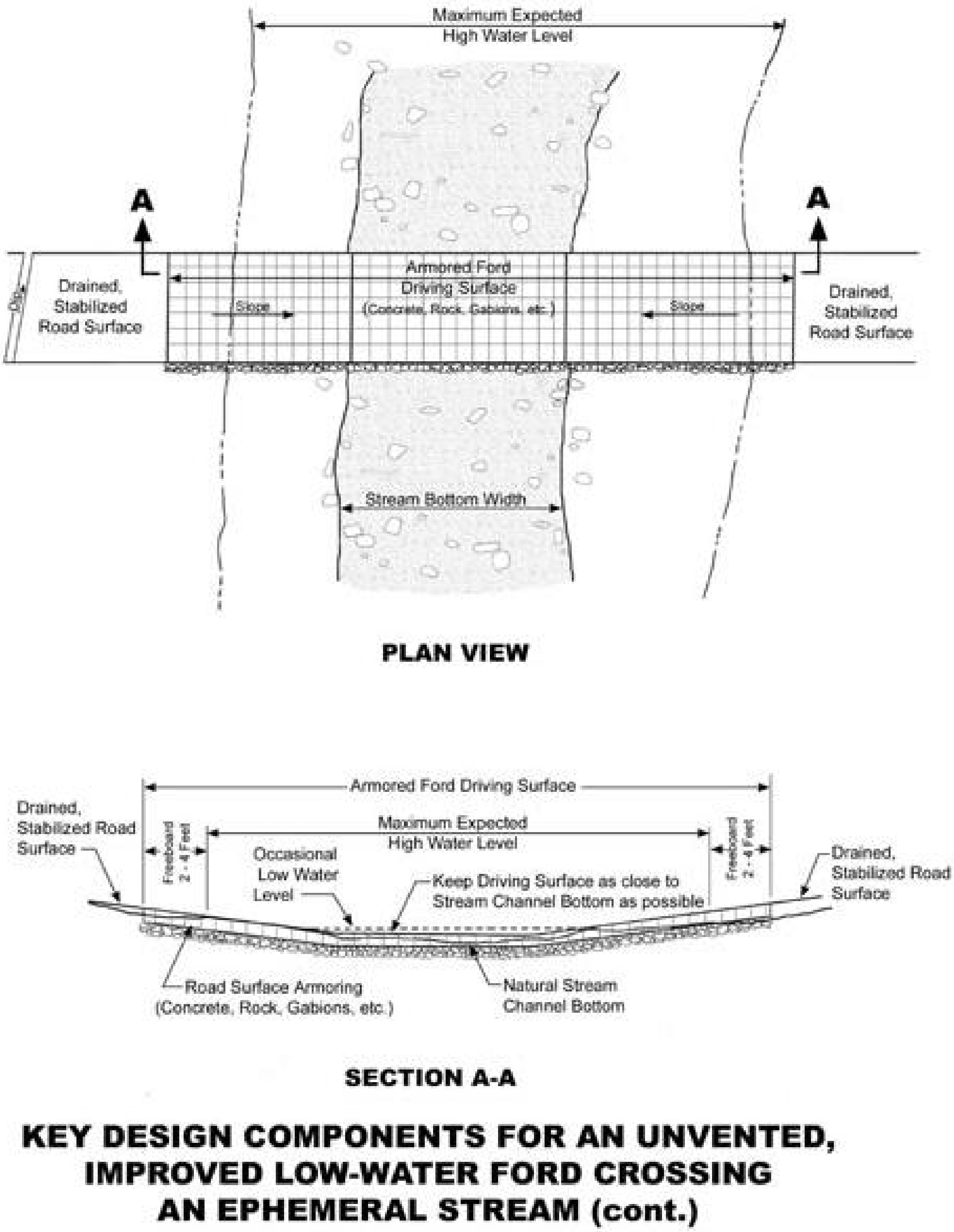


Figure 4.1B—Plan and cross section views of key design components.

Table 4.1—Summary of key engineering design elements for low-water crossings.

<u>Structure-Site Compatibility:</u> Select and design structures to maintain the function and bedload movement of the natural stream channel. Conform to the natural channel shape and elevation where possible.

- Avoid "damming" the natural channel or adjacent flood plains. Keep the channel open.
- Do not cause significant aggradation in the channel upstream of the structure, or degradation or downcutting downstream of the structure.
- Do not confine or narrow the normal (bankfull) flows.
- Do not increase the natural stream channel velocity.
- Accommodate major flood flows without significant drops in the water surface profile.
- Align structures perpendicular to the stream channel.

<u>Fish and Aquatic Organism Passage:</u> Select structures that will pass all aquatic species, particularly fish, where needed and appropriate. For vented fords, open-bottom or embedded box culvert structures with a high VAR are often best. For simple fords, a roughened driving surface conforming to the grade and shape of the natural stream channel is best. A low-water bridge may be the best solution.

- Maintain natural streambed substrate material, roughness, slope, and form through all or part of the structure.
- Avoid accelerating the velocity of streamflow, particularly at normal and low flows.
- Build a structure, with either single or multiple spans, that is at least as wide as the bankfull width of the natural channel.
- Provide areas of diverse flow velocity and depth.
- Maintain swimmable low-flow depths.

<u>Roadway and Site Geometry:</u> Build a structure that fits the site, with a vertical and horizontal alignment that will be safe and will allow the design vehicle to pass over the crossing.

- Select a site with a relatively straight road alignment.
- Locate a crossing at a straight reach of the stream.
- Conform to the natural dip of the channel as much as possible.
- Limit grades into the ford to 10 percent or less if possible.
- Use a vertical curve dip through the ford, sufficiently gentle not to catch the bumper or undercarriage of vehicles passing through the ford.
- Provide enough space for backing up and turnaround when needed.

<u>Site Hydrology:</u> Ideally use either a flow-duration or flood-frequency (peak discharge) design approach to specifically size the low-water crossing structure. Nonetheless, when site hydrologic conditions are unknown or difficult to determine, low-water crossings make a good structure choice. They can easily be designed to overtop a large volume of water and/or debris, and they are not sensitive to the exact flow quantity. Determining the hydrologic properties of a site should be an interdisciplinary process, involving hydrologists and engineers.

- Determine the peak design flows (Q_{50} or Q_{100} events) to select the maximum size of the structure and identify maximum high-water level.

Table 4.1—Summary of key engineering design elements for low-water crossings—*continued.*

- Determine low-flow information (baseflow to Q_2, or bankfull flow) to size the vents in a structure, and estimate the frequency of probable delays.
- Quantify flows suitable for fish passage through structure or vents.
- Estimate traffic-delay times using either flow-duration data or field knowledge of the site.

Hydraulic Design: Determine the site hydraulic factors needed for prudent structure design.

- Determine flow capacity through vents and over the structure, up to the high water elevation.
- Use computer models, Manning's Equation, pipe capacity nomograms, or broadcrested weir formulas to determine flow through and over respective components of the ford.
- Determine stream velocities (through the structure) that will require riprap or other scour protection measures.
- Limit velocities to those suitable for needed fish passage using FishXing.

Scour, Bank Protection, and Preventing Channel Changes: Protect the channel, the structure, and its foundation against scour and erosion.

- Prevent accelerated stream flows that can damage structures, wash out the approaches, or provide a source of sediment into the watercourse.
- Prevent a "waterfall" and other scour-critical areas by keeping structures low to the channel and by avoiding channel constriction and mid-channel structures or obstructions.
- Install scour protection or energy dissipation measures, including rock riprap, concrete aprons and cutoff walls, gabion basket aprons, or plunge pools.
- Protect streambanks with vegetation, biotechnical measures, erosion control or reinforcing mats, gabions, concrete blocks, rock riprap, etc.
- When riprap is used, size and place the rock to prevent rock movement resulting from the velocity and force of water.

Structural Design of Driving Surface: Design low-water crossings to support the design vehicle for the onsite soil conditions.

- Unless otherwise indicated, design all elevated structures (slabs, box culverts, or pipes) and bridges to support an 80,000 pound, HS-20-44 "legal" design load, in accordance with AASHTO "Standard Specifications for Highway Bridges" requirements.
- Provide at least 1-foot compacted soil cover over culverts, or a concrete slab (typically at least 6 to 8 inches thick) over box culverts, based upon manufacturers' requirements or structural analysis.
- Construct the roadway driving surface with material durable enough or heavy enough to resist the shear stresses or lateral forces of the water flow.
- Protect the entire "wetted perimeter" of the ford (the area of the entire high flow), plus freeboard (typically 2 to 4 feet of additional height).
- Remove soft or organic subgrade soils and replace the soil with select, structurally sound material in a layer thick enough that will support the traffic without deformation.

Table 4.1. Summary of key engineering design elements for low-water crossings—*continued.*

Traffic Control and Safety: Consider all traffic safety issues to produce a safe crossing site.

- Ideally locate low-water crossings at sites where the road is straight and where good sight distance exists.
- Build 6- by 10-inch wood or 15-inch-high concrete curbs to define the roadway and keep traffic on the structure.
- Place object markers along the road at each corner of the structure to define each entrance of the structure.
- Install warning signs to identify the approaching ford and warn drivers of flooding and possible traffic delays.
- Use marker posts that indicate the depth of flow.
- Consider making the ford extra wide for traffic safety, and wherever possible, using 4:1 or flatter foreslopes on embankments.
- If site evaluation determines that a ford would be unsafe, choose a conventional structure such as a culvert or standard bridge.

Materials Selection: Choose strong, durable, cost-effective materials for construction of low-water crossings. The driving surface may be made of local rock, aggregate confined in geocells, gabions, concrete planks, asphalt, masonry, or a massive concrete slab. Most vented box fords are made of structural steel-reinforced concrete, because of its strength and durability.

- Use local riprap where appropriate, cost effective, and available in the necessary size. (Riprap is unsuitable if it is undersized and if the forces of water can move it.)
- Where suitably large rock is not available for scour protection, use alternative materials such as gabions, grouted riprap, rootwads with boulders, concrete blocks, or massive concrete.
- In relatively low-velocity, low-energy areas, use vegetative or biotechnical streambank stabilization measures, erosion control mats, turf reinforcing mats, etc.
- Maintain materials quality control in the structure in accordance with appropriate standard specifications.

Best Management Practices (BMPs) for Erosion Control and Water Quality Protection: Use BMPs and incorporate erosion-control measures into the design, construction, and maintenance of low-water crossings to protect water quality.

- Incorporate construction dewatering into the project. Avoid working in the water!
- Develop a project "erosion-control plan," including appropriate physical, vegetative, or biotechnical measures, types of materials, and timing.
- Choose appropriate project BMPs and include them in project budgets, design, and project implementation. Monitor them for implementation and effectiveness.
- Periodically inspect and maintain the structure to ensure that it is functioning properly.
- "Disconnect" the road from the stream crossing by diverting road surface water before reaching the crossing, armoring ditches, and stabilizing the roadway surface approaching the crossing.

Key Design Reference Documents

This document only summarizes key information on low-water crossing design. When designing a project, use the following basic references for more detailed information.

- Lohnes, R. A.; Gu, R. R.; McDonald, T.; Jha, M. K. 2001. Low-water stream crossings: design and construction recommendations. Final Report CTRE Project 01-78, IOWA DOT Project TR-453. Ames, IA: Iowa State University, Center for Transportation Research and Education (http://www.ctre.iastate.edu/).
- Gu, R. R.; Waugh, J.; Lohnes, R. A. [and others]. 2003. Low-water crossing study: design approach. FHWA-CFL/TD-05-013. Lakewood, CO: U.S. Department of Transportation, Central Federal Lands Highway Division. 136 p. Vol. II. (also see Volume I, Literature Review).
- Motayed, A. K.; Chang, F. M.; Mukherjee, D. K. 1982. Design and construction of low-water stream crossings. Report No. FHWA/RD-82/163. June. Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

4.2 Structure-Site Compatibility and Crossing Location

4.2.1 Structure-Site Compatibility

Numerous factors must be taken into consideration when fitting a structure to a specific site (review table 3.3). To be compatible with its site, a structure should preserve **channel function** as well as providing for safe traffic use. The structure should conform to the site as shown in figure 4.2. Broad, shallow (slightly entrenched) channels are the ideal shape for unvented fords. Slightly to moderately entrenched channels can be well-suited for crossings with vented fords. Deep, entrenched channels are typically least suited for fords, but in special circumstances rock-fill fords and vented fords are appropriate crossings even in these channels. For examples, see case studies 6 and 16.

Structure-site compatibility includes the following elements:

- The structure should conform to the shape and channel capacity of the natural channel.
- The structure should not form a “dam” across the channel.

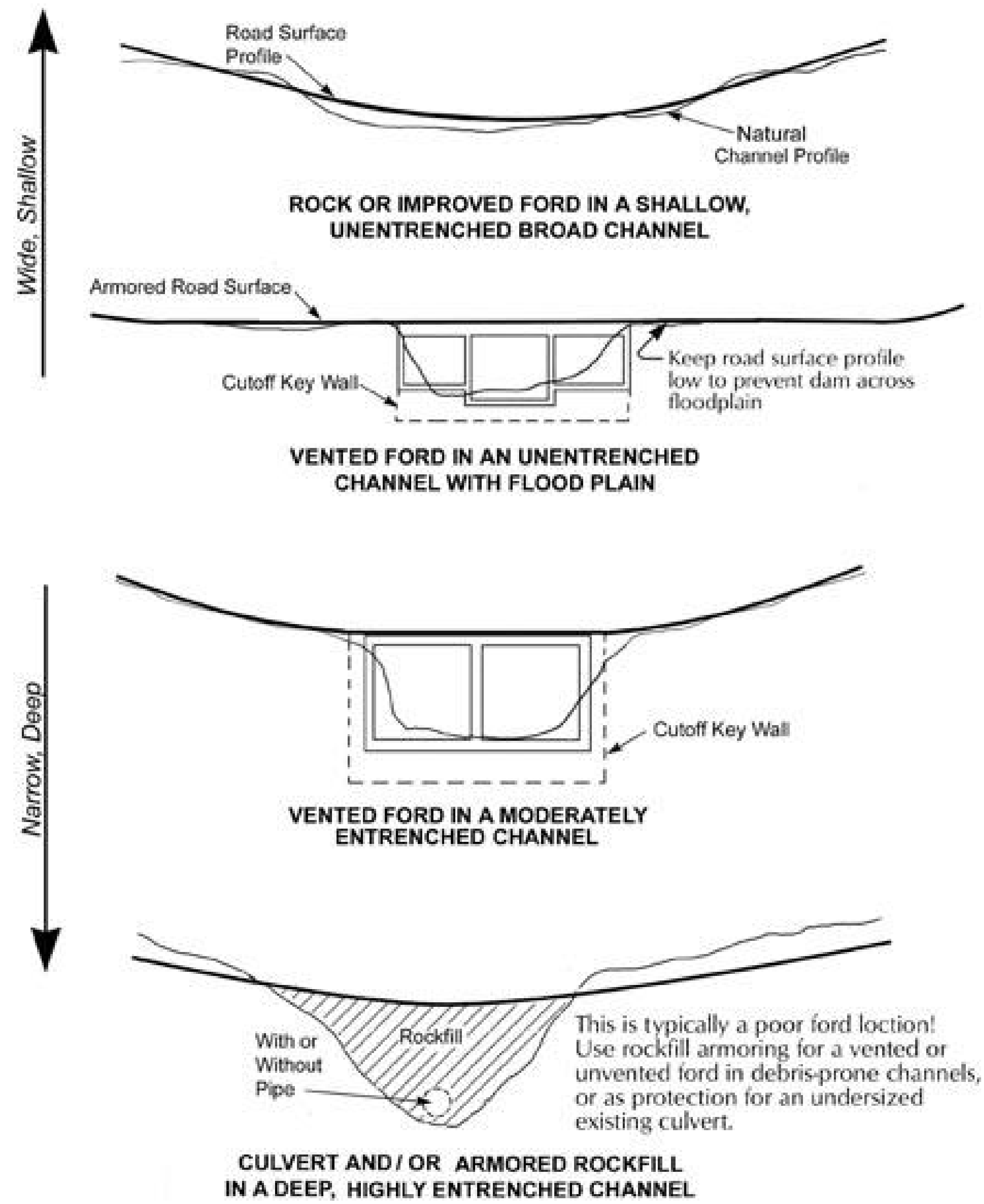


Figure 4.2—Matching channel shape and ford type.

- The structure should have a high percentage of open area or a high VAR across the channel (see fig. 1.4.).
- The structure should prevent or minimize the acceleration of flow velocities through the structure.
- Approaches to the structure should not dam the flood plain where substantial overbank flow occurs.
- The structure should cross perpendicular to the channel to minimize the disturbance area and reduce costs.
- The structure must safely pass the anticipated vehicles, as well as fit the site.

Structures maintain channel function by accommodating channel dynamics, shape, slope, and site characteristics. Streams move mass and energy along the channel and through the flood plain. A properly functioning channel can transport its natural volume of water and sediment, maintain lateral and vertical stability (without excessive scour or deposition), and preserve the channel's width-to-depth ratio. Because completely matching structure to channel dimensions or roughness is impossible, mitigation measures are often necessary, particularly for protection against accelerated velocities. Section 4.7 (Scour, Bank Protection, and Preventing Channel Changes) addresses commonly used mitigation measures.

A structure usually needs a maximum capacity adequate to pass the design flow ($\mathbf{Q_{50}}$ to Q_{100}) within its armored cross section. Flows exceeding channel or structure capacity will spill over or around the structure, or onto an adjacent flood plain. Narrowing the channel focuses flow through the structure at a greater velocity and increases downstream scour potential and bank erosion. Structures with a low VAR, such as vented fords with small culvert pipes, are most likely to create a decreased channel capacity, a damming effect, and cause upstream deposition. Accelerated velocities through the culvert pipes usually cause downstream scour. As a result, mitigation measures such as channel armoring, stilling basins, or other energy dissipators become necessary.

On deeply entrenched steep channels, the channel will contain the flow, but the road needs protection from the high stream energy, and debris passage must be available. Small bridges are commonly used, particularly if aquatic passage is required. Where aquatic passage is not an issue, however, well-armored rock-fill fords and vented fords have been used successfully on these channels (case study 3), particularly where the channel is prone to debris flows.

In slightly entrenched channels (fig. 2.1d) flood flows often overtop the channel and flow across a flood plain. To avoid damming the flood plain in this setting, keep roadway fill approaches to fords low and flat, reflecting the shape of the natural topography. Ideally, the roadway should be overexcavated, backfilled with structurally sound material, and kept at the flood plain elevation. These actions help disperse flows across the flood plain, reducing the chance of concentrated return flows that cause bank erosion. If the roadway must be raised, make sure it has periodic dips or relief culverts across the road for distributing the flood flows. Figure 3.2 shows upstream deposition and downstream scour from a long, elevated low-VAR ford across an unconfined, dynamic channel in Arizona. In this case, the channel and part of the flood plain were dammed, causing channel widening and shifting upstream.

The Jones Wreckum low-water bridge (case study 21) is an example of a structure compatible with its site. The bridge is located immediately upstream of a 90-degree bend in the channel with a gravel point bar on the inside of the bend. Bridge designers appropriately treated this point bar as part of the active channel and spanned it. Debris accumulated under the bridge has increased sediment deposition on the point bar, but channel form is substantially the same as when the bridge was built.

Knowledge of the local stream system and the road needs is necessary to properly assess structure-site compatibility. Field data should include stream channel profiles extending far enough upstream and downstream from the crossing to show whether the natural channel is stable, aggrading, or degrading. Channel cross sections should also be surveyed, and they should be wide enough to cover the possible extent of high water on the flood plain. The cross sections best show how a certain type of low-water crossing will conform to the shape of the natural stream channel. The Hydraulic Structure—Initial Site Examination Form in appendix B is a useful checklist of items to examine in the field and a good tool for documenting channel and other site characteristics. The form includes enough site information to make preliminary design decisions. In addition to the form, all sites should have a site sketch and accurate surveys of channel longitudinal profile and cross sections. Difficult or complicated sites should receive a more indepth investigation.

The longitudinal profile in conjunction with the cross sections will show how the stream has adjusted to the existing structure. It is common to see some sediment accumulation upstream and scour downstream. Using stable grade controls as endpoints, it is possible to project the slope and elevation of the streambed through the crossing, as if no structure were there. That will be the design streambed elevation through the crossing (the profile to which the stream will adjust after the new structure is built) unless the goal is for the new structure to control streambed elevation. If the new structure is to function as a grade control, use the longitudinal profile when selecting the elevation to avoid modifying stream slope and sediment transport processes as much as possible.

Similarly, the cross sections will show channel adjustment (usually widening, deposition, and scour) around the existing structure. They can help assess the volume of sediment that might be mobilized after the structure is removed. It may be necessary to remove some accumulated sediment during construction to prevent it from affecting downstream habitats.

If new structure objectives include preserving or reestablishing stream continuity for the purpose of AOP, it will be necessary to take some cross sections outside the area influenced by any existing structure—some distance upstream or downstream from the structure. Ideally, the cross sections would be taken in a reference reach (an undisturbed reach representing natural channel form and slope) near the crossing site. The reference reach cross sections can be used to determine channel width and depth through the crossing, and to design bank reconstruction or other channel restoration elements.

Observe how mobile the streambed materials are. Streambeds composed of loose gravels and finer materials are usually very mobile; that is, sediment moves frequently and the channel will adjust rapidly to a new structure. Depending on slope, rock size, and channel stability, cobble-boulder streambeds may not change much until a large runoff event occurs. The longitudinal profile and cross sections will help with this evaluation, by showing the degree of adjustment to the existing structure. Channels with more mobile materials generally show larger responses to structures that partially interrupt sediment transport.

Streambed material size and mobility affect scour potential and depth around structures. They also affect the decision to backfill an embedded structure such as a box culvert or allow it to fill naturally. Embedding a structure without backfilling it to streambed elevation creates a steep drop, causing the upstream streambed to erode (headcut) until the hole fills and the slope equilibrates. The effect of this erosion on the upstream channel depends in part on how much sediment is available and how mobile it is. If the streambed is mobile, the structure will probably fill rapidly under moderate flows and the stream may not be noticeably affected. If bed material is immobile (i.e., does not move until fairly large flows) little sediment will be available immediately. The structure should probably be filled during construction to avoid destabilizing the upstream bed. If it is not filled, a headcut may move upstream, lowering the streambed elevation. The degradation may detrimentally affect bank stability, habitats, buried infrastructure, etc.

Another item to assess is the quantity and size of debris moving through the system. Some small sediment and debris will move through almost any type of structure. If the channel has a lot of mobile sediment and debris, small vents that backwater high flows will tend to plug. Large woody debris can block even large vents. Because they have an open cross section, simple unvented fords are ideal for crossing drainages carrying a lot of debris.

Vented fords and low-water bridges have problems with debris plugging, but are designed to sustain plugging without failing and can still pass additional debris over the top. Trapped debris does require periodic cleaning.

4.2.2 Crossing Location

The ideal crossing location is straight, stable, moderately broad, and moderately entrenched. When channel bed and banks are stable and have firm structural materials, road crossings are least likely to encounter difficulties with changes in channel form, such as widening or incising. Ideal locations include bedrock-controlled channels and those with a rocky bed and banks. Compared to slightly entrenched channels, moderately entrenched channels are also less likely to overflow, outflank the structure, and cause road damage (see section 2.2).

Poor locations for fords include channels with structurally soft bed or banks such as are often found in wide alluvial (meadow) valleys, meander bends, unstable, unconfined reaches or braided channels, and settings with rapid slope change, such as from a mountain to a valley stream where deposition occurs. Alluvial fans are particularly poor locations because they can be very unstable.

Study these sites in detail to ensure the structure and road geometry fit the channel. Protect the channel against local scour and properly key the structure in place. Placing a structure in a poor location usually leads to relatively expensive designs with higher protection and maintenance costs. Simple unimproved fords may be most practical in poor locations because they require minimum investment if the crossing is destroyed in a flood.

A history of structure or channel problems at a site suggests the need to relocate the crossing. Regardless of aquatic resource, structure, and channel impacts, however, features such as other existing infrastructure, archeological sites, rights-of-way, or high moving costs may dictate the crossing remain in its current location. In these situations, maintenance and repair costs, as well as environmental impacts, are likely to remain high.

4.3 Fish and Aquatic Organism Passage

Why do aquatic organisms need to be able to move freely through road crossings?

Even where animals do not "migrate," they still need to move to find food, mates, better water quality, or simply to disperse. Local habitat characteristics change over time as weather and flow vary, and aquatic animals move at various times to escape poor conditions or seek better ones. Even ephemeral and intermittent streams often support fish and other aquatic species for part of the year. For example, during snowmelt runoff, side channels and intermittent tributaries may provide refuge from high, turbulent flow in the mainstream river. Headwater streams not supporting fish may provide excellent amphibian habitat, and the juvenile lifestages of many amphibians are completely aquatic (Jackson 2003). Even adult lifestages of some species may be unable to move over a dry surface. Due to the many different species potentially involved and their different movement needs, a biologist should determine the need for passage at any specific site.

Where passage for all aquatic organisms is desired, streambed continuity through the crossing should be maintained. Although stream simulation is a crossing design technique usually applied to culverts, it can also be applied to bridges and some crossings designed to sustain overtopping. Stream simulation structures are large enough to enable the channel to maintain characteristics like width, depth, slope, and streambed roughness through the crossing. Areas of diverse water velocity and depth are therefore available through the structure just as they are in the natural channel. The structure is at least as wide as the natural bankfull cross section so that it neither widens nor constricts flow, and it provides margins for crawling species most of the year. Fish passage is accommodated at low flows and at most flow levels. Aquatic organisms should be able to pass during their normal migration periods. In most cases, stream simulation culverts or bridges are also large enough to pass most materials moving downstream even during floods. Nevertheless, in streams with heavy debris, ice, or bed material loads that might plug the structure, they can be designed to overtop (fig. 4.3).

One low-water crossing style that is used increasingly where aquatic species and habitat protection are important is a series of embedded box culverts that look and perform like a bridge. Crossings described in case studies 17, 18, 19, 20, and 21 appear to provide full passage for most swimming species, if not all aquatic species. The structures are either low-water bridges or embedded box culverts with continuous streambed material through the structure. Some pass the 25-year flood under the deck; others are submerged by bankfull flow. The one characteristic these structures have in common is that they match—or nearly match—channel width. We do not know how stable the streambeds are inside these structures during large floods. If they do wash out, however, they refill with sediment as flow recedes or during later more moderate flows.

Unvented at-grade fords can also be designed for passage of many aquatic species by keeping streambed materials nearly continuous across the driving surface. The ford at Fitzpatrick Creek on the Coos Bay BLM district uses cable concrete mats at a site where debris jams had washed out very large culverts and their fills several times (case study 6). The mats enable streambed material deposition between the blocks, and appear to have sufficient surface roughness so flow velocities remain low enough for juvenile salmon passage at low flows. The availability of full passage for all aquatic organisms is unknown. In some situations, an at-grade ford with a simple rock and gravel driving surface can also provide adequate fish passage (case study 2). Similarly, geocell structures infilled with aggregate, such as those on the Bighorn, Ashley, and Humboldt-Toiyabe National Forests, provide some degree of fish passage (case study 7). When animals and traffic are present at the same time, however, the tradeoffs at an unvented ford call for serious consideration, because some animal mortality is likely. To minimize the impacts to the fish, additional limitations on road use might be considered during spawning periods.

Designers have used some creative techniques to achieve fish passage over concrete floors or slabs (case study 14). Key hydraulic design considerations for passage of any swimming species are water depth, velocity, resting areas, and drops or plunges. The combination of surface roughness and slope is important for maintaining swimmable depths and velocities. For example, an unembedded box culvert on the Eldorado

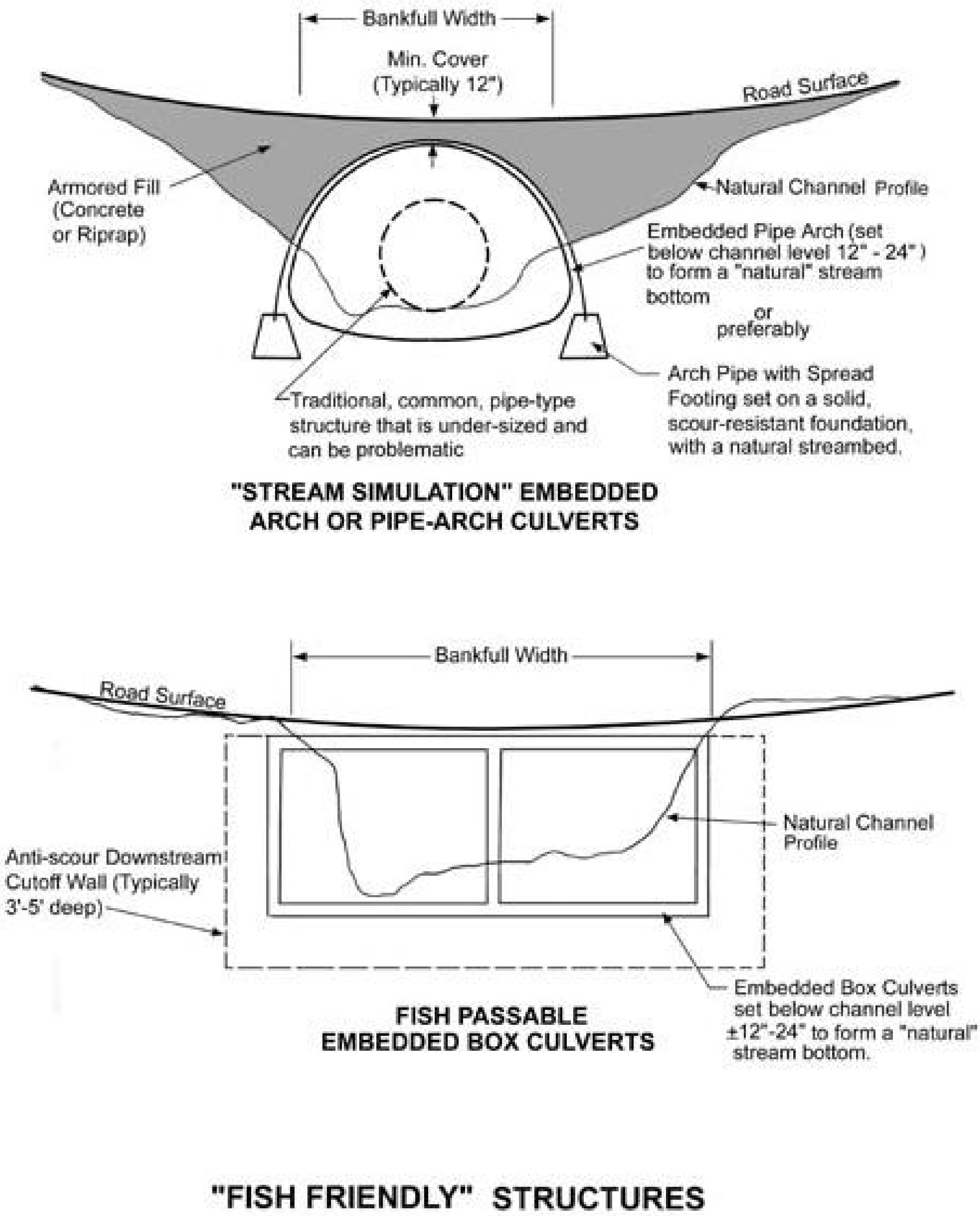


Figure 4.3—Low-water crossings that provide passage for fish and other aquatic species. The embedded culverts would have a layer of streambed material at least 1- to 2-foot thick covering the culvert floor.

National Forest (case study 13) fails to pass small fish because the concrete box floor, set to match channel slope, is so smooth even extreme low flows are a velocity barrier.

Concrete fords with slots can provide fish passage and keep vehicles out of the water during low flows. The slot design is important for ensuring that velocities and depths are appropriate at low flows, and that the slot does not plug. The Mesman ford (case study 9) works for the following reasons:

- The slot is designed to meet the velocity and depth criteria for trout at normal low flows.
- Gravels in transport are small compared to the 4-inch-wide slot, so plugging is not an issue.
- Riprap placed immediately upstream of the inlet creates an additional protection against small debris plugging.

In contrast, the Grubbs vented ford (case study 12) has a 3-foot-wide slot designed for fish passage. The slot regularly fills with the very mobile boulder-sized rock this channel transports. Fortunately some fish movement has been observed over the structure. Fords constructed of concrete planks, with a 6-inch space between the planks (case study 5), also provide some degree of animal passage when the structure is submerged.

Generally, the closer the structure can imitate and blend in with the adjacent natural stream channel, the better the aquatic species passage.

FishXing is a program that helps designers deal with fish passage issues. A team headed by Michael Furniss, principally funded by USDA Forest Service and U.S. Department of Transportation, Federal Highway Administration, developed FishXing, which is available at http://www.stream.fs.fed.us/fishxing/index.html. FishXing is a hydraulic model that calculates water velocity and depth in a culvert, and then compares them with the swimming capabilities of specific fish species. The model can reveal at what flows fish cannot pass the culvert and what the obstruction is. To find velocity and depth criteria for the target fish and lifestage, review the FishXing help files, or other sources such as Beamish (1978).

FishXing is not designed for slab fords. For slabs, designers can use HEC-RAS, or simply Manning's equation to determine velocity and depth over the ford (see Section 4.6 Hydraulic Design).

4.4 Roadway and Site Geometry

Roadway geometry must be adequate for safe passage of the design vehicle. Moreover the road profile should conform to the shape of the natural channel as much as possible. To minimize damming of the channel, any elevated structure should maintain as high a VAR as possible. Low-water crossing structures are designed with a vertical sag, or dip, in the middle of the structure to concentrate overtopping flow to the midchannel, and minimize flow against channel banks. To pass the design vehicle, which may be a log truck, lowboy, or trailer, the vertical curve across the top of the crossing must be broad enough and have a gentle transition to avoid scraping the bumper, trailer hitch, or stinger of the passing vehicle. It may be necessary to control the opening size (box height) of vented fords to help establish the shape and depth of the dip in the roadway surface. Doing so will obviously affect the vent capacity.

4.4.1 Channel Geometry

Ideally, a ford is located on a straight, stable reach of the channel, with the structure crossing perpendicular to the channel to minimize the structure length and maximize sight distance. Angled road approaches may be necessary to fit the terrain or reduce the road grade; however, the design will likely be more difficult, have more site disturbance, cost more, or require additional mitigation measures. Poor alignment may cause or aggravate problems with channel stability. Placing structures with multiple openings on bends should be avoided because the stream usually chooses one opening to carry most flow and the other openings fill with sediment (case study 19). If the structure crosses the channel at an angle that focuses stream energy into the bank, bank erosion and decreased lateral stability will occur. The structure itself, particularly the vents, should be centered on the channel and oriented parallel to the direction of the average bankfull flow.

In slightly entrenched broad shallow channels, fords are often easy to construct, conforming to the natural channel shape. In entrenched deep channels, the dip may be radical with a tight vertical curve, consequently restricting some vehicle passage. Because a raised platform would partially dam the channel, consider a vented ford with a raised roadway platform to accommodate the design vehicle. (Review fig. 2.1 for definition of entrenchment.)

Some sites, like moderately entrenched channels with locally steep banks, require changes to the channel shape to accommodate a ford. Flattening a streambank requires bank excavation, subsequent channel widening, and possibly mitigation measures for bank stabilization. The widened point decreases flow velocity and increases the possibility of local channel aggradation (case study 7). Road maintenance will probably be necessary after major flows to remove the deposited material.

4.4.2 Roadway Design Geometry

The road width of a ford is typically as wide as the normal roadway width, usually 10 to 12 feet wide at a minimum. On elevated structures, AASHTO *Guidelines for Geometric Design of Very Low-Volume Local Roads* (2001) recommend at least 15 feet for safety reasons. Ideally, the roadway surface should have an outslope of 3 to 5 percent to promote drainage and debris passage during overtopping. If the roadway curves across the drainage, the horizontal curve radius should be a 50-foot minimum to accommodate the turning ability of most vehicles and logging trucks, or a 35-foot minimum for light vehicles. Curved crossings, however, are discouraged due to poor sight distance and safety concerns, particularly in situations where the roadway platform is elevated such as vented fords and low-water bridges.

The design vehicle limits the vertical curve (dip) geometry. Dip geometry is a function of grade into and out of the ford, the vertical-curve length, the depth of the dip, and the wheelbase distance. The most severe limitations often come from chip vans, low boys, trailers, or long recreation vehicles. The AASHTO *Policy on Geometric Design of Highways and Streets* (2001), Chapter 5, and the USDA *Forest Service Handbook (FSH) Preconstruction Handbook, Section 4.3 Alignment* (FSH 7709.56) offer specific guidance for both vertical and horizontal curve design. Where practical, 10 percent is the recommended maximum approach grade. Grades into and out of fords have been in the 15- to 20-percent range (see case study 6, where moderate earthwork was needed), but steep grades require additional stabilization on the approach road to avoid excessive sediment delivery to the creek.

4.5 Site Hydrology

Streamflows are used for several purposes in low-water crossing design. The high design flow determines the maximum expected high water level and the length of roadway that will require surface armoring for scour protection. The high design flow velocity helps determine the necessary type of scour protection and riprap size. Duration and volume of low flows, or **normal flows**, help determine whether a ford is suitable at the site. For vented fords, low flows are also used to determine vent capacity.

Figure 4.4 shows flood hydrographs that illustrate the response of two hypothetical watersheds to the same rainstorm. In the flashy watershed, streamflow rises and drops rapidly and the traffic delay is brief. Such brief, sharp flow peaks are associated with small watersheds and areas with frequent bedrock outcrops, shallow soils, little vegetative cover, or urbanization. Desert areas receiving brief but intense thunderstorms often exhibit this “flashy” type of runoff. If we consider only hydrology, the flashy watershed would be more suitable for an unvented ford. The second watershed has deep soils and forest cover and most rainfall infiltrates the soil. In this watershed, the flow takes longer to peak, peaks at a lower flow rate, and is sustained over a longer period of time. Traffic delays on this stream, if they occur, would be longer. Thus this site may be less suitable for a ford.

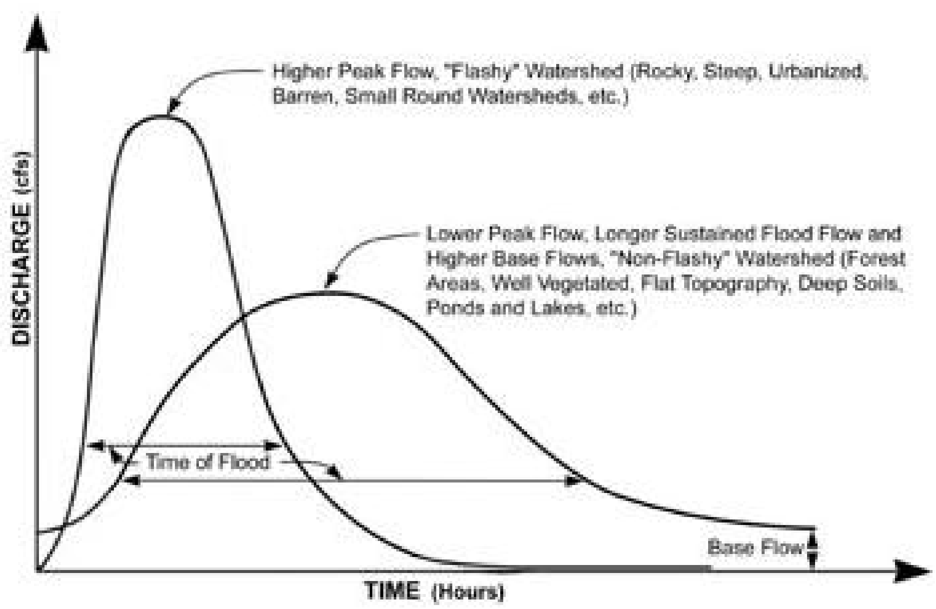


Figure 4.4—Hypothetical flood hydrographs for flashy and nonflashy watersheds.

In low-risk situations, designs are often based on local information, such as rough estimates or field observations of annual flow levels, bankfull flow estimates, high water marks, and estimated traffic delays. Nevertheless, such minimal amounts of information, which may come from too short an observation period, are inadequate for most designs and can lead to failures.

Two quantitative approaches should be considered in the hydrologic design of fords. The first approach involves using flow-duration data to estimate the typical annual delay time at a ford and the needed capacity of vents. The second approach involves using (a) flood-frequency data to estimate peak flow values for design of total structure capacity, and (b) local knowledge of low-flow characteristics to determine the type of ford, vent size, and estimate delay times. Because interpretation of flow-duration curves or flood-frequency data can be complicated, we recommend professional help from a hydrologist familiar with the area or watershed.

The more rigorous low-water crossing design approach uses a flow-duration curve developed from daily streamflow data for the specific drainage being crossed. A flow-duration curve based on annual data gives an estimated percentage of time (number of days in the year) that a certain flow will be exceeded. Crossings can be designed so traffic delays occur no more than an acceptable number of days per year. These curves are useful where the total delay time due to structure inundation is important, such as on rural roads accessing communities, homes, or significant public routes. Gu (2003) addresses this design methodology in detail in the recent FHWA publication on Low-Water Crossings.

Figure 4.5 shows a typical annual flow-duration, or exceedence curve. The curve is useful for estimating the time a ford may be impassable and for determining the size or capacity of vents in a ford. Although this data describes the percent of days in a year the road may be impassable, it cannot specify when, how many hours, or how many times per year the delays will occur. Local observations of flow characteristics can help estimate frequency and length of delays.

As discussed in section 4.3 dealing with fish passage, the ideal way to determine the vent width is to match the channel bankfull width. However, vents also can be sized based on hydraulic capacity. In this method, the vent is designed so that fish can swim the length of the culvert at the “fish passage flow.” The fish passage flow is a flow or range of flows that occur when the “design fish” is naturally moving in the channel. It varies for different species, lifestages, and areas, and many States have required standards. When stream simulation is achieved through the structure, specific flows or velocities are not an issue because a natural diversity of conditions exists.

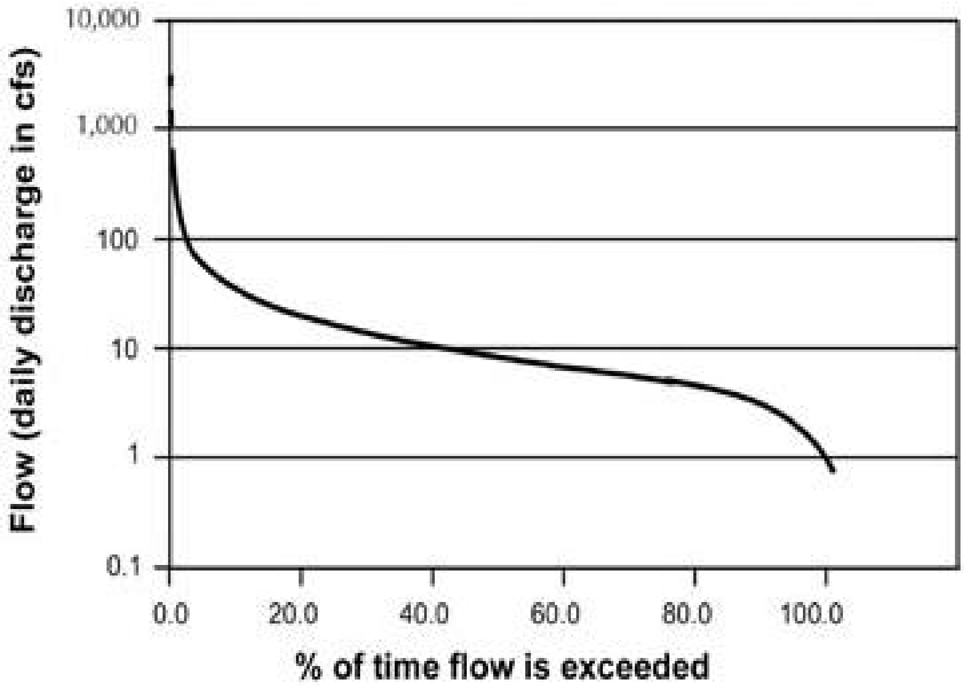


Figure 4.5—Typical flow-duration curve.

The simplest, most common approach for designing fords, particularly in the USDA Forest Service, involves using flood-frequency analysis. In this approach, we estimate the peak flow likely to occur or be exceeded every 'x' years on average (the recurrence interval for that flow). This method identifies the probability of exceeding different peak flow levels, but does not estimate the timeframe the road may be closed during inundation. Crossings are usually designed so that the armored cross section contains the 50- or 100-year flow.

Use an appropriate *high frequency* flood, such as a ½ - or 2-year event, to determine vent capacity. A ½ year event ($Q_{½}$) is a peak flow occurring (on average) twice per year and a 2-year event (Q_2) occurs on average once every 2 years. The objective would be to keep most traffic out of the water.

The USDA Forest Service most commonly uses the flood-frequency approach in arid areas where high flows are infrequent and of short duration, on roads closed during periods of peak runoff (seasonal road closure), or on roads where infrequent traffic delays do not create problems for users. This approach is very practical because it is possible to estimate peak flows on many small drainages, but reliable flow-duration data will not be available.

A variety of methods exist to estimate design flows for either whole-structure capacity or vent capacity. Use more than one method to estimate flows because errors (which can be significant) are inherent in each method. Supplement these methods with information from road maintenance records, old flood photos, field observations, interviews with knowledgeable local residents, and professional judgment.

Excellent summaries of hydrologic design tools for fords and road drainage structures are available in *Highway Hydrology, FHWA Hydraulic Design Series No. 2* (McKuen et al. 2002), and the AASHTO *Highway Drainage Guidelines* (1999). Common flow estimation methods include the following:

- U.S. Geologic Survey Regression Equations can be found in the National Flood Frequency Program available on the USGS Web site. These equations are based on statistical analysis of existing gauging data and use watershed area, as well as other variables, such as annual precipitation, mean elevation, or watershed latitude. Some areas also have regression equations for bankfull, mean annual, or 7-day low flows for various recurrence intervals. Background information about development and application of the equations, including the users' manual, is in Ries and Crouse (2002).
- Computer programs can help determine specific design flows from published rainfall data. Some commonly used programs are: FHWA's HYDRAIN, the USDA's Natural Resources Conservation Service TR-20 (now WinTR-20), and the U.S. Army Corps of Engineer's HEC-1. Reminder: a 50-year rainfall does not necessarily produce a 50-year flow.
- For small watersheds (under about 300 acres), use simple methods such as the Rational Method, for determining peak flows. The runoff coefficient in this method can be modified to reflect changes in watershed characteristics occurring over time.
- The slope-area method estimates flow volumes (Q) at any given flow level for which there are high water marks (bankfull, flood flows, etc.) and field observations of channel cross section characteristics and geometry. Determine average flow velocity (V) using Manning's or other equations, then multiply it by cross-section area to calculate flow volume. For this analysis, use a cross section in a straight, uniform reach outside the crossing's area of influence.

Numerous hydrology and hydraulics texts and manuals, such as HDS 4 (Schall et al. 2001), explain how to use the Rational Method and

Manning's Equation. The program WinXSPRO allows calculation of velocity using Manning's or other equations for simple or complex cross sections (Hardy et al. 2005). It is available at the USDA Forest Service Stream Systems Technology Center Web site.

Leopold (1994) gives some values to use when making an initial estimate of high water level for 50-year events in various parts of the United States. Very roughly, the data he used showed that the flow depth in a 50-year flood is between 1.4 and 2 times bankfull depth. It is often possible to estimate recent high water levels from field observations of flood-eroded banks, sediment deposits over soils, flood plain swales, and floating debris deposited on the banks and in vegetation.

Understanding design flow depth and volume helps ensure protection of the full wetted perimeter of the ford against the high flow. Add at least 2 feet of additional freeboard to guarantee that high water does not scour around the structure. In broad flood plain areas, armor the ford up to a level where water spreads out across the flood plain. Armor the roadway surface across the entire flood plain area and install cross-drainage.

Because low-water fords are designed to be overtopped, they can usually accommodate very large flows over the structure—plus large amounts of debris—so they are forgiving rather than sensitive to imprecise flow calculations. The "vented" portion of a vented ford has a finite capacity, as do typical culvert installations. Once the structure is overtopped, however, all additional water and debris can flow over the top of the structure.
In areas with large flow fluctuations, where the difference between low flow and peak flow is extreme, designing a culvert or bridge capable of handling extreme flows can be either expensive or difficult. Low-water crossings can handle these situations and are especially appropriate in desert environments and ephemeral channels.

4.6 Hydraulic Design

For hydraulic design of a low-water crossing, two or three different calculations are usually necessary to determine the water velocity (V) and flow capacity (Q) of the channel, the entire ford, or through the vents.

Use Manning's Equation to determine flow capacity through simple unvented fords, as well as flow capacity through low-water bridges where most of the natural channel cross section is open. Use the broad-crested weir formula to determine flow over a raised ford. Select appropriate nomograms and programs from various Federal Highway Administration publications (figs. 4.7 and 4.8) to determine the capacity of pipes or vents, as well as velocities through the structures. Figure 4.6 shows some typical low-water crossing types and hydraulic flow analysis methods most appropriate for those structures. Information about scour potential and scour protection measures is found in Section 4.7.

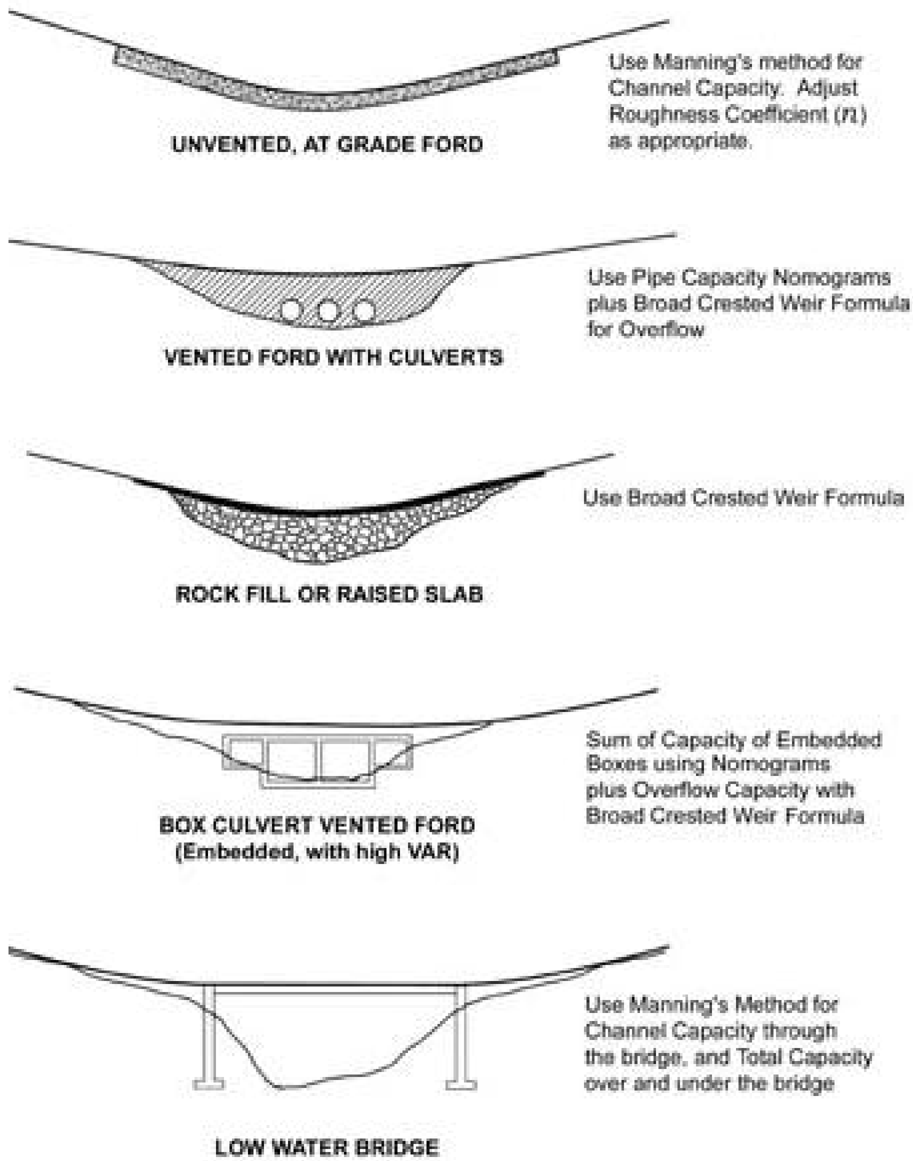


Figure 4.6—Low-water crossing types and applicable flow analysis methods.

When designing a vented ford, select a vent size that not only has adequate capacity, but also minimizes velocity accelerations and maximizes the VAR. In other words, base structure size on channel dimensions rather than exclusively on flow capacity. To best maintain channel function, minimize channel changes, and prevent their associated problems, the opening width should be equal to or larger than the bankfull width (fig. 4.3). This typically results in a very large vent flow capacity.

Flow Capacity

As mentioned previously, Manning's Equation is a very useful tool for determining flow capacity of a natural stream channel or an unimproved ford. In entrenched channels, use Manning's Equation after obtaining an accurate cross section of the channel and determining the channel slope and roughness characteristics.

In unentrenched channels where part of the flow is across a flood plain, the channel cross section is typically broken into two or more segments to reflect the faster velocities and greater capacity in the main channel and the slower velocities found in the shallower flows (see WinXSPRO program, Hardy et al. 2005). In this case, use Manning's Equation on each separate part of the channel and add the results to get the total flow. On complicated channels or structures, use programs like the U.S. Army Corps of Engineers HEC-RAS models (USACE 1991) to route water through a varying or complicated reach of the stream. Be aware, however, this program requires extensive field data to produce good results.

Use the broad-crested weir formula to determine the flow capacity over simple unvented fords with a raised roadway driving surface, along with the depth of flow over the raised platform. Use the same formula to estimate the additional flow capacity over vented fords (beyond what goes through the vents). Gu (2003) presents examples of the use of the broad-crested weir formula. Using these formulas requires an iterative process to determine the depth of flow for a given discharge. In these examples, Gu assumes that, for traffic safety, the maximum allowable depth of flow over a weir is 6 inches. The equations in Gu's examples reflect his design assumptions.

The broad-crested weir formula has limited application on some USDA Forest Service structures because raising the platform of an unvented ford any significant height is generally undesirable. Raising the platform creates both a damming effect and a downstream waterfall, each adversely affecting channel function.

To determine flow capacity through ford vents for round culverts and small box structures in inlet control, use simple design curves for culvert pipe size versus design flow for various entrance conditions (Gu 2003). Alternatively, by using the families of nomograms available in the FHWA publication HDS 5, *Hydraulic Design of Highway Culverts* (Normann, 1985) and the FHWA program HY8 (part of HYDRAIN), flow capacity can be determined for a wide variety of culvert types (round pipes, arches, concrete boxes, etc.) for both inlet control and outlet control conditions, as a function of size, entrance type, and headwater depth. The American Iron and Steel Institute's *Handbook of Steel Drainage and Highway Construction Products* (Fifth Edition 1994) also contains considerable useful information on steel culvert design and installation.

Figures 4.7 and 4.8 present the two HDS-5 nomograms most commonly used to determine capacity versus size for round corrugated metal pipe and concrete box culverts, with various inlet types and for varying headwater depth. These nomograms should be used for inlet control conditions, the condition most often encountered for upland pipe installations. These

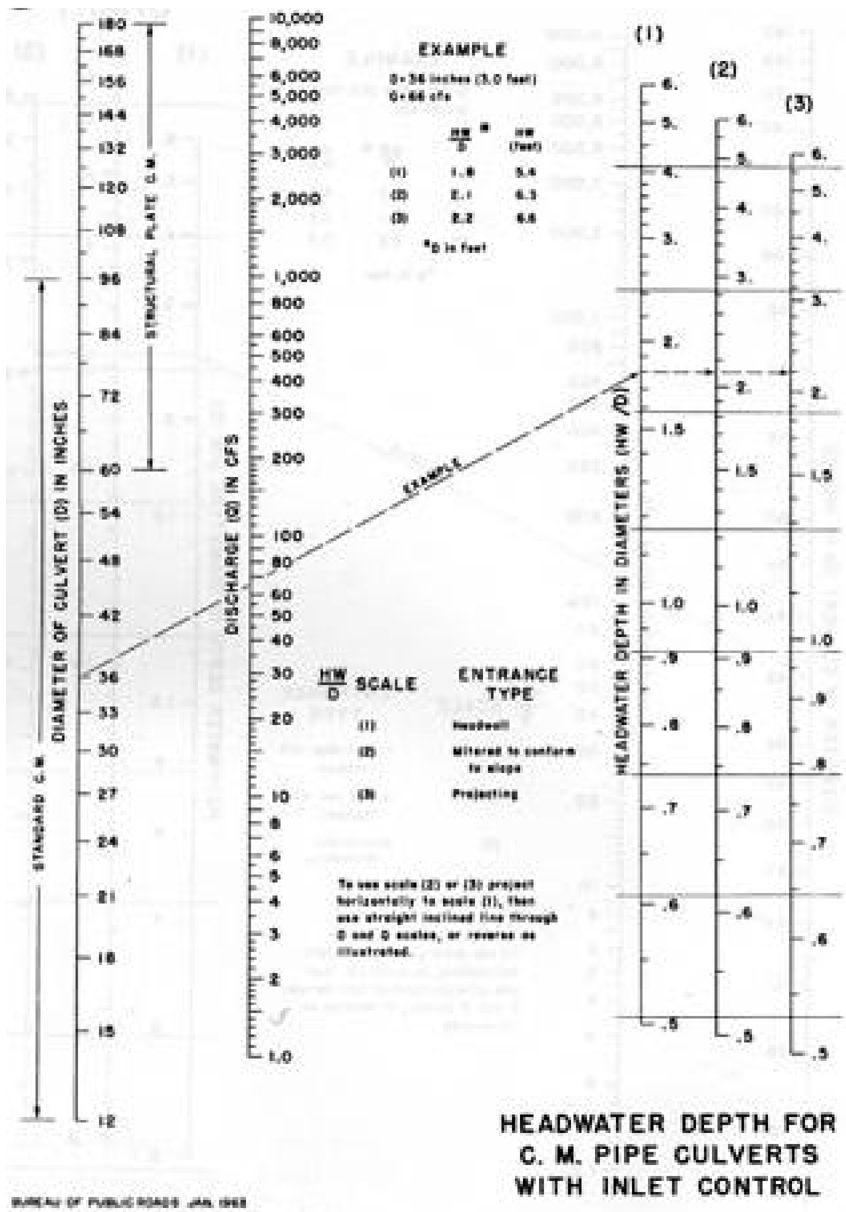


Figure 4.7—Corrugated metal pipe capacity nomograph. (Normann, 1985)

nomograms are strictly for fluid capacity. They are not valid for partially embedded pipes (which have a natural stream bottom for fish passage), nor do they reflect the size needed to pass sediment or debris. Therefore, use local experience and knowledge of the characteristics of the watershed and channel to estimate additional pipe capacity needed for sediment and debris passage

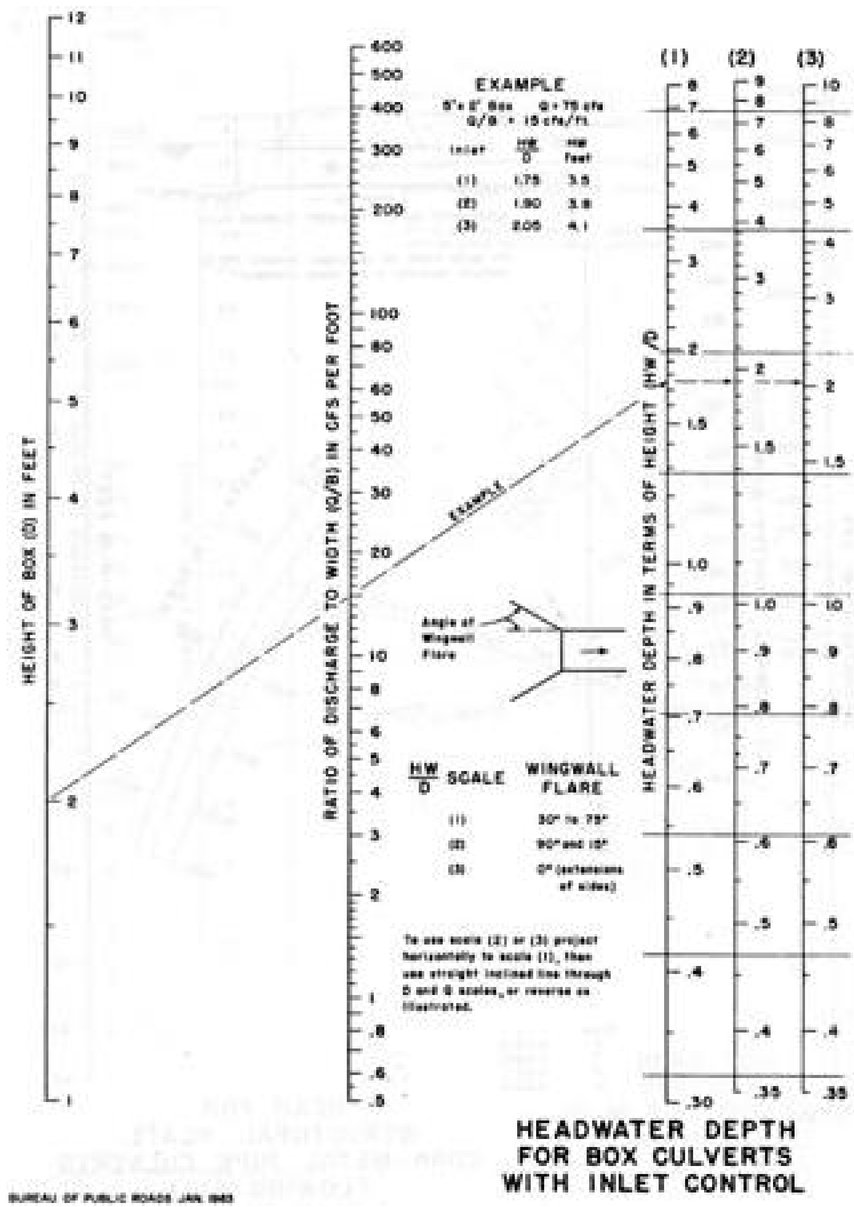


Figure 4.8—Concrete box culverts capacity nomograph. (Normann, 1985)

As mentioned in section 4.5, one of the great advantages of fords is their adaptability in conditions where good design flow predictions or local data do not exist, and where there are large amounts of sediment, debris, or trash in the channel. Such conditions make determining culvert capacity either very difficult or unrealistic. Although no rational design criteria for debris passage exists, fords are generally able to pass a large flow with a small increase in flow depth over the ford. They can also pass large quantities of debris with minimal damage. Therefore, fords are excellent candidates for sites with these uncertain conditions.

If the channel has significant debris, the vents may periodically plug. Therefore, design to accommodate the entire flow over the structure. Alternatively, increase the size of the vents or use trash racks. If using trash racks, incorporate them into the structure itself at a sloping vent entrance to minimize pipe plugging. The Sibley Creek crossing on the Mount Baker-Snoqualmie National Forest uses a trash rack in this way (case study 16). Trash racks will require periodic cleaning and maintenance.

If an existing culvert is undersized for the anticipated flows, one alternative is to modify it to act like a vented ford by armoring a dip and the fill over the pipe. Although this type of modified structure may not be as effective as a designed ford, it can minimize or prevent site damage or failure from flows overtopping an undersized or plugged pipe.

Flow Velocity

In low-water crossing design, it is necessary to estimate average or local velocities for the following reasons:

- To determine the scour potential and scour depth in parts of the channel.
- To determine the size of bed material that will move in the channel.
- To select vegetation, biotechnical measures, riprap, or other armoring adequate in preventing bank erosion.
- To size rock riprap properly.
- To determine fish passage limitations or needs.

Bed-material movement is directly related to the shear stress of water flowing against the channel substrate. Some professionals use water velocity in place of shear stress, because velocity is generally an easier parameter to estimate. Nevertheless, local velocities around midchannel piers or obstructions, over waterfalls, cascading over rock-armored slopes, etc., are actually hard to determine, so scour protection measures often rely on model studies or empirical observations.

In natural channels, local flow velocities are highest midchannel and near the surface, and slowest along the banks. However, the average velocity—

averaged across the entire cross section of flow—is used for most design purposes. Manning's Equation is most useful for determining average flow velocities in natural or constructed open channels, including embedded or open-bottom culverts where the inlet is not submerged. Velocities can be adjusted across smooth or roughened channel surfaces by modifying the "roughness coefficient" in Manning's Equation. Programs that calculate streamflow velocities include the U.S. Army Corps of Engineers HEC-RAS, and WinXSPRO, which is available on the USDA Forest Service Stream Systems Technology Center Web site.

Velocities accelerate when flow is confined and forced through a smaller area, such as in a channel constriction. Figure 4.9 shows the pattern of exit flow and velocities from small, constricting pipes as opposed to larger pipes. Traditional small culverts that constrict the channel and accelerate flow velocities can cause bank, fill, and channel scour, both at the pipe inlet and outlet. The higher velocity may also impede or prevent fish passage.

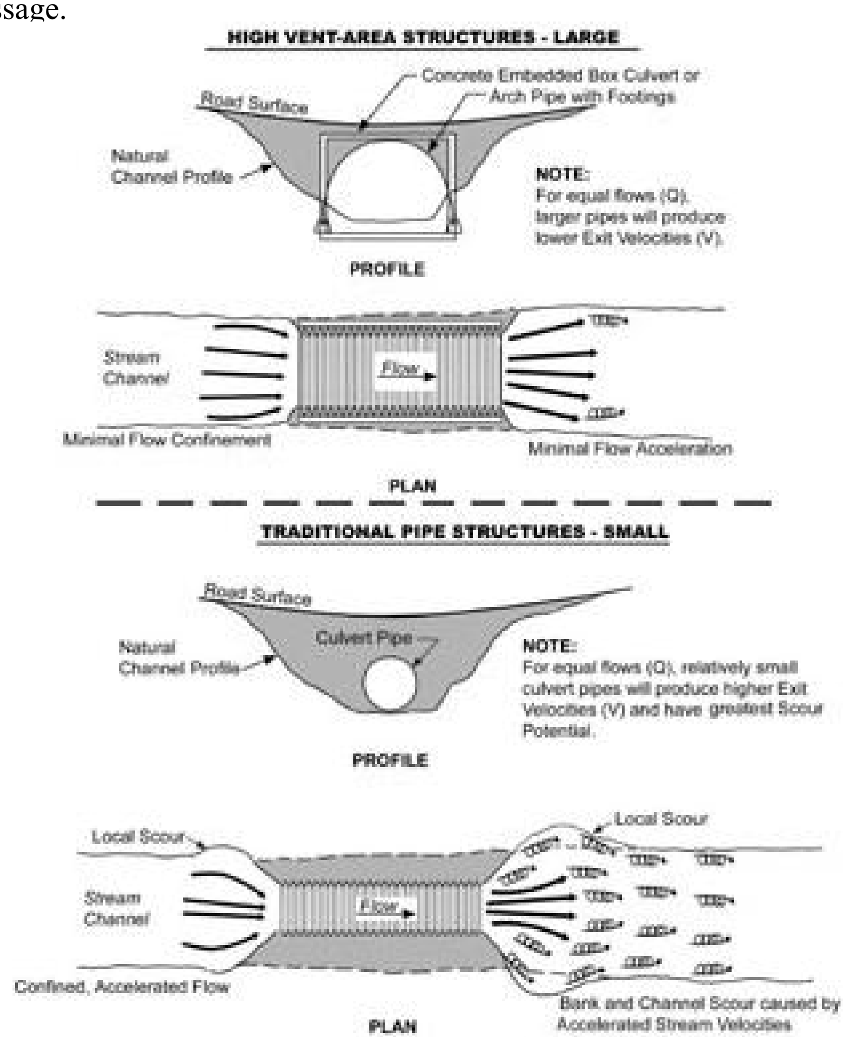


Figure 4.9—Outlet flow patterns and local scour from culverts of different widths.

When determining exit velocities for pipes or vents, use programs like HY-8, the design charts in the FHWA manual HDS 3 (*Design Charts for Open Channel Flow*) (1961), or simply divide flow volume (cubic feet per second) by the flowing pipe area. For an outlet-controlled pipe flowing full, use the area for that pipe diameter. To determine the area of flow for an inlet-controlled pipe where the pipe is flowing only partially full, find the critical or normal exit flow depth and use it to calculate flow area. To determine critical flow depth, use charts in HDS3 or use a trial-and-error solution of Manning's Equation.

Pipe exit velocities are often quite high, requiring significant scour protection or energy dissipation, and creating a fish passage barrier. Designing to minimize channel confinement, prevent head buildup over pipes, and maintain flow across roughened or rocky surfaces helps reduce flow velocity. If a ford is built to simulate natural stream conditions (such as matching bankfull width), problems with both channel stability and fish passage will be minimized. Fish passage issues are discussed earlier in sections 3.2 and 4.3. Again, FishXing is a very useful program to evaluate fish passage potential for anticipated flow velocities.

4.7 Scour, Bank Protection, and Preventing Channel Changes

If local or average velocities exceed the permissible velocities of the materials for movement, erosion and scour will result. Therefore, either take measures to reduce the velocities, redirect the flow, dissipate the energy of the flow, provide stability below the likely depth of scour, or armor the areas with various materials that can resist the forces of the flow.

Scour protection and maintaining channel stability—fundamental parts of hydraulic structure design—are particularly important in low-water crossings. Design the crossings to withstand overtopping. Protect or armor the structure to the "wetted perimeter" or the maximum expected high water level, incorporating some additional height for freeboard. In a small drainage, a foot of freeboard may be adequate. In large drainages or steep canyons an additional 2 to 4 feet of freeboard is desirable. Different types of fords create different scour risks; for example some accelerate flows through pipes or vents, some confine channel flow, some accelerate flow across the driving surface, and some create a water drop off the downstream edge. These areas commonly need protection.

Depending on the velocity of flow, erosion, scour protection, and bank stabilization come in many of the following forms:

- Vegetation, erosion control mats, or small riprap for low velocities.
- Soft-armor systems, such as biotechnical treatments, vegetated turf reinforcing mats, rootwads, logs, and boulders, for moderate velocities.
- Hard-armor systems, such as articulated concrete blocks, gabions, large riprap, grouted riprap, or concrete for high channel velocities or high shear-stress areas, where flows are turbulent or impinging upon the streambank.

Figure 4.10 (adapted from Thiesen, 1997) provides general guidelines for selecting channel and bank stabilization measures as a function of mean channel velocity. Choose among vegetation and soft- or hard-armoring systems, based upon both velocity and the duration of flow (i.e., how long the area is subject to inundation). McCullah and Gray (2005) present an excellent summary of the many channel and bank stabilization options available today in the National Cooperative Highway Research Program Synthesis 544—Environmentally Sensitive Channel and Bank Protection Measures.

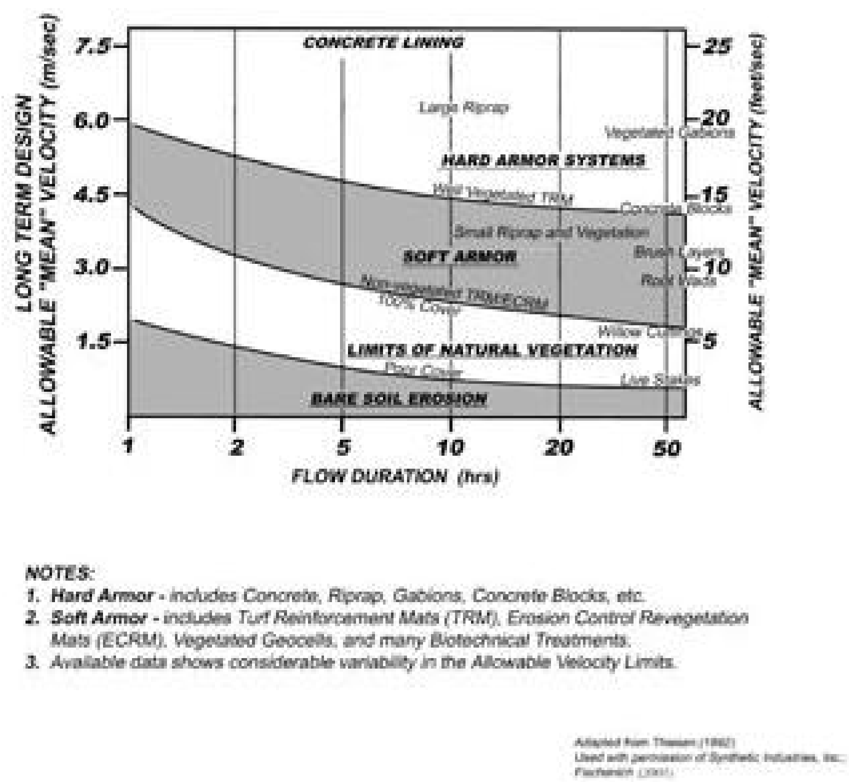


Figure 4.10—Allowable velocities and flow duration for various erosion and bank protection measures.

Use criteria developed by the U.S. Army Corps of Engineers (USACE 1991a) to estimate maximum permissible mean channel velocities acceptable for various natural or imported channel materials (see table 4.2). When flows impinging on these materials exceed the permissible velocity, the materials may move, requiring that the structure have additional protection measures against local scour (see section 4.7.2).

Table 4.2—Suggested maximum permissible mean channel velocities (Adapted from USACE 1991a).

Channel Material	Permissible Mean Channel Velocity (ft/s)
Fine sand	1.5
Silt loam	2.0
Coarse sand	2.0
Fine gravel	2.5
Coarse gravel	3.0
Cobbles and gravel (to 3 in.)	4.0
Earth	
Silty sand	2.0
Silty clay	3.5
Clay	4.0
Cobbles and small rock (to 6 in.)	7.0
Small boulders (to 10 in.)	10.0
Medium boulders (to 25 in.)	15.0
Large boulders (to 50 in.)	20.0
Grass lined earth channel (slopes< 5%) (for 5-10%, reduce velocity by 1 ft/s, for >10%, reduce velocity by 2 ft/s)	
Bermuda grass	
Sandy silt	6.0
Silt clay	8.0
Kentucky blue grass	
Sandy silt	5.0
Silt clay	7.0
Poor in-place rock—usually sedimentary	10.0
Soft sandstone bedrock	8.0
Volcanic ash	3.0
Soft shale	3.5
Good rock (usually igneous or hard metamorphic bedrock)	20.0+

4.7.1 Scour

Because scour, local erosion, or structure undermining are such common problems with hydraulic structures, the best approach for scour protection is to locate a structure in hard, durable, and scour-resistant material such as a bedrock channel, coarse rocky material, or dense, well-cemented soils. At the many sites where such locations are not available, the alternatives are either (a) to place structural foundations, cutoff walls, or scour prevention keys to a depth greater than the expected scour depth, or (b) to armor a surface area against scour. Alternatively, it is possible to construct simple, inexpensive, expendable fords that will need repairing or replacing after major events.

Where alluvial deposits are loose and fine-grained (e.g., silts and sands), scour protection is most critical, and scour depth can be significant (10 to 50 feet). In gravelly and cobbly channels, scour depth may be in the range of 2 to 10 feet. Scour depth in coarse, rocky, and boulder-lined channels is typically a few feet. Scour depth will depend on a number of complex variables, including bed material, channel conditions, type and location of channel obstruction, and depth of flow.

Conditions that produce relatively high scour include the following:

- Midchannel structures (e.g., piles, piers) causing local water turbulence.
- Blunt obstacles or protrusions in the channel (smooth or pointed features cause less scour).
- Flow depths substantially greater than the size of streambed material.
- Relatively fast local flow velocities.
- Flow acceleration against the banks on the outside of bends.
- Fine uncemented soil deposits, such as fine sands and silts.

Key areas needing scour protection are as follows:

- Along banks, on the outside of a river bend, where flows are directed against the streambank.
- Along the downstream edge of the structure, where water dropping off a structure produces a waterfall with high erosive energy.

- Around or beneath midchannel piers, posts, or box walls that create turbulence or accelerate flows.
- Along the edges and beneath abutments and footings, where locally accelerated flows and scour are normally expected.
- Around the approaches to structures (outflanking), where high water level exceeds the elevation of armoring or road surface reinforcement.

Figure 4.11 illustrates common areas in channels where natural or structure-related scour can be a problem. In a computer program called CAESAR (Cataloging and Expert Evaluation of Scour Risk and River Stability at Bridge Sites), the University of Washington developed a qualitative method for evaluating the risk of scour. This program is a useful tool for assessing both scour potential and the subsequent need for more detailed investigation of scour mitigation measures. Some States (e.g., Colorado) also have developed simple scour vulnerability rating systems. These scour risk tools are available in *Bridge Scour Evaluation: Screening, Analysis, and Countermeasures*, by Kattell and Eriksson (1998). FSH 7709.56b requires a scour evaluation be made for any USDA Forest Service road bridge, and this policy should be applied to any questionable hydraulic structure, including low-water crossings.

Three types of scour may affect a low-water-crossing structure. They are general channel scour, constriction scour, and local scour. General channel scour, or degradation, may result from a change in runoff volume and rate, a headcut migrating upstream, a change in sediment load, or an upstream structure. This type of scour affects an entire reach of a stream, as well as any new structure in that channel. Using a ford as a grade-control structure is one way to prevent general channel scour initiated downstream from affecting an upstream channel reach. The Plumas National Forest chose the Moonlight crossing vented ford (case study 15), rather than a bridge, to stabilize the channel against downcutting and headward migration of a headcut in Lights Creek.

Constriction scour results from the constriction of the stream channel and the associated increase in velocity when the flow goes through a relatively narrow opening. Avoid this type of scour by using stream-simulation structures that maintain the natural channel width.

Local scour results from flow disturbance and vortices around objects such as abutments or midchannel piers. Prevent local scour by avoiding midchannel structures or obstructions. If midchannel piers or walls are necessary, minimize scour depth by minimizing the walls' widths or by using rounded or pointed edges.

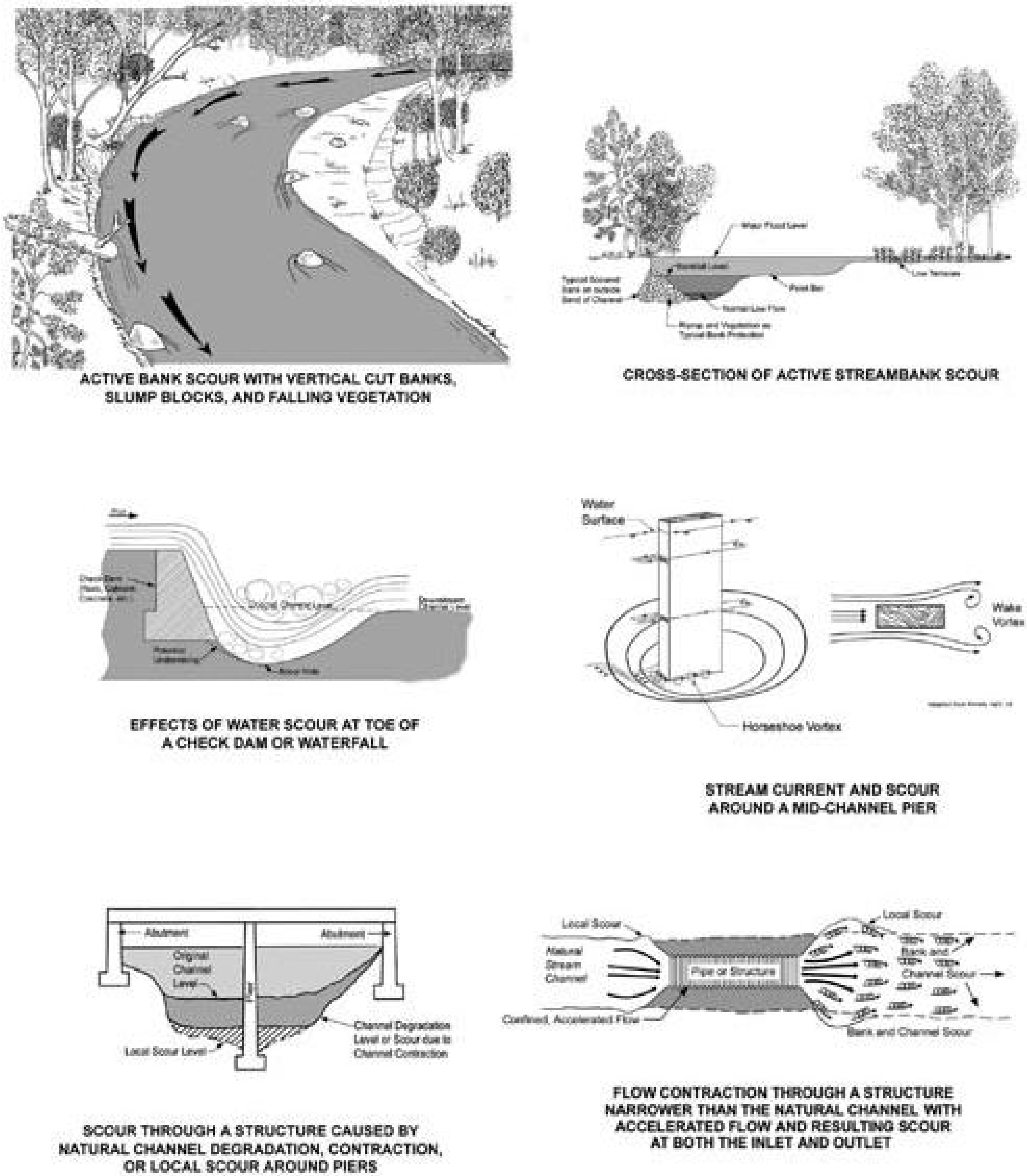


Figure 4.11—Common scour problem areas in channels and due to structures.

For thorough scour analysis, scour-depth-determination methods, and equations for various scour types and conditions see the FHWA reference HEC 18, *Evaluating Scour at Bridges* (Richardson 1995). Most scour-depth equations involve variables such as maximum flow depth, mean channel material size, and amount of channel contraction. In addition, computer models such as the U.S. Army Corps of Engineers program HEC-RAS (USACE, 1991) include modules for determining scour depth.

HEC 20, *Stream Stability at Highway Structures* (Lagasse 1995), discusses geomorphic and hydraulic factors affecting stream stability, and presents some stream stability countermeasures. Actual local scour depth can vary greatly, and rivers are known to have local scour holes much deeper than the average channel bottom depth. Evaluate field evidence and observations. Where possible, probe the bottoms of pools and scour holes to assess the amount of infilling and depth.

In some instances, drilling or other subsurface investigation methods may be the only way to conclusively determine the depth of materials susceptible to scour. HEC 23, *Bridge Scour and Stream Instability Countermeasures* (Lagasse 1997), provides further information on a wide range of scour countermeasures and bank stabilization measures. Common types of mitigation measures for protecting structures against scour include the following:

- Choosing locations where the local materials are not scour susceptible, such as areas of coarse rock and bedrock.
- Designing structures to avoid constricting the flow channel, thus avoiding flow acceleration.
- Armoring the entire channel with materials (grouted gabions, riprap, concrete, etc.) to resist scour.
- Protecting the channel, streambanks, and waterfall areas locally against scour, using vegetation, rootwads and logs, riprap, sack cement, articulated concrete blocks, vegetated turf reinforcing mats, gabions, etc.
- Redirecting stream channel flow with barbs, spur dikes, weirs, cross vanes, etc.
- Using deep foundations, placed below the anticipated scour level, such as relatively deep spread footings, or piles drilled/driven to bedrock.
- Using shallow scour cutoff walls, gabion or concrete splash aprons, plunge pools, or a riprap layer along the downstream edge of a structure.

- Using deep cutoff walls or deep sheet piles installed to a depth below the depth of scour, or to scour-resistant material, such as bedrock.

It is possible to protect against undermining or scour locally, particularly along the downstream edge of the structure, using concrete, gabion or rock aprons, an armored plunge pool, or cutoff walls. Although cutoff walls constructed with materials such as gabions, concrete, or sheet piles are commonly 3 to 5 feet deep, they can be much deeper. Determine their depth from the expected depth of scour. The downstream cutoff wall should be deeper than the upstream cutoff wall. In fine alluvial channels, install sheet piles to substantial depths or to the depth of bedrock. For a collection of specific mitigation measures used on low-water crossings to protect against downstream scour, see fig. 4.12.

The length of the downstream apron needed to protect against scour and undermining of the structure depends on several factors including bed material, velocity of flow, or height of falling water. Horizontal aprons are often at least 1.5 times the height of a vertical waterfall (FSH 7709.56b). In coarse rock channel material, one gabion basket or several feet of armoring is typically adequate. In deep, fine-grained deposits, the apron length should be roughly equal to the possible depth of scour so the material can fall into the scour hole and still protect the structure.

On very steep channels, keying a low-water-crossing structure into the streambank or using vertical cutoff walls can help prevent sliding of the structure and piping. In incised stream channels, keying the structure into the streambanks can enable it to resist the force of high flow and prevent outflanking of the structure.

4.7.2 Rock Riprap for Channel and Bank Protection

Rock riprap is one of the most commonly used erosion and scour protection measures because of its resistance to high stream velocities, and relatively low cost, durability, aesthetics, adaptability to many sites, and some self-healing aspects of loose rock. Other channel protection and bank stabilization measures include mats, vegetation, tree trunks with rootwads, gabions, and concrete, and are discussed in section 4.7.3. Because riprap is a loose rock structure, to some degree it can move, deform, and conform to scour areas and still offer erosion or scour protection. It can effectively armor an entire channel cross section (above water and under water), armor streambanks to the expected high water level, and armor a plunge pool or stilling basin. Place the riprap at the outlet of pipes, along the downstream edge of a structure, in a scour hole, or around and along channel protrusions (such as piers).

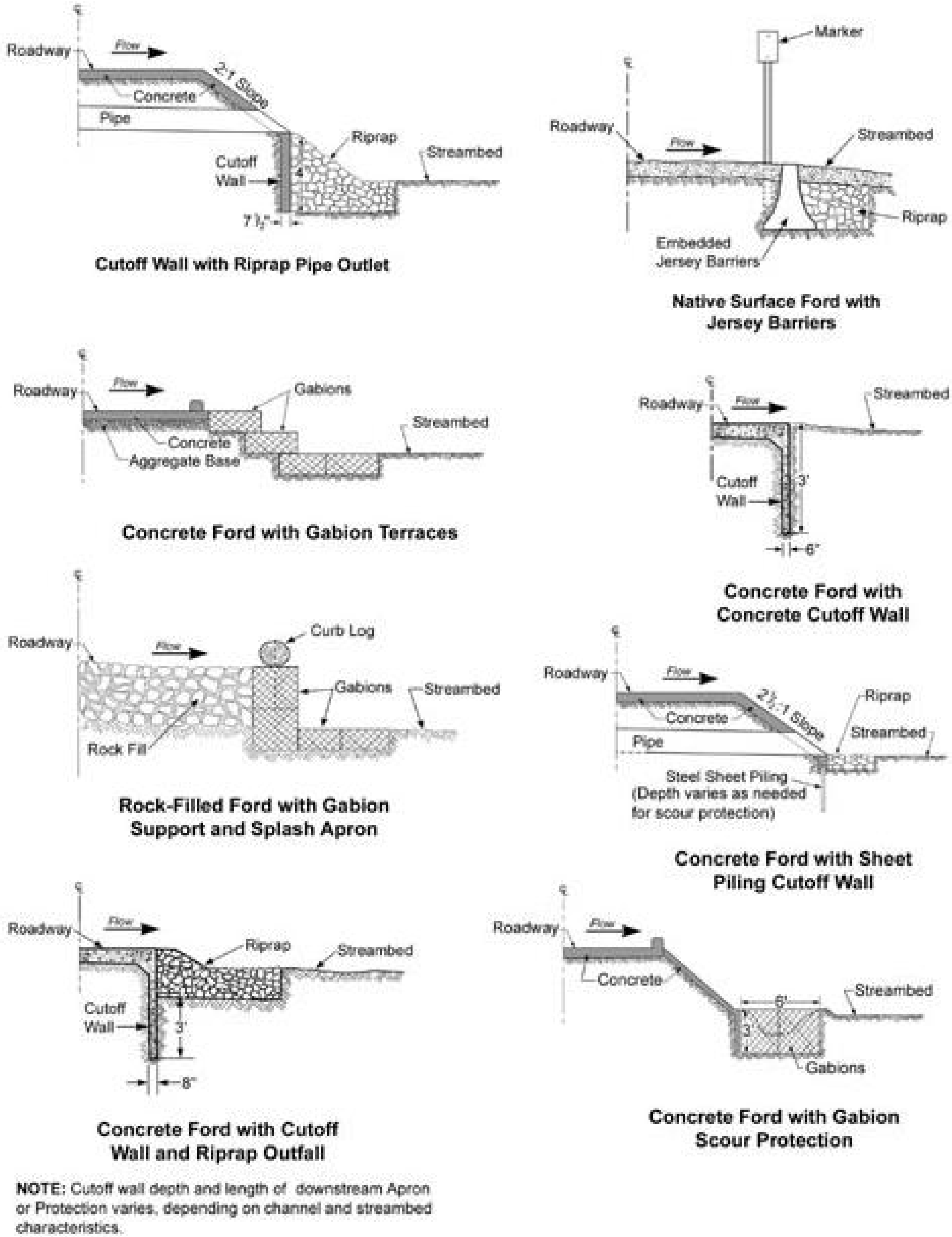


Figure 4.12—Common downstream protection measures used against scour on low-water crossings.

Riprap-sizing criteria have been developed by many agencies. The most rigorous criteria are based upon shear stresses or tractive forces exerted by flowing water along the rock surface. The FHWA publication HEC 11, *Design of Riprap Revetments* (Brown 1989), provides a comprehensive design process for riprap sizing, using permissible tractive forces and velocity, along with design examples. Criteria based upon permissible velocity are often used because velocity information may be available from Manning's Equation, direct measurements, or other sources. Gu (2003) gives a variety of commonly used criteria for sizing riprap based on velocity. For high-risk structures, evaluate riprap size using both velocity and shear-stress methods, and use the largest rock size required.

In figure 4.13 the median rock size (diameter or weight) is directly determined from average flow velocity and streambank or road surface slope. This method determines the size of riprap needed to protect the streambank and stay in place. Rock size is specified as the median, or **D_{50}** size. Roughly half the riprap is larger than the size specified, and the maximum size (D_{100}) rock is approximately 1.5 to 2 times the diameter of the median size. On straight stream segments, the velocity of water parallel to and near the bank (V_p) is assumed to be about 2/3, or 67 percent the average velocity (V_{ave}) for the purpose of this analysis. On the outside of a bend, water flowing near the bank impinges on the bank, and the impinging velocity (V_i) is taken to be about 4/3, or 133 percent of the average velocity (V_{ave}) (Racine et al.1996). In other words, riprap in an area with relatively fast flow, such as a bend in the channel, will have higher stresses and require larger rock than the size needed in a straight part of the channel.

Several other design and installation details are important when using riprap:

- Use only well-graded riprap to provide a dense armoring layer. Although poorly-graded or uniform-size riprap can actually resist larger flows, it is not selfhealing and can fail catastrophically. Riprap specifications are generally for graded rock, with a size range of large to small.
- The riprap layer should be at least as thick as the maximum rock size, and preferably 1.5 times the maximum.
- Use hard, durable, and angular rock, as specified in **FP-03**—*Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects* (2003), or other agency specifications.
- Place riprap on a filter layer of either gravel or geotextile. This placement allows water to drain from the soil while the filter

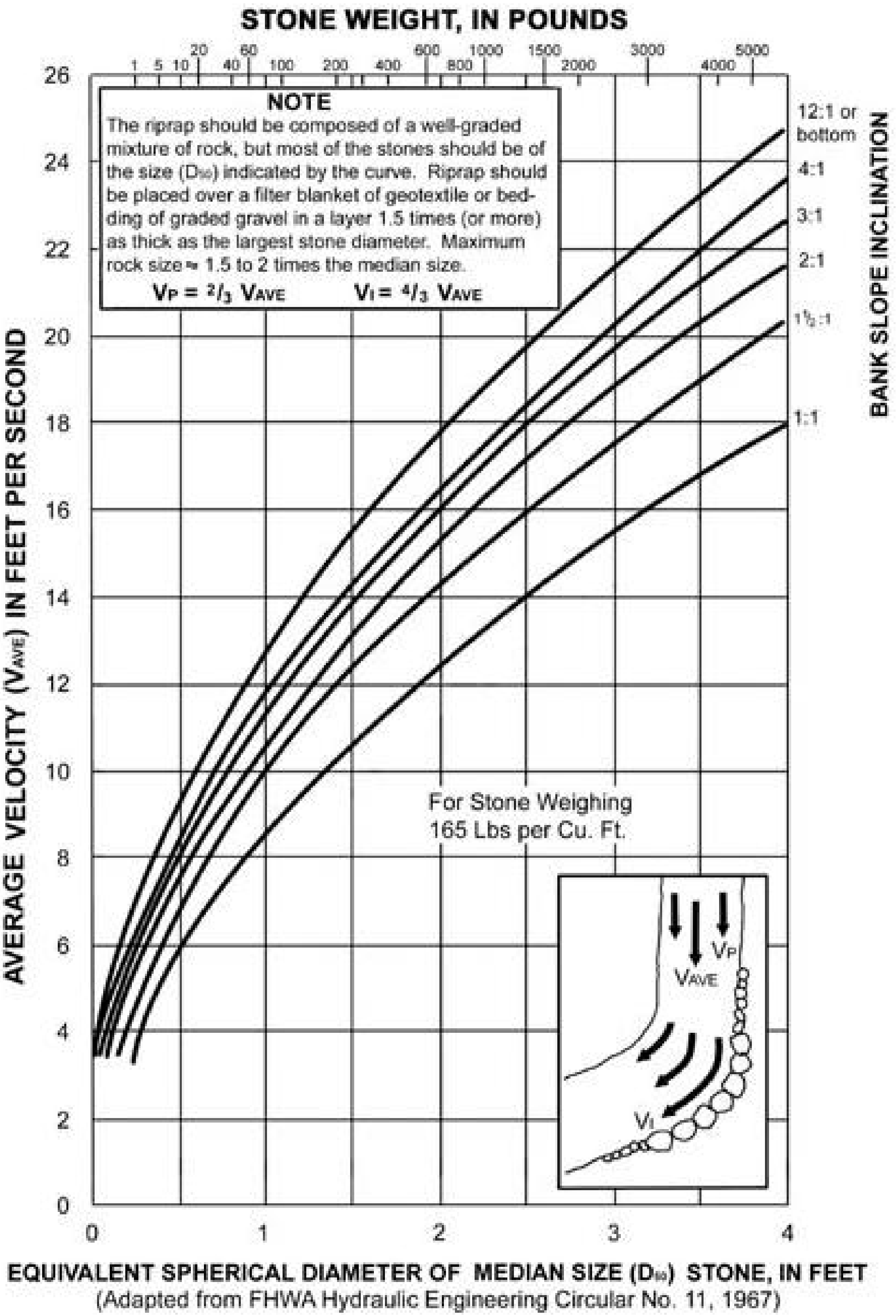


Figure 4.13—Size of stone needed to resist displacement by flowing water.

simultaneously prevents soil particle movement and retains fine soil in place. In critical applications, a multiple layer of filter material may be desirable. Filter aggregate is commonly either coarse sand or graded gravel placed in a 6-inch minimum thickness layer. Geotextiles, most often used today in filter applications under riprap, are usually a needle-punch nonwoven fabric weighing at least 6 ounces per square yard. Alternatively, it is possible to use a woven geotextile where the opening percentage and size are designed to the specific gradation of the soil it is protecting. Geotextiles also help protect fine soils against erosion where there are voids in the large rock riprap (fig. 4.14).

- **Key in** riprap around the layer's perimeter, particularly along the toe of an armored slope and at the ends of the rock layer. Extend the protection through a curve or beyond the area where fast or turbulent flow is expected. Excavate the toe key to the depth of expected scour, or to at least several feet deep. For additional scour protection, place extra rock at the toe or in a layer on the channel bottom. Figure 4.15 illustrates the common application of riprap for streambank protection and some of the installation details. Figure 4.16 shows a riprap bank that was not properly keyed into the channel and around its ends. Figure 4.17 shows a combination of large riprap and vegetation, a biotechnical treatment used for streambank stabilization at a vented ford.

Figure 4.14—Poplar Creek riprap streambank stabilization structure under construction, Plumas National Forest, 1998. The geotextile prevents erosion of fine soil through the voids in the riprap.

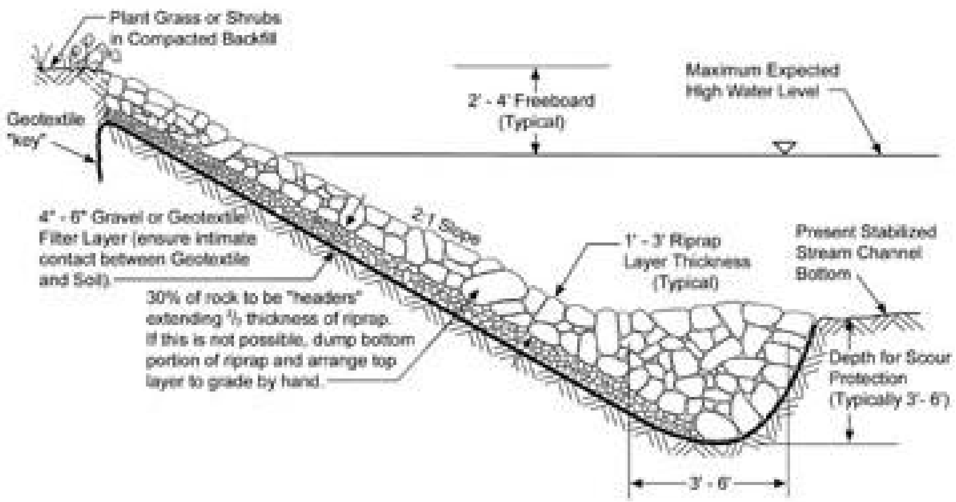


Figure 4.15—Typical riprap streambank protection details.

Figure 4.16—Looking downstream at a failed riprap installation on Red Clover Creek, Plumas National Forest.

Figure 4.17—Large riprap with vegetation used for streambank stabilization, French Creek Crossing, Plumas National Forest.

The maximum rock size used in remote areas is often dictated by the available size of rock. If large rock is not available, then grout a smaller rock with concrete or use gabions. Otherwise, risk of failure becomes higher. Most riprap-sizing criteria are for flow along relatively flat channels. Riprap-sizing criteria at the outlet of culvert pipes, in steep channels, and for cascading flow over rock, such as on a 1½ to 1 (67 percent) sloping fill face, are difficult to calculate and are, therefore, based upon modeling or observations. The U.S. Army Corps of Engineers manual, *Hydraulic Design of Flood Control Channels* (USACE, 1991a), presents equations for steep-slope riprap design and toe protection design. FHWA publication HEC 15, *Design of Roadside Channels with Flexible Linings* (Chen 1988), also presents charts for riprap design in sloping channels up to 25 percent as a function of discharge through the channel. FHWA publication HEC 14, *Hydraulic Design of Energy Dissipators for Culverts and Channels* (1983), covers riprap outlet protection and stilling basin design for culverts.

4.7.3 Vegetation, Other Channel & Streambank Protection Measures

Vegetation is the most desirable method of streambank protection (as well as some channel protection where vegetation can grow) because of low cost, aesthetics, and compatibility with the natural environment. Vegetation alone, however, is typically suitable only for streambank protection with velocities in the range 1 to 5 feet per second. It is not adequate for protecting turbulent flow areas, areas of fast or impinging flows, midchannel piers, or areas generally underwater. Vegetative stabilization performance can be significantly improved by using it in conjunction with rootwads and boulders (figs. 4.18 and 4.19), biotechnical treatments, and reinforcing mats.

Figure 4.18—Rootwads and boulders used to stabilize a high streambank, Wolf Creek restoration project, Greenville, California, 1990.

To resist velocities up to 4 to 6 feet per second, use simple vegetation treatments with live stakes or brush mats. Well-installed biotechnical slope protection measures—using vegetation along with rootwads, tree trunks, or boulders—are suitable for velocities of at least 6 to 10 feet per second (Gray and Sotir 1996). For velocities greater than approximately 15 feet per second, hard armor systems are most commonly used (see fig. 4.10). In addition to NCHRP 544 (McCullah and Gray 2005), another excellent reference is the USDA NRCS (1996) *Engineering Field Handbook, Chapter 16*, *Streambank and Shoreline Protection*, which provides many examples of streambank protection measures with and without vegetation. Ideally, vegetation should be native, deep-rooted, and adapted to local site conditions. A variety of species, including willows, is commonly used.

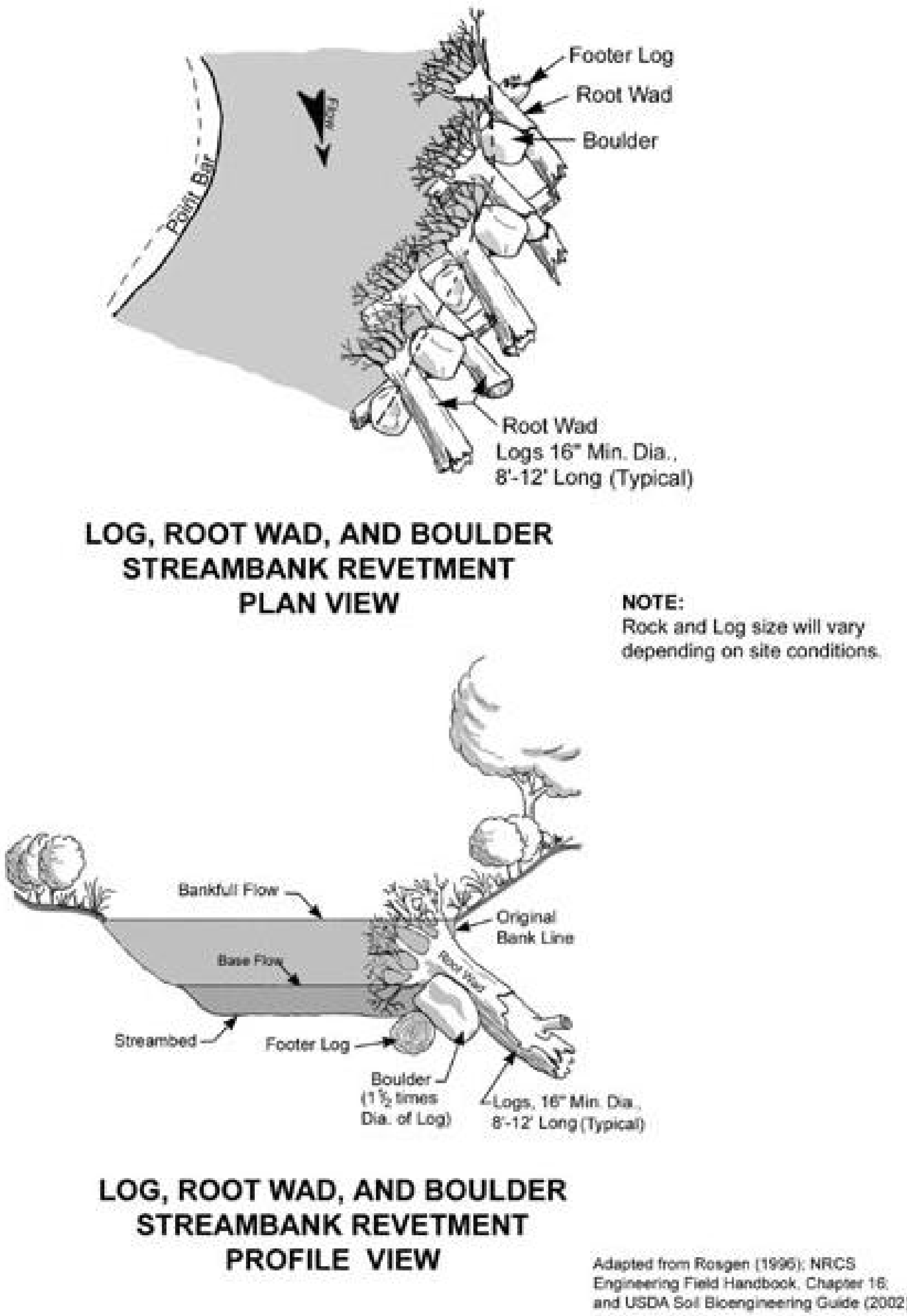


Figure 4.19—Typical applications of logs, rootwads, and boulders for streambank stabilization. (After Rosgen 1996, USDA NRCS (1996), and Eubanks and Meadows (2002)).

In-channel scour protection treatments differ from treatments on the streambank. In-channel stabilization measures are principally rock, gabions, or concrete whereas streambank stabilization measures, especially above bankfull levels, are commonly vegetation, either alone or in conjunction with the more rigid measures.

As mentioned previously, if available rock is smaller than desired, either grout the small rock, put it in gabions, or build a solid concrete slab. Gabions are typically formed by filling the 1- to 4-cubic yard baskets with relatively small 4- to 8-inch cobbles. This effectively creates large rock baskets with small rocks. Generally, loose rock riprap is preferable because it is less expensive than gabions and can deform better in cases of local scour or undermining of the structure. Furthermore, gabion baskets can eventually fail by abrading or rusting out, requiring costly repairs or replacement (fig. 4.20). The useful life of gabions may only be 15 to 30 years—or less in aggressive environments—depending on location of the baskets, local corrosion conditions, type of corrosion protection, and the amount of abrasion from bed-load movement. When using gabions, protect them against scour by placing a filter layer (usually a geotextile) behind the baskets. Also, using them in conjunction with vegetation can improve their effectiveness.

The entire low-water-crossing structure can be used as a grade-control structure (case study 15) to protect the channel against degradation or downcutting. In such cases, include local scour prevention in the ford design. To determine the effect of the structure on the dynamics of the stream system, evaluate not only specific channel velocities and characteristics, but also the entire reach of the stream.

Structure placement or design can cause downstream deposition if the structure causes local scour immediately below the structure. When this happens, the sediment load increases beyond the amount normally carried by the stream, and the extra load is deposited farther down the channel. The result is a scour hole below the structure, followed by bar development farther downstream. Scour and deposition are examples of factors that must be considered when choosing the type of ford, its location, and its protection.

Again, structure protection must extend across the ford to at least the area of the structure's wetted perimeter (the part sometimes under water), and preferably include 2 feet of freeboard to allow for flow uncertainties. Downstream of the structure, a scour cutoff or apron should be used. If waters will flow around the structure and over the banks, as in a broad flood plain environment, protect the banks both upstream and downstream of the structure with riprap or vegetation.

Figure 4.20—Gabion-basket failure and maintenance. a) Looking down at gabion baskets constructed to stabilize streambanks on Soda Creek, Plumas National Forest. Wire has rusted, allowing rock to wash away. b) To repair the stabilization structure, a concrete wall was poured in front of the damaged gabions.

4.8 Structural Design of the Driving Surface

Most fords should be designed to pass a minimum legal 80,000-pound load, often designated as an **HS 20-44** legal load (highway semi, 44-ton limit)[1]. If there is a load restriction on the road, post the weight limit at the ford. If overloads are anticipated, such as yarders or special construction equipment, the design (or temporary supports) must support those loads. Elevated structures such as box culverts, other vented fords, and low-water bridges should meet the same structural requirements as a normal structure designed for that site and span, as required in the FSH 7709.56b. For corrugated metal pipe structures, use a 1-foot minimum soil cover, unless the manufacturer recommends otherwise. Concrete pipe may require 18 inches of cover. When designing structures for lower load limits and lighter design vehicles, post the crossing (particularly if it is an elevated platform) for the allowable load limit.

For at-grade structures on granular soils, a legal load can usually be accommodated with a layer of aggregate 6- to 12-inches thick. The ford surface needs to resist the forces of low-water flow so we recommend a relatively coarse 1½- to 2-inch minus, well-graded aggregate. To prevent displacement at high flows, place this surfacing aggregate over a layer of small to medium size riprap. Size the riprap based on figure 4.13, using the curve for the flattest slope. Geocells can be used to confine the aggregate, provide structural support, and prevent the aggregate from washing away. The geocells are typically covered with an additional 4 to 6 inches of aggregate to prevent damage to the cells. Compact any surfacing aggregate, and replace it periodically after high-flow events (case study 7). A stockpile of extra aggregate can be stored near the ford for periodic replacement.

Box structures and low-water bridges must have appropriate footings or foundations to support the traffic and dead load of the structure and to spread the load across the encountered soil or rock conditions. Reinforced concrete slabs, 6 to 8 inches thick, are commonly used on small box structures for the deck and abutment. In some cases, designers support the slab or vent on spread footings at least 2 feet wide and deeper than the expected depth of scour. Structures must have durable driving surfaces, curbs, and other features that can survive periods of inundation and have debris both hit them and go over them. Structural design should be based upon structural analysis and meet the current AASHTO bridge design requirements for the anticipated loads. Many box-culvert designs are

[1]The load reduction factor methodology (LRFD), which is expected to come into common use in the near future, may change the legal load. A future edition of AASHTO's *Standard Specifications for Highway Bridges* will describe this methodology.

structurally adequate if built to the manufacturer's recommendations. Preapproved designs from State departments of transportation are also used occasionally (case study 19).

Soft subgrade soils, such as silts, clay, and organic deposits, usually require overexcavation and backfilling with aggregate or select material for a 1- to 2-foot thickness. Very soft soils may require a subsurface investigation and site-specific design. Imported backfill material and/or the top foot of native material are often compacted to at least 90 percent of their AASHTO T-99 maximum density to provide adequate load-bearing support.

Vehicle use may compress organic meadow soils on the road approaches to a structure. As the soil compresses, the approaches lower in elevation, the channel widens at the crossing, and the original armoring on the roadway ceases to cover the entire wetted perimeter during high flow. Case study 7 demonstrates this problem. To remedy this type of situation, protect the banks by keying the structure in along the outer limits of the structure (well beyond bankfull), remove soft materials, replace them with aggregate, and reinforce the approach roadway to the structure.

For fords where vehicles drive through water most of the time, wave erosion can be an issue, both on the driving surface and on the streamside areas adjacent to the ford. Extend roadway surface armoring beyond the wetted perimeter to the likely height or distance of wave action (case study 7, fig. A38). Local streambanks may require additional vegetative or rock slope protection.

Where a road crosses an active flood plain the road surface should be very low or preferably at-grade with areas with the flood plain to prevent obstructing or funneling flood flows. For structural support on fine or organic meadow soils, it may be necessary to overexcavate the roadway footprint and backfill it with select structural material, coarse rock, or aggregate. Place geotextile between the fine meadow soil and the roadway material to separate the materials and prevent contamination of the aggregate. Although an elevated porous rockfill embankment can be used (Zeedyk 1996), it will likely plug with time and dam the flood plain.

4.9 Traffic Control and Safety

Traffic safety is a principal concern on low-water crossings. These crossings present particular safety issues, especially when driving through water and where there are dips in the roadway vertical alignment. For high-traffic use and high-standard, high-speed roads, low-water crossings are usually inappropriate, so this safety issue becomes irrelevant.

Because fords involve water periodically flowing over the road, they are inherently dangerous during those periods of inundation. As figure 3.1 shows, flows more than 1 to 2 feet deep have enough lateral force to push a vehicle off the ford. Fast water velocities are dangerous! Annually, numerous people are killed across the United States attempting to drive through fords or inundated sections of roads.

Despite warning signs and obviously unsafe road conditions suggesting the crossing not be used, fatalities still occur at these sites. Practicality and cost-effectiveness, however, dictate the use of low-water structures at many sites, particularly on low-volume roads. To provide for safety where fords are used, traffic engineers and resource managers must use prudent design and safety measures (such as traffic warning devices) along with aggressive driver education programs. When common sense indicates that a crossing may be especially hazardous—such as where the roadway platform is high above water, alignment is poor, speeds are relatively high, flows are swift and deep—the design should be carefully evaluated and a risk assessment made for the site.

Conventional guardrails and borders, typically 2 to 3 feet high, cannot be placed along most low-water-crossing structures because they will act as trash racks during overtopping, and are likely to be damaged during high flows. We recommend low curbs, borders, or delineators for defining the roadway, identifying the edge of the structure, and keeping traffic on the structure, particularly where the structure is raised. For safety and to minimize flow and debris obstruction, use 6- by 10-inch-high timber curbs, preferably raised to 12 inches with blocks for scuppers, or use 15-inch-high concrete curbs (FSH 7709.56b). See case studies 14, 18, 20, and 21 for examples. Use object markers to define each corner of the structure, but place them out of the active flow channel to avoid snagging debris.

The need for safety measures increases with the height of the structure, particularly on vented fords and low-water bridges where the roadway platform is elevated more than a couple of feet. When conventional bridge railings are not used, USDA Forest Service policy for structures states the site will be evaluated for safety based upon traffic speed, traffic volume, alignment, structure dimensions, other local hazards, and curb design. This analysis (design warrant) is then documented and kept in the project design file. If the ford cannot be made safe, then a conventional bridge with safety railings or another type of structure should be built.

Ideally, low-water crossings should be located where the road is straight and sight distance is good. Adequate warning signs are critical for identifying the approaching ford and warning drivers that the crossing may be flooded and have periodic traffic delays. Marker posts indicating the depth of flow are desirable, particularly with unvented, at-grade fords. FHWA uses a safe but conservative design criterion for vented fords that limits water depth over the structure to 6 inches during the high-design flow. This limit greatly reduces the likelihood of a vehicle being swept away if it enters the water. This criterion, however, may require large vents and is impractical or costly to implement on many unvented fords on rural or forest roads. Therefore, warning devices are the more practical solution in most applications.

Use traffic warning signs along the road, notifying traffic that it is approaching a low-water crossing and that there is the possibility of flooding. Suggested warning signs should include “FLOOD AREA AHEAD,” “IMPASSIBLE DURING HIGH WATER,” and “DO NOT ENTER WHEN FLOODED.” A suggested arrangement of these signs, as recommended by FHWA (Gu 2003), appears in figure 4.21. Similar signing is recommended in the *USDA Forest Service Sign Manual*, FS EM 7100-15.

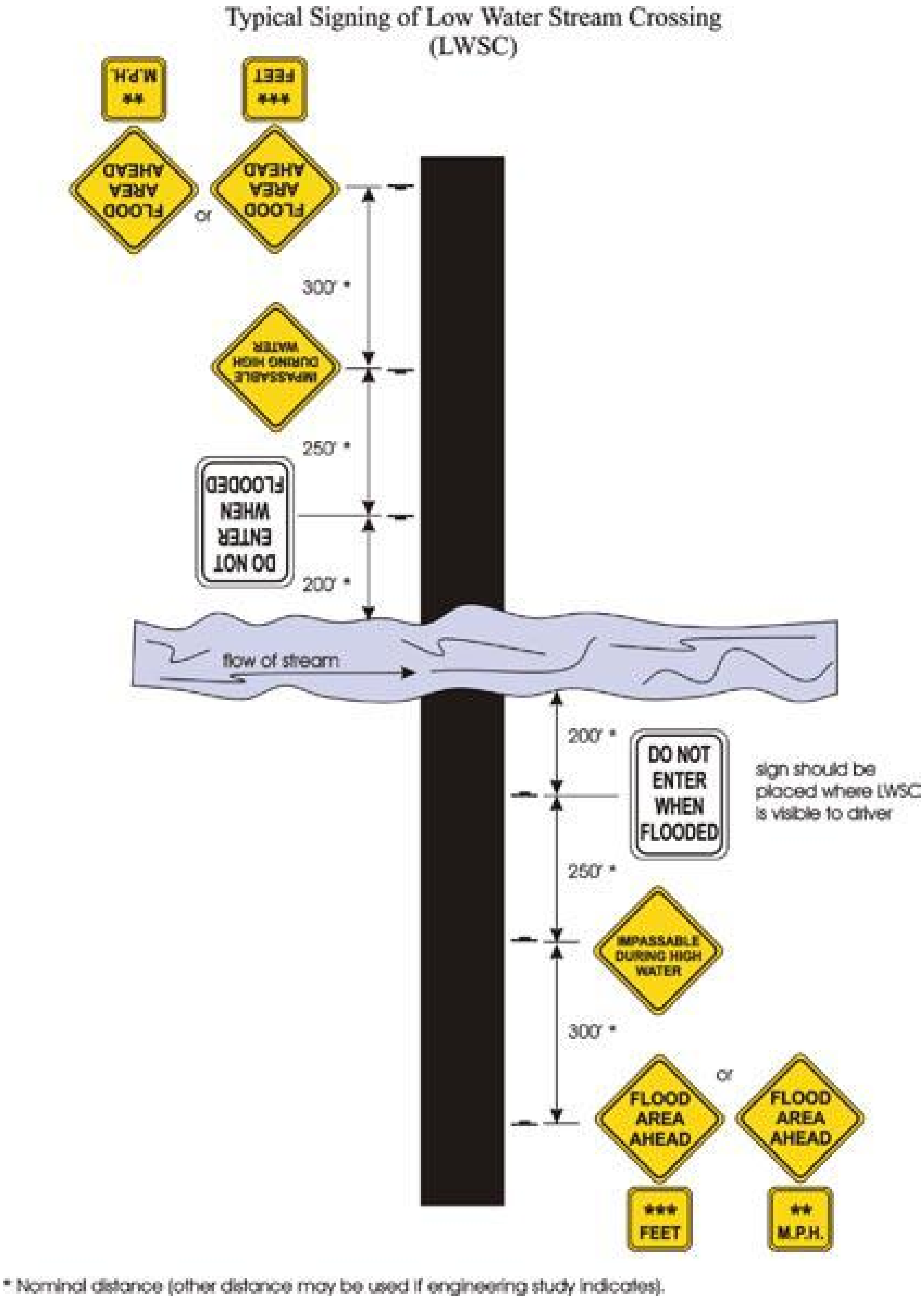


Figure 4.21—Recommended warning signs for fords from Carstens and Woo 1981, reprinted in Gu 2002.

Where practical, use depth markers to indicate the depth of flow over the structure (fig 4.22). Depth markers may be impractical or require periodic maintenance in channels carrying a lot of debris. Alternatively, a system of colored posts could be used where flow level green suggests safe passage, flow level yellow suggests marginally safe conditions, and flow level in the red zone indicates an unsafe condition.

Figure 4.22—Typical depth marker, Missouri county road.

For additional traffic safety, we recommend extra width through the structure (an additional several feet), particularly with at-grade fords. On raised fords with embankments, a 4:1 (horizontal:vertical) or flatter slope is desirable. Minimize safety problems by avoiding steep road grades and curves into a crossing.

Safety requirements and signing needs will vary depending on the traffic use, design vehicle, and geographic area of the ford. Greater safety measures are necessary when there is high traffic use and the ford is close to populated or urban areas. In remote areas with low traffic volume, simple warning signs are usually adequate. In populated areas, with a higher risk that passenger vehicles will try to enter a flooded area, multiple warning signs are necessary, along with other possible measures such as flashing lights, temporary gates, posted local detours, and very obvious depth markers.

4.10 Materials Selection

Materials selection is important in several aspects of low-water crossing design and construction. These aspects include the driving surface, the structural design of vented fords or low-water bridges, and the selection of streambank and scour protection measures. Choice of materials for constructing a low-water crossing depends on many factors, including the following:

- Type of structure.
- Availability and cost of materials.
- Proximity of materials to the site.
- Desired useful life of the structure.
- Anticipated stream channel velocity.

Many fords use local rock for both the roadway surface and bank protection. Rock is simple to use, usually inexpensive, natural, and aesthetic. Although local rock and riprap may be available and inexpensive, they will be suitable only if hard and durable, and if the material's size is large enough to resist movement by the forces of water. Local stream channel material, both rock and finer material, is ideal for refilling embedded box culverts to achieve stream simulation or create as natural a channel condition as possible through the structure.

If large enough rock is not available for scour protection or streambank stabilization, use alternative materials, such as gabions, a mix of boulders and logs, grouted riprap, masonry, or massive concrete. Use gabions when a structure is needed and cobble-size materials (4 to 8 inches) are plentiful. For advantages and disadvantages of gabions, as well as other alternatives, see section 4.7. In relatively low-velocity areas, vegetative material alone may be suitable for bank protection.

Structural concrete is the most commonly used material for vented fords, complicated structures, and even simple improved fords placed in a dynamic stream environment. Structural concrete is strong and durable. If properly mixed and placed, and not undermined, it can have a design life of 100 years. For vented fords and low-water bridges with slabs or spans supporting a traffic load, its structural strength often makes it the best choice. It is resistant to abrasion, does not corrode (if the steel reinforcement is properly placed in a good mix), and requires minimal maintenance. Alternatives to concrete use are masonry walls and abutments. For improved aesthetics, the concrete can be colored, textured, shaped, faced with rock, or hidden behind vegetation.

The roadway driving surface can be constructed of a wide variety of materials including local rock, aggregate confined in geocells (case study 7), gabions, concrete planks (case studies 5 and 10), asphalt, cable concrete blocks (case study 6), or a massive concrete slab (case studies 8 and 9).

Materials such as gabions, precast Jersey barriers (K-rail), or low concrete walls can be used to support or build up the downstream edge of a ford. Choice will generally depend on cost. Jersey barriers are often used for temporary structures in storm damage repair or after forest fires because they are relatively durable, portable, and reusable (fig. 5.12).

4.11 Best Management Practices for Erosion Control and Water Quality Protection

4.11.1 Maintaining Water Quality

Road-stream crossings are critical areas of concern for water quality due to the potential for large road fills, road surface drainage entering the stream network, and limited opportunities for mitigation. (Also see appendix D.) Stream crossings are the point where the road and water courses most directly connect. Using outsloped roads or insloped roads with frequent cross-drains will minimize the concentration of water on a road surface and minimize sediment delivery to crossings. Adding a rolling dip or cross-drain exiting into a stable buffer area just before the crossing, will further minimize the connectivity. Locate the rolling dip or cross-drain as close to the crossing as possible to minimize the amount of connected road surface, but far enough away to have an adequate filter strip to settle out sediments draining from the rolling dip or cross-drain. Finally, armor the roadway surface nearest the crossing to the first cross-drain or break in slope. If the roadway slopes smoothly to the crossing, armor at least the last 150 feet.

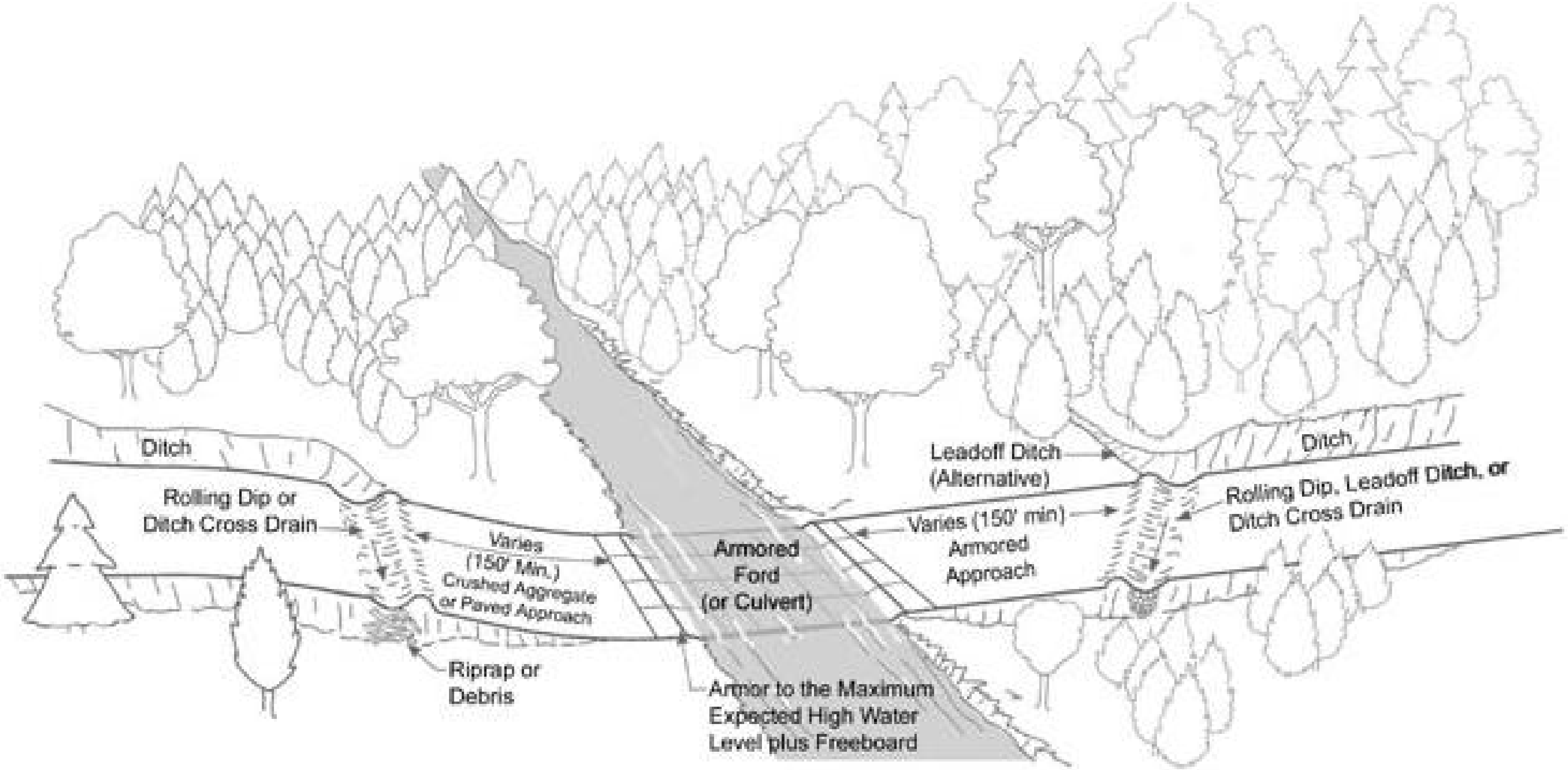
Although fords with unsurfaced approaches provide the most obvious potential sediment source, with the road surface as the conduit, other structures may have ditches that are neither armored nor vegetated. Depending on slope and soil type, those ditches may not only transport road sediment to the stream but also undergo active incision, thus adding their own sediment. Even well-maintained graveled road surfaces will deliver some sediment (Reid and Dunne 1984) to nearby streams. Well-drained and armored crossings will minimize this sediment delivery. Also, crossings with a broad surface area or multiple crossings on a drainage can increase water temperature to some extent. The amount and significance of any temperature increase should be evaluated on a site-specific basis.

To best protect water quality, create a general erosion-control plan and a project plan incorporating specific structure design elements aimed at preventing bed and bank erosion and local scour, and implementing BMP's. See section 4.7 for structure design elements that deal with changes in velocity and the effects on the in-stream environment. BMP's exist for a wide variety of management activities, including those both in and near the channel.

Material collected on the dry road surface and in ditches washes into the stream when it rains. Excluding vehicle use during rainy periods reduces but does not prevent road sediment transport to the stream (Bilby et al 1989). Low-water crossing sediment control measures are shown in figure 4.23. They include the following:

- Armoring the roadway approaches and driving surface through the crossing.
- Using vented fords to avoid driving through the water most of the time.
- Using armored ditches approaching the crossing.
- Diverting the ditch water with cross-drains and leadoff ditches before it reaches the crossing channel.
- Diverting surface water with rolling dips before it enters the crossing.
- Armoring the entire structure and channel area affected by the structure.
- Maintaining the structure and roadway adequately.

Construction dewatering of the site is an excellent way to protect water quality and minimize sediment production during construction. Working in water and preserving water quality is very difficult, particularly if water is flowing. Working in a dry, isolated, and dewatered site is much simpler for both construction and water-quality protection. Plan construction projects during the dry season or periods of low flow if possible. Dewatering ford sites commonly involves working during periods of minimum flow, building an upstream cutoff wall or diversion dam, and running the flow through a culvert (often 12- to 24-inch corrugated metal or polyethylene pipe) around the construction site. At some sites, dewatering systems need to accommodate fish passage.



Armor or stabilize the actual stream crossing (ford) structure and add surface armoring to the roadbed and approach. Drain water off the road surface before reaching the crossing. Road surface armor should be a minimum of 150 feet and should extend to the nearest cross-drain structure. Actual distance depends on road grade, soil type, rainfall, etc.
For fords, set stream channel armoring at the elevation of the natural stream bottom. Armor outlets and fills as needed.

Figure 4.23—Sediment protection measures at stream crossings.

At sites with seasonal or ephemeral flow, conduct work when the site is dry, but be prepared for potential storms. Use sump pumps to keep the site dry during low flows or if excavation extends below the local groundwater table. Discharge pumped water into a holding tank or sediment catchment basin before returning it into the flowing stream. Sediment-laden water can sometimes be treated by spreading it over a vegetated area away from the flowing stream, where the water can infiltrate trapping sediment in the soil. Water containing leachates from cement is toxic to most aquatic organisms so this contaminated water should be kept out of the stream and disposed of properly.

4.11.2 Erosion Control

Plan and schedule all construction activities to prevent erosion and sedimentation, which could cause water quality degradation and possible adverse effects on aquatic species. Erosion control measures for fords include the following:

- Netting, vegetation, and ground cover for any disturbed areas such as work areas, storage areas, materials sources, and exposed earthwork, both during and after construction.
- Controlling water in ditches flowing into the crossing and across disturbed or denuded earthwork areas.
- Trapping sediment in catchment basins, behind silt fences, or in-channel with sediment mattresses.
- Minimizing sedimentation from construction in-channel.
- Protecting exposed overflow areas.

Other elements of erosion control include scheduling the work to reduce the risk of erosion, stopping work during rainfall events, keeping clean and dirty water separated, minimizing site disturbance, installing erosion control measures before site disturbance occurs, and periodically maintaining the erosion control measures. It is important to integrate erosion control into as many design considerations as possible, including the selection of materials sources, revegetation of all working areas, and drainage control through the construction site.

Erosion control is most relevant during construction and for the first year after construction. During construction, keep the work out of flowing water, or use sediment catchment areas. Limit disturbed or denuded areas to areas small enough to be protected during rainstorm events, or limit construction to the dry season.

Develop a project-wide erosion control plan to ensure a variety of feasible erosion control treatments are considered and include the cost of those measures in the project budget. A wide variety of erosion control measures are usually workable, including physical methods (e.g., ditches and berms, mats, riprap), vegetative methods (e.g., grasses, brush, trees) and biotechnical measures (e.g., brush layering, use of live stakes, vegetation, and rock wattles). Promote the long-term success of the measures by providing for maintenance, monitoring, and follow-up work. Erosion control measures are well-documented in numerous references such as Gray and Sotir (1996) and ABAG (1995).

4.11.3 Best Management Practices

To satisfy water-quality concerns, incorporate standard erosion and sediment control practices (BMPs) into all projects as needed, particularly during construction. You must adapt all BMPs to site-specific conditions, as discussed in *Water Quality Management for Forest System Lands in California—Best Management Practices* (USDA Forest Service 2000) and in the draft national standards, *Best Management Practices—Nonpoint Source Management*, USDA, Forest Service, May 2005. Review project design to ensure appropriate BMPs are incorporated into the design and construction requirements. Monitoring the implementation and effectiveness of BMPs is also necessary for resource and structure protection and for identifying additional maintenance needs. The following is a partial list of typical BMPs that apply to the construction of low-water crossings:

Erosion Control Plan

Create this plan before starting the project. Include the specific practices to be implemented for controlling erosion and preventing management-caused sediment from reaching the drainage. Ensure compliance by frequent inspections.

Stream Crossing Location

Like all stream crossings, locate low-water crossings perpendicular to the channel on a straight stretch, whenever possible. Although difficult when retrofitting old crossings or working with certain landforms, this positioning will reduce the effects of streamflow energy on the structure itself as well as impacts resulting from the redirection of flow against channel banks.

Timing of Construction Activities

When feasible, schedule activities in and near the channel during the dry season, or for a time period when precipitation and runoff are unlikely. Stop construction during times when soils are too wet for equipment to operate without damaging the soil resource and increasing the potential for water quality degradation.

Timely Erosion Control Measures on Incomplete Stream Crossing Projects

Whenever a project must remain only partially completed for a time, use the following erosion prevention measures:

- Remove temporary culverts, diversion dams, or other structures that could obstruct or narrow streamflow, increase scour or bank erosion potential (by increasing the velocity and flow through a narrow opening), or increase erosive power against channel banks.
- Install necessary erosion control structures such as temporary culverts, side drains, flumes, cross-drains, diversion ditches, energy dissipators, dips, sediment basins, berms, debris racks, or silt fences.

Construction of Stable Embankments

Construct approaches and road surfaces with adequate strength to support the treadway, shoulders, subgrade, and traffic loads. When fills are required, stabilize embankments with retaining walls, confinement systems, plantings, or a combination, as needed. Adequately compact all road surfaces.

Control of Road Drainage

A great number of methods can help reduce the effects of increased runoff and sediment transport caused by low-water crossings and road ditches. These methods include dips that shunt water off the road near the crown of the approach, culverts that carry water from a road ditch and disperse it on the other side away from the channel, paved approaches, and armored ditches. In areas without sufficient distance for safely dispersing road and ditch water, slow the flow by using sediment basins, check dams, contour trenching in the discharge area, or other similar methods.

Servicing and Refueling Construction Equipment

Keep service and refueling areas well away from wet areas, surface water, and drainages. Minimize soil contamination potential by using berms around these sites, and using impermeable liners or other techniques to contain spills (see forest Spill Prevention, Containment, and Countermeasures plan).

Controlling In-Channel Excavation

Heavy equipment should cross or work in and near streams only under specific protection requirements. Excavation in these areas should follow all of the following minimum water quality protection requirements:

- Do not excavate outside of caissons, cribs, cofferdams, or sheet pilings, unless previously authorized.
- Do not disturb natural streambeds adjacent to the structure.
- Keep disturbance of banks to a minimum, and stabilize any banks that are disturbed.

Diversion of Flows Around Construction Sites

Divert streamflow around construction sites and return it to the natural streamcourse as soon as possible after construction, or before the wet season. Stabilize all disturbed areas before the wet season or as needed.

Specifying Riprap Composition

Size and install riprap to resist erosive water velocities. Do not include any material that might add to the sediment load, such as weakly structured rock, organic material, or soil. To prevent undermining, it may be necessary to use filter blankets or other methods.

Control of Construction and Maintenance Activities Adjacent to Stream Areas

Properly functioning streamside areas act as filters for sediment, provide shade and habitat, stabilize banks, and help slow velocities and limit the erosive potential of floodwaters. Establish the width of these areas and keep fill and similar materials out of them, except for specifically designated areas. Protecting these areas may necessitate stabilizing adjacent fillslopes to prevent sediment accumulations within the stream side areas.

Structure Maintenance

Structures and approaches may suffer deterioration from either large runoff events or normal use. Provide the basic maintenance to protect the structure and prevent damage to resources. This high level of maintenance often requires an annual inspection to ensure structure and channel compatibility, function, and stability.

Water Quality

Although implementing effective BMPs gives a high degree of water quality protection, there are locations where protection can be verified through a testing program. Water quality parameters and test methods should be specified by an established water quality monitoring plan.

Low-water crossing designs have multiplied as structures were adapted to meet site-specific conditions, cost feasibility, available materials, and resource issues. This section summarizes the most common low-water crossing types, along with some of their advantages, disadvantages, construction details, and other factors unique to each type of structure.

5.1 At-Grade Rock Fords

Unimproved at-grade fords are crossings where vehicles simply drive across the channel without the benefits of hardening or grading. The ideal site for an unimproved ford is one with rocky, hard substrate (fig. 5.1) or bedrock. Even where the channel bottom is hard, the streambanks can be soft and erodible. In such cases, traffic generally causes the stream to widen as the banks break down and wash away. This problem can be fixed by "improving" the ford—removing soft soils and replacing them with select coarse rock.

Figure 5.1—Unimproved rock ford on the East Fork San Gabriel River, Angeles National Forest, California.

Improved at-grade rock fords are typically the least expensive and easiest ford to construct. They work best on ephemeral channels and on low-velocity streams, where the armoring rock will not be moved by the current. They should be kept "at-grade" (close to the natural stream channel bottom elevation) to minimize channel changes or fish barriers (fig. 5.2). The rock surface should be coarse to minimize water velocity acceleration across the ford and to resist movement of the rock.

Where existing or imported rock is too coarse (greater than 3 to 4 inches), it is commonly in-filled (choked) with finer (1½- to 2-inch) graded aggregate to facilitate traffic, because very coarse, loose rock is difficult to drive through. Nevertheless, finer gravel and material will need periodic replacement after high flows (case studies 1 and 2).

Improved rock fords are usually constructed by overexcavating the roadway area 6 to 8 inches deep and backfilling the excavation with well-graded coarse rock back to the natural stream channel level. Coarse rock size should be selected to resist movement at maximum flow velocities, and mixed with finer material for trafficability. Often two separate layers of rock are needed to satisfy both concerns. The downstream outlet area of the ford may be stabilized with moderately large riprap. A naturally coarse rocky stream channel bottom or a smooth bedrock area is ideal and requires no overexcavation.

Figure 5.2—At-grade improved rock ford, Plumas National Forest.

Simple at-grade rock fords have occasionally been improved by armoring with grouted rock, masonry, or a layer of asphalt concrete. Although this material can make an erosion-resistant driving surface, keying in the material around the edge of the structure is important. Asphalt layers are relatively thin and lightweight, and can float off the site due to uplift forces during high flows. The driving surface should be kept as rough as possible to minimize flow acceleration. At-grade structures that simulate the natural channel shape will best maintain channel processes and minimize aggradation or degradation problems.

5.2 Concrete Slab Fords

Although concrete-slab fords are relatively simple and very durable, they are expensive compared to simple rock fords. The structure can be at-grade with the stream channel bottom, or raised to minimize the depth of water driven through. Concrete slabs are some of the best structures in many applications (if kept at-grade) because of their durability and minimal effect on the stream system. If raised, however, they dam the channel and cause aggradation upstream, and degradation or scour problems along the downstream edge. Virtually all slab fords are at least slightly elevated above the stream bottom. Because they are located right where most bedload transport occurs—on the channel bottom—they tend to trap bedload upstream. If the slab is high enough, the accumulated bedload may fill the channel, destabilizing the banks. If the channel is not well-entrenched, this process may cause it to shift location or braid.

Concrete slabs can withstand a large amount of debris or sediment overtopping the structure without damage (fig. 5.3). They are relatively common on flashy desert streams, even streams large enough to provide at least intermittent fish habitat. Except when backwatered, they commonly create fish passage problems because of the increased flow velocity and shallow flow across the smooth concrete slab (case study 8). Roughening the slab with embedded boulders or a rough concrete finish may help promote passage, but will not solve the problem completely. Elevated slabs or flat slabs in a steep channel with a water drop along the downstream edge require more downstream scour protection and often create a jump barrier (fig. 5.4).

Carefully designed slots formed into a slab and positioned parallel to flow will concentrate low flows and can facilitate small fish passage (case study 9). Careful design is necessary to avoid frequent plugging problems (case study 12).

This design usually consists of a simple “at or near grade” reinforced concrete slab 6 to 8 inches thick, with upstream and downstream cutoff walls several feet deep for scour protection. The slab usually has a 2- to 4-percent minimum downstream cross-slope (maximum 8 to 10 percent). Ideally, the cross-slope matches the natural channel gradient. Although a nearly flat cross-slope helps minimize velocity acceleration, it may create a waterfall at its outlet in a steep channel (see case study 8). Such a waterfall is detrimental to fish passage and can create scour problems. As flows deepen over the slab during high flows, the flow velocity is less affected by the slab and its slope. A flat slab may also tend to accumulate sediment during periods of low flow.

Holes may be needed through a large concrete slab to minimize uplift pressure and keep the slab from floating away. Alternatively, a thick, heavy slab, as well as the use of cutoff walls, can prevent uplift. Uplift forces should be examined during the design of the structure.

At-grade rock fords or improved fords with a variety of armored surfaces, including concrete, masonry, gabions, asphalt, or concrete planks, are ideal for semiarid and desert environments where flow fluctuations are extreme and floods may carry large amounts of debris.

Figure 5.3—Old concrete slab ford with grout apron, Ashdale Administrative Site, Tonto National Forest. (case study 8)

Figure 5.4—Concrete slab creates fish barrier at low flow, Seven Springs, Tonto National Forest.

5.3 Precast Concrete Planks

Precast concrete planks also are used in at-grade fords to provide a concrete-hardened driving surface. The structure typically consists of individual 12-inch by 12-inch by 16- to 20-foot long, steel reinforced, precast concrete “planks” or logs, bolted together with iron flanges to hold their spacing (McNemar 1983). The planks are placed upon a prepared, graded rocky surface. The outlet may be armored with riprap to protect against the increased flow velocities across the planks and through the small channels between the planks (case study 5). The structure acts like a vented ford (with small vents) at low flow, with a dry driving surface and with flow going between the planks (fig. 5.4).

Figure 5.5—Concrete plank ford at edge of the North Fork Clearwater River, Clearwater National Forest, Idaho.

The bed for the planks is prepared by smoothing the subgrade and channel bottom, placing a thin layer (a few inches) of gravel or fine rocky bedding material, and laying the planks in place. In very rocky or boulder-lined channels, some rock will have to be overexcavated and backfilled with small rock to form a smooth base for the planks. Although enough small rock to form a smooth bed for the planks is necessary, the fine bedding material may be susceptible to scour and movement. Damage observed to precast concrete plank structures has come from scour of the bedding material beneath the planks causing movement and deformation of the structures (case study 5). This problem can be minimized with a thin, well-compacted rocky base, and geotextile placed between the rocky bed and the planks. Where feasible, a solid concrete slab is generally preferable and more durable.

This structure is not recommended for fish passage. Although the 6-inch-wide channels between the concrete planks may provide partial passage, they tend to fill up with gravel and rock, limiting passage. Best passage is attained when the entire structure is submerged.

The Black Canyon ford on the Clearwater National Forest (case study 10) uses steel-reinforced, precast 8- by 15-inch-wide by 14-foot-long planks, placed 1 to 2 inches apart at the toe of a debris avalanche chute. They are set on a very rocky foundation with gravel cushion. Fish passage is not an issue at this site. To minimize cost, the planks were cast offsite by forest crews.

Advantages of precast planks include minimizing onsite construction time, avoiding working with fresh concrete in the stream environment, reducing the quantity and cost of both concrete and formwork, and providing small channels for aquatic organism passage. Disadvantages include the relatively small, independent planks that can move individually and are subject to scour between them. This type of structure is particularly unsuitable for channels with fine-grained alluvial materials readily susceptible to scour.

5.4 Cable Concrete Blocks

Cable concrete blocks, or articulating concrete block fords, are made of 1-foot-square concrete blocks held together with a light cable. The concrete-block mats come in dimensions of 4- to 8-foot-wide by 8- to 16-foot-long sheets. Block thickness varies from 2.5 to 8 inches. The mats are placed upon a shaped, compacted subgrade, at or near the stream channel bottom elevation, but overexcavated to accommodate the thickness of the concrete blocks. Some blocks come with a geotextile backing. Otherwise, a layer of geotextile should be placed upon the prepared subgrade before placement of the cable concrete block mats (fig. 5.6). Gravel may be placed into the voids between the blocks to produce a smoother driving surface immediately, or they can be left to fill naturally.

For scour protection, one row of the blocks (approximately 1-foot wide) is buried at least 6 inches into the stream channel completely around the perimeter of the concrete-block mat. Additional depth or other scour protection, such as riprap, may be needed along the downstream edge of the structure. The mats can be anchored in place simply with rebar and cable clamps, or with soil or rock anchors in a dynamic environment.

Figure 5.6—Cable concrete block ford, Bighorn National Forest, Wyoming. Note that mat should extend higher to protect the crossing adequately.

Having a smooth, uniform, compact bed underneath the blocks is critical. Because each block is independent, it can settle, rotate, or tilt if the foundation material settles or if there are boulders just beneath the blocks. In addition to producing a nonuniform driving surface, irregular blocks can also become snagged on bumpers or trailer hitches and possibly be pulled out of place if the vertical curve of the driving surface is not sufficiently smooth. In addition, the cable connecting the blocks can get caught and either be pulled out of the blocks or break and lose its anchorage.

Because each mat is large, heavy, and flexible, the Bighorn National Forest fabricated a rigid lifting bar made of small steel I-beams welded to size to handle the mats (Golden, personal communication). A backhoe with chains can pick up the mats and lifting bar, and move them to the site. The lifting bar can then be fitted onto the backhoe for lowering the mats into position. Adjoining mats are held in place by cable clamps which join the cables from both mats. See also case study 6, figure A30.

5.5 Geocell Fords

Geocells, or plastic cellular confinement structures, have been used on some very low-use roads to confine fine gravel and rock, forming a stable driving surface with the confined material (Pence 1987). The geocells are made of an expandable high-density polyethylene plastic (HDPE) with 6- to 8-inch-diameter cells and a thickness of 2, 3, 4, 6, or 8 inches. The expanded sheets are 8-feet wide by 16- to 20-feet long but can be cut to size easily. Geoweb geocells have been the most common type of material used to date, and they can be purchased solid or with perforations (holes) in the cells for drainage.

The site should be dewatered to facilitate construction and minimize site sediment production. Then, the roadbed is excavated to the depth of the geocells plus cover, and prepared by removing boulders, filling voids with gravel, leveling, and compacting the base of the crossing (fig. 5.7). The first step in installing the mat is to place the geotextile layer on the base. Second, the geocells are expanded in place across the area on top of the geotextile, and staked down. Third, the geocells are backfilled with 1½- to 4-inch-minus gravel or smaller crushed rock by dumping the material directly into the expanded cells. Finally, the geocells are covered with a 4- to 6-inch-thick layer of a relatively coarse aggregate (a thicker layer of aggregate can be used if more structural support is needed). Ideally, all materials should be well-graded, angular, and relatively free of fines to minimize sediment in the creek. The top of the cells, plus some cover rock, should be at the level of the natural stream channel bottom (case study 7).

Figure 5.7—Geoweb installation on the South Fork Tongue River, Bighorn National Forest, Wyoming. Note exposure of geoweb due to traffic and water flow.

Geocell fords appear best suited for crossings in a relatively "low energy" environment with relatively flat stream gradients, low channel velocities and debris loads, and minimal scour potential. Although the geocell itself is not particularly strong, the composite structure gains its strength by confining the aggregate. Because vehicles should not drive directly on the geocell mat, a minimal aggregate cover thickness of at least 2 inches is recommended. Edges of the structure can be overexcavated and bent down (keyed) into the streambanks and streambottom, roughly twice the cell depth. The edges can also be anchored and protected by placing riprap on the backfilled cells along the streambank or along the downstream edge of the structure. To minimize settlement in soft, fine streambank soils, either overexcavate the fine material and backfill with aggregate, or compact it to create a firm foundation.

The collapsed geocell sheets come in bundles approximately 11 feet long and 5 inches thick. Although the geocells are easy and quick to expand and fill, after their bedding is prepared, they can be easily overstretched if their dimensions are not carefully checked (overstretched cells lose some of their capacity). Once the geocells are properly cut to size, expanded, and laid out, they can be staked in place with 3-foot-long rebar and bent into a hook-shaped stake. If work is done in the stream current (note: this is not recommended), only short sections of geocell should be filled at a time. If the relatively fine cover material is washed off during a flood or by traffic, it will need periodic replacement. This low-water crossing is best suited for light traffic such as local administrative traffic or access into campgrounds. Tire action and fast water flow can remove the gravel cover and expose the geoweb (figs. 5.7 and 5.8).

Figure 5.8—Geoweb exposed by tire action on road approaches, Ashley National Forest, Utah.

5.6 Porous, Large Rockfill Fords

Porous, large rockfill fords are raised rockfills built to be overtopped by high flows or debris flows (fig. 5.9; see also fig A111). They are used in steep topography and in deep, incised channels where a crossing requires a high fill for good road alignment. Initially, they are porous so some water passes through the fill, but with time, they usually “silt in,” becoming impermeable and allowing flows to go over the top of the structure. They are, therefore, best suited for headwater areas where streamflows are relatively low, but carry considerable debris.

Figure 5.9—Dooley rockfill ford under construction, Plumas National Forest, California.

Rock size is usually determined by the largest materials available, and the rockfill should be constructed of angular, well-graded material. Class 3 to Class 5 riprap (15- to 27-inch size) may be specified in this application. The fill height (depth) will be determined by both (a) the channel’s depth and slope and (b) the roadway elevation needed to produce a suitable road grade or vertical curve. In steep topography or steep channel gradients, the rockfill may be 5 to 15 feet high (case study 3). Because it essentially dams the channel, this rockfill does not allow for fish passage and prevents the passage of fish and possibly other aquatic species. The face of the fill should be U-shaped in plan view to keep water and debris in the middle of the channel, and prevent erosion along the structure’s margins where the rockfill contacts native soil (fig. 5.10). This shape will also help prevent bank scour immediately downstream of the structure.

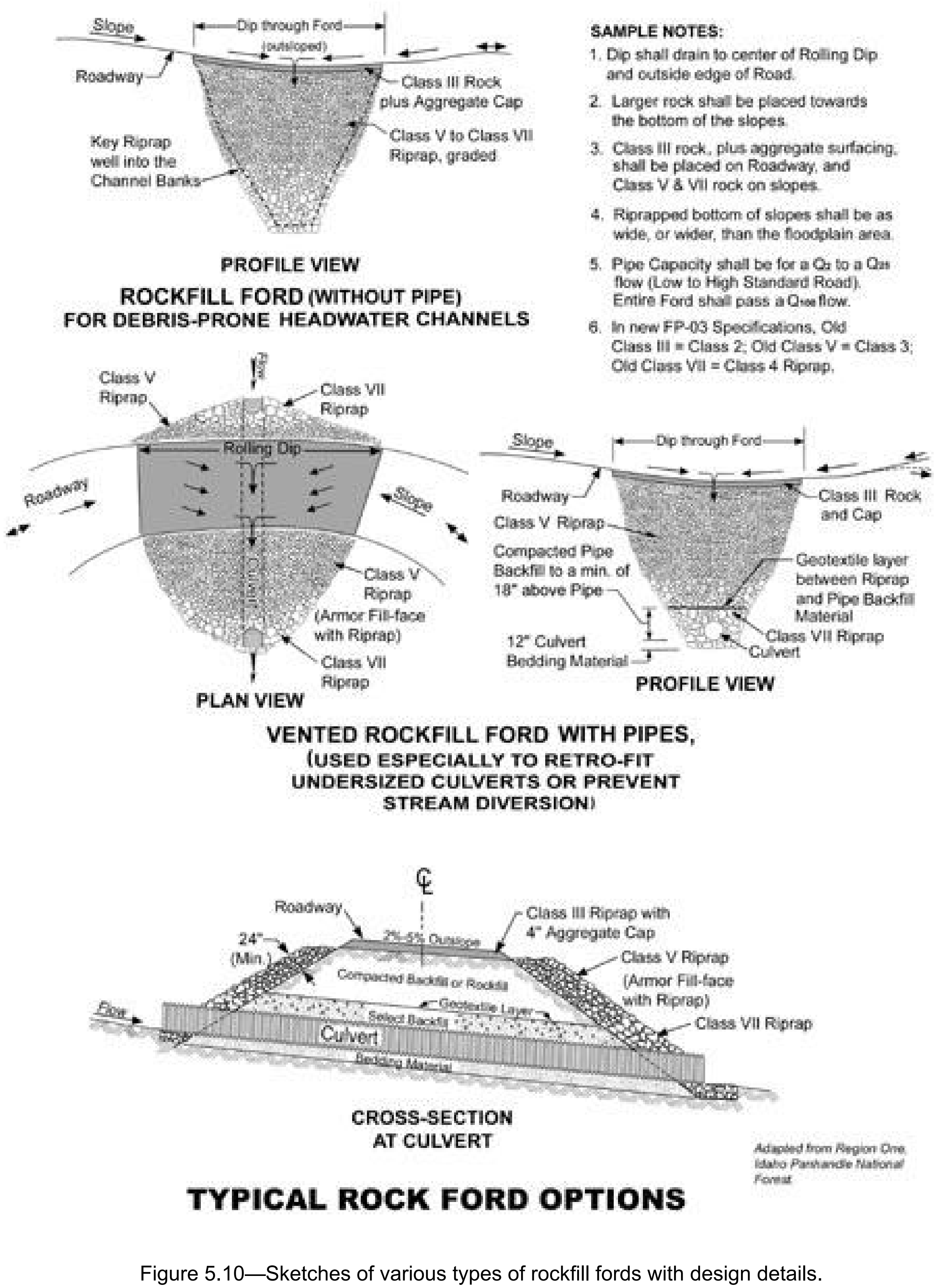


Figure 5.10—Sketches of various types of rockfill fords with design details.

A rockfill ford may also be constructed with a pipe or pipes, producing a vented rockfill ford. Vented rockfill fords are sometimes used where an existing conventional culvert pipe is undersized and protection is needed in the event of overtopping (case study 3). Like all crossings with diversion potential, vented rockfill fords require a dip over the pipe to ensure overtopping flows stay within their own creek boundaries (fig. 5.10). These structures are created by forming a dip in the roadway over or near the culvert, and armoring the fillslopes with riprap. Ideally, rock is placed upon a geotextile filter in a layer 1 to 2 feet thick.

5.7 Gabion and Jersey Barrier Sill Fords

Gabions, jersey barriers (sometimes called "K" rail), other concrete walls, or even logs have been used in relatively low-gradient channels (up to 10-percent slopes) to hold the road prism in place (case study 4) (Leydecker, 1973) To ensure the gabions or jersey barriers do not move, it is common to partially bury them forming a sill on the road's downstream edge. Frequently, the actual roadway platform is then made of local rocky channel material, placed with a 3- to 5-percent outslope across the road and the sill. The barriers should be placed to form a gentle U-shaped weir across the channel (the U faces downstream) to concentrate flow midchannel. The structure usually creates a low waterfall below the crossing, so the structure may be a barrier to fish and other aquatic species. Therefore, this type of structure should not be used in channels where AOP is needed (fig. 5.11).

Figure 5.11—Gabion ford, Tonto National Forest, Arizona.

Because of the waterfall created by the structure, some downstream protection—such as additional gabion baskets, **Reno mattresses**, or coarse riprap—may be needed along its downstream edge for scour protection. The sill structures should also be keyed into the natural streambank to prevent end scour. Fine roadway material may need to be replaced periodically but the basic structure should be heavy enough to resist movement and damage. Logs have been used successfully in small streams with low-flow velocities and relatively flat gradients.

If Jersey barriers are set too high, the crossing may be too flat and sediment may deposit on the road during high flows. The waterfall over the downstream edge of the ford will also promote toe scour, and the barriers may be pushed over by the lateral pressure of the road fill (fig. 5.12). Ideally, Jersey barriers should be set into the stream channel at roughly half their height to prevent them from overturning or sliding downstream. Actual grade and height of the sill will depend on the channel gradient and other conditions.

Figure 5.12—Jersey barriers used for a temporary ford after the Ojai wildfire in 2004, Los Padres National Forest, California.

Gabions are typically set on the channel grade or are embedded several inches into the stream channel bottom. Actual elevation will depend on scour considerations and the design elevation of the roadway. Gabion sills can be capped with asphalt across the driving surface. Although these structures can work for low-velocity environments, there are sites where the asphalt layer was damaged or floated off the gabions. Gabion structures may also be so porous they take the flow through the structure rather than over it. In time, the structure may silt in, but until then, water going through the baskets can cause piping or scour under or behind the structure. The best way to prevent piping and scour problems is by wrapping the gabion with a filter such as a geotextile, and compacting material firmly around and behind the gabions.

5.8 Vented Fords with Small Single or Multiple Culverts

Many raised vented fords with multiple, small diameter culverts (vents) were built from the 1960s to the 1980s throughout the National Forest System. Culvert pipes were set near the streambed level, and the crossing was backfilled with compacted material. In most cases, at least a foot of cover was placed over the culverts. The embankment material was then protected against overtopping with riprap, gabions, or concrete. Single, double, or multiple culverts were used.

Vented fords enable low flows to go through the pipes, therefore preventing most vehicles from driving through the water and maintaining water quality. The structure can be relatively low profile, or the embankment can be relatively high. If the ford surface is 3 feet or higher during overtopping, the flow drop on the downstream side of the structure will generally cause scour. Scour protection on the downstream edge is critical, both because of the water drop at high flows and because of the accelerated stream velocities exiting through the culverts. Downstream scour protection has been achieved with vertical cutoff walls, gabions, riprap, or simple plunge pools.

The major disadvantage of this structure is that it typically has a low VAR and acts as a dam across the channel at high flows (case study 11). The damming effect causes upstream backwater and aggradation (fig. 5.13a) and sometimes downstream degradation and scour. Both processes contribute to channel instability and high maintenance costs. Pipes in these structures often plug with debris and usually require, at the least, cleaning in the inlet area after a major storm event (fig. 5.13b). In addition, these structures often prevent fish passage where culvert outlet velocities are high, where flow depth is very shallow in the pipes, or where there is a drop at the culvert outlet. Low water velocities and backwater through the culvert can allow for some fish passage.

Figure 5.13a—Murdock vented ford, Plumas National Forest, California looking upstream (note excavated sediment upstream of ford).

Figure 5.13b—Murdock ford, looking downstream at inlets partially plugged with woody debris after a high flow.

Conventional culvert installations are sometimes converted to vented fords by constructing a dip over or near the culvert and hardening the fill to sustain overflow. This might be done, for example, where a wildfire or a landslide occurred in the watershed, making the existing capacity of the culvert inadequate for expected flows. In some cases, an existing pipe may simply be undersized and require additional protection. The downstream face of the fill usually needs to be armored and its toe protected against scour. This type of "retrofit structure," similar to rockfill fords discussed in section 5.6, can offer inexpensive protection against a total pipe failure in many settings.

5.9 Vented Ford with Concrete Box Culverts

Vented fords are often constructed with raised platforms and box culverts to pass low to moderate flows (fig. 5.14). Vehicles are kept out of the water at all times except during high flows. Although these structures are similar to vented fords with culvert pipes, they commonly have a larger waterway open area across the channel, or a high VAR. They also tend to be shorter in the along-stream direction than crossings with pipes. They readily pass small debris through the structure but can still plug with large woody debris in a major storm event. The box structures are typically structural concrete and may have either a solid bottom or vertical walls set upon spread footings, with a natural channel bottom. The roadway surface may be solid reinforced concrete, or it may consist of metal grating, such as cattleguard material, which can be removed to clean debris from the structure. Typically, these structures are relatively expensive, but they can perform very well, minimize traffic delays, and maximize channel function and aquatic organism passage (case studies 13, 14, 15, 16, 18, and 19).

Figure 5.14—Long Creek embedded concrete box high-VAR ford constructed in 2005, Ouachita National Forest, Arkansas.

The number of box openings depends upon the design flows and the width of the channel. To minimize channel constriction, the flow area should include the majority of the channel cross section. Depending on the extent to which flow area is constricted during bankfull or higher flows, the structure will cause sediment deposition, usually in the outer boxes (see case study 19). Ultimately, the sediment may need to be cleaned out to avoid backwatering and flow acceleration in the remaining open boxes.

If a continuous streambed is maintained through the structure, this is one of the best for maintaining channel function. Where foundation conditions are good enough to construct an open-bottom box with a natural stream channel bottom, the structure is ideal for fish and aquatic organism passage. If a full concrete box is built, the box bottom can be embedded 1 to 2 feet below natural stream channel bottom elevation and filled with streambed material. Low gradient channels with mobile bed material may need at least a 2-foot embedment. Steeper channels where streambed materials are coarser and less mobile may need minimal embedment, although 1 foot is a reasonable minimum value.

The embedded box can be backfilled to the channel level with rocky material, or left to fill naturally with stream substrate. Angle iron bed material retention sills have been built into conventional culvert structures to help retain materials, particularly on steep channels. Cutoff walls several feet deep should be added along the downstream embedded box edge for scour protection.

Except where the crossing is backwatered, if the bottom of the box is not embedded, water flowing over the smooth concrete floor will be faster and shallower than in the natural channel, impeding fish passage. On the Ouachita National Forest (case study 14), boulders were set into the concrete to roughen the surface and provide some fish habitat. Alternatively, to concentrate low streamflows and promote low-flow fish passage, small channels have been formed into the bottom of the concrete box, or a slight V shape has been built into the base. These measures may help downstream fish passage at very low flows (case study 13).

These relatively large, high-VAR structures also are used on steep channels prone to debris torrents. The large openings can pass a large amount of water (thus minimizing traffic delays). Debris rides over the top, and the road can be easily reopened by pushing remaining debris off the structure (case study 16).

Also, this type of structure has been used successfully as a grade control structure. In case study 15, a bridge structure was considered, but the low-water ford was less expensive and it offered a solid structure across the channel holding the elevation of the channel upstream of the structure and preventing further headcutting. Although such structures are massive and relatively expensive, they can be significantly cheaper than a longspan bridge. Because this structure maintains a large elevation drop across the crossing, a fish ladder or other measures may be needed for fish passage.

Because the structure driving surface is typically elevated at least several feet higher than the vent or above the natural channel elevation, some curbing is desirable or may be required for traffic safety.

5.10 Vented Fords with Large Open-Bottom Arch Culverts

This vented ford is desirable because it offers some of the economic advantages of culverts with the broad-span advantages of a bridge. The structure usually has a high VAR and can or should span the entire drainage, preferably to the bankfull width. Ideally, the structure is a bottomless arch with spread footings parallel to the stream channel, minimizing disturbance to the middle of the stream channel and preserving the natural substrate. This structure is ideal for “stream simulation,” where the natural channel width and bottom material are preserved (fig. 5.15).

Figure 5.15—Metal bottomless arch high-VAR ford, San Bernardino National Forest, California.

Alternatively, a large arch pipe can be used. The pipe is buried several feet below the natural stream channel bottom and in-filled with streambed material. The arch pipe has to be oversized to account for the flow capacity lost in burial.

The disadvantage of this structure is the pipe may be relatively high, so maintaining the dip through the crossing can be difficult. Low profile pipe shapes available today can minimize this problem. Moreover, scour protection against overflow conditions must be well-selected. Ideally, the roadway driving surface and fillslopes will be concrete-armored or formed out of structural concrete. Usually large arch pipe culverts are not used in low-water crossing structures, but they can be made to work in some stream channels.

5.11 Low-Water Bridges

In this publication, we define low-water bridges as structures supported by piers or spread footings with a natural stream channel bottom. They can look quite similar to embedded box-culvert fords, but are commonly longer and have no floor. Low-water bridges have a raised superstructure over a natural stream channel bottom, a total span of more than 20 feet, and are designed to sustain overtopping (Brink 1974 and 2000). Generally, they have the highest VAR of any of the low-water crossing structures. To function as "low-water" bridges, the structures need to be above bankfull elevation to pass flow most of the time, yet be low enough to be overtopped by larger floods (Webb 1994) (fig. 5.16).

Figure 5.16—Capps low-water bridge, Eldorado National Forest, California.

Although low-water bridges are usually the most expensive low-water crossing structures, they can maintain the best channel function and have the least adverse effect on fish and other aquatic organisms. The structures can also be very useful for other wildlife species passage along the riparian corridor, particularly if the bridge span is considerably wider than the low-flow channel. This structure is also very useful in broad flat rivers where considerable base flow exists but peak flows and/or debris loads are extreme. Although the structure may be relatively expensive, it can still be much less expensive than a longspan conventional bridge high enough to pass all the flow during an extreme high-flow event (case studies 20 and 21).

Because the structure is periodically inundated and may trap debris, particularly large limbs and rootwads (case study 18), the abutment and girders or slabs must all be well-connected and anchored to resist the lateral forces of the flow and debris. Anchorage may include heavy concrete abutments or piers, or cables anchored to deadmen buried in the streambanks. Protection against local scour around the abutments or any midchannel piers is also usually needed

In some broad channels, conventional or low-water bridges may be used in conjunction with other unvented or vented fords, accommodating main channel flows, overflow channel flow, and a large amount of debris passing through the system during flood flows (Eriksson 1984).

Traffic safety, which is critical with an elevated structure, may be difficult to achieve on low-water bridges because normal bridge railings cannot be used. With an elevated platform—usually at least several feet high—the structure needs railings or curbs to keep traffic safely on the deck. The taller the railings are designed, the safer the traffic conditions will be. Because a ford is periodically overtopped, the structure needs as low a profile as possible since any railing acts as a trash rack, trapping debris. The best compromise appears to be using high curbs, 6 to 12 inches high for wood structures, or 15 inches high for concrete structures (FSH 7709.56b). In addition, object markers and warning signs placed well before drivers reach the active channel can improve traffic safety. Remember the FSM requires any bridge structure, including low-water bridges, be designed by a licensed engineer and reviewed by the regional office. Warrants must be developed evaluating the safety of the structure.

Chapter 6—Summary

Like all crossing structures, low-water crossings involve compromises and tradeoffs among the following three competing and often conflicting objectives:

- To transport traffic safely on the road.
- To permit water, sediment, debris, and wildlife free passage in the stream and on the flood plain. (This objective involves maintaining wildlife populations and their habitats as well as protecting the structure from failure. Aquatic and many riparian habitats depend on periodic disturbance and replenishment from channel transport processes.)
- To limit lifetime structure costs (construction, maintenance, replacement).

Designing a crossing is an optimization challenge in which we try to achieve each objective as fully as possible. Road access needs and site characteristics (valley shape, channel size and shape, flows, etc.) largely control whether a structure designed for overtopping (i.e., a low-water crossing) will be successful.

On roads where traffic interruptions are *not* tolerable, providing for freely functioning channel processes, AOP, and habitat protection at stream crossings can be expensive, especially in high energy or disturbed streams. The job requires spanning the channel, either with a bridge or a stream simulation culvert. Where traffic interruptions *are* permissible, many more crossing options are available. Structures designed to overtop can help minimize not only channel and flood plain blockages, but costs as well. Overtoppable structures are especially useful:

- Where periodic peak flows are much higher than normal flows.
- Where sediment and debris are major problems.
- Where a channel is shifting location.

This publication has outlined the considerations involved in locating low-water crossing structures, selecting the structure best suited to the site and road objectives, and designing it to both serve the road user safely and permit channel functions to operate as freely as possible.

Low-water crossings are no longer just an inexpensive way to get a backroad across a stream. They can be an effective way to maintain channel continuity and protect a stream from road failures. At a different site, or with a different design, they can also be barriers to wildlife passage, agents of habitat degradation, and safety hazards. The final result depends on how well the structure accommodates channel processes while providing safe traffic passage.

AASHTO (American Association of State Highway and Transportation Officials). 2000. Highway drainage guidelines, 3rd edition. Washington, DC: American Association of State Highway and Transportation Officials. 800 p.

AASHTO. 2001a. Guidelines for geometric design of very low-volume local roads (ADT<400). Washington, DC: American Association of State Highway and Transportation Officials. 96 p.

AASHTO. 2001b. Policy on geometric design of highways and streets. 5th edition. Washington, DC: American Association of State Highway and Transportation Officials. 872 p.

AASHTO. 2002. Standard Specifications for Highway Bridges, 17th edition. Washington DC: American Association of State Highway and Transportation Officials. 1,028 p.

ABAG (Association of Bay Area Governments). 1995. Manual of standards for erosion and sediment control measures. Oakland, CA: Association of Bay Area Governments.

AISI (American Iron and Steel Institute). 1994. Handbook of steel drainage and highway construction products, Fifth edition. Washington, DC: American Iron and Steel Institute. 518 p.

Askin, R. W. 1992. Armoured fords: an alternative drainage crossing system for debris torrent prone mountain channels. In: Proceedings of international mountain logging and 8th Pacific Northwest Skyline symposium. Bellevue, WA.

Askin, R. W. 2002. Personal communication. Principal engineer, Integrated Watersheds Ltd., Ladysmith, British Columbia, Canada.

Beamish, F. W. H. 1978. Swimming capacity. In: Hoar, W. S.; Randall, D. J., eds. Fish Physiology. New York: Academic Press: 101-187. Vol. VII.

Bilby, R. E.; Sullivan, K.; Duncan, S. H. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. Forest Science. 35(2): 453-468.

Brink, S. A. 1974. Use of cattleguard superstructures for low-water crossings on secondary forest roads. Engineering Field Notes. Washington, DC: U.S. Department of Agriculture, Forest Service, Engineering.

Brink, S. A. 2000. Jones Wreckum Road low-water crossing revisited. Engineering Field Notes. Washington, DC: U.S. Department of Agriculture, Forest Service, Engineering.

Brown, S.; Clyde, E. 1989. Design of riprap revetment. Hydraulic Engineering Circular 11 (HEC-11). FHWA IP-89-016. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 156 p. (original version of HEC-11 *Use of Riprap for Bank Protection* published in 1967).

Calamusso, Robert. 2005. Personal communication. USDA Forest Service, Tonto National Forest, Phoenix, AZ.

Carstens, R. L.;Woo, R. Y. 1981 Liability and traffic control considerations for low water stream crossings. Engineering Research Institute Project 1470 Final Report. Ames, IA: Iowa State University.

Castro, J. 2003. Geomorphic impacts of culvert replacement and removal: avoiding channel incision. Portland, OR: U.S. Department of the Interior, Fish and Wildlife Service. http://www.library.fws.gov/Pubs1/culvert-guidelines03.pdf.

Chen, Y.; Cotton, G. 1988. Design of roadside channels with flexible linings. Hydraulic Engineering Circular 15 (HEC 15), FHWA IP-87-7. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 124 p.

Chow, V. T. 1959. Open channel hydraulics. New York: McGraw-Hill Book Company. 680 p.

Deiter, D. 2006. OHV stream crossing monitoring. Presentation. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region, Integrated Resource Workshop.

Doyle, Jim. 2002. Personal communication. Fisheries biologist, Mt. Baker Snoqualmie National Forest, Mountlake, WA.

Eubanks, C.; Meadows, D. 2002. A soil bioengineering guide for streambank and lakeshore stabilization. FS683. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 187 p.

Fausch, K.D.; Rieman, B.E.; Young, M.K.; Dunham, J.B. 2006. Strategies for conserving native salmonid population at risk: tradeoffs in using barriers to upstream movement. Gen. Tech. Rep. RMSR-GTR-174. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 44 p.

Fischenich, C. 2001. Stability thresholds for stream restoration material. EDRC TN-EMRRP-SR-29. Vicksburg, MS: U.S. Army Corp of Engineers Research and Development Center, Environmental Laboratory. 10p.

Flanagan, S. A.; Furniss. M. J. 1997. Field indicators of inlet-controlled road-stream-crossing capacity. Gen. Tech. Rep. 9777 1807–SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

French, J.; Ing, R.; Von Allmen, S.; Wood, R. 1983. Mortality from flash floods: a review of National Weather Service reports, 1969-1981. Public Health Reports 98(6):584-588.

Furniss, M. J.; Roelofs, T. D.; Yee, C. S. 1991. Road construction and maintenance. In: Meehan, W. R. ed. Influences of forest and rangeland management on salmonid fishes and their habitat. Bethesda, MD: American Fish Society: 297-324. Special Publication 19, Chapter 8.

Gagen, C. J.; Rajput, S. 2002. The effects of road crossings on fish community structure and abundance in streams of the Ouachita Mountains. Report to the Ouachita National Forest. Hot Springs, AR: Arkansas Technical University, Russellville, AR.

Gibson, Bill. 2005. Personal communication. U.S. Department of the Interior, Bureau of Land Management, Arizona State Office, Phoenix, AZ.

Golden, H. 2002. Personal communication. Fisheries biologist, USDA Forest Service, Bighorn National Forest, Sheridan, WY.

Gray, D.; Sotir, R. 1996. Biotechnical and soil bioengineering slope stabilization—a practical guide for erosion control. New York: John Wiley and Sons, Inc. 378 p.

Groenier, Scott. 2005. Personal communication. Engineer, USDA Forest Service, Missoula Technology and Development Center, Missoula, MT.

Gu, R. R.; Bousselot, A. J.; Waugh, R. A. [and others]. 2003. Low-water crossing study: Volume 1. Literature review. DTFH68-02-C-00024. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 124 p.

Gu, R. R.; Waugh, J.; Lohnes, R. A.; Klaiber, F.W. 2005. Low-water crossing study: design approach. FHWA-CFL/TD-05-013. Lakewood, CO: U.S. Department of Transportation, Central Federal Lands Highway Division. 136 p. Vol. II.

Gubernick, B.; Bates, K. 2003. Design and construction of aquatic organism passage at road-stream crossings: stream simulation. In: 2003 Proceedings of the International Conference on Ecology and Transportation. Edited by C. Leroy Irwin, P. Garrett, and K. P. McDermott. Raleigh, NC: Center for Transportation and the Environment, North Carolina University. 10 p.

Hardy, T.; Panja, P.; Mathias, D. 2005. WinXSPRO, a channel cross section analyzer. User's manual, version 3.0. Gen. Tech. Rep. RM-147. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 94 p.

Harrelson, C. C.; Rawlins, C. L.; Potyondy, J. P. 1994. Stream channel reference sites: an illustrated guide to field technique. Gen. Tech. Rep. RM-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 61 p.

Harris, G. 2001. Personal communication. North zone hydrotechnician, Idaho Panhandle National Forest, Sandpoint, ID.

Hyman, W. A. and Vary, D. 1999. Best management practices for environmental issues related to highway and street maintenance. National Cooperative Highway Research Program Synthesis of Highway Practice 272. National Academy Press. Washington, DC: Transportation Research Board, National Research Council.

Jackson, S. 2003. Design and construction of aquatic organism passage at road-stream crossings: ecological considerations in the design of river and stream crossings. In: 2003 Proceedings of the International Conference on Ecology and Transportation, Irwin, C. L.; Garrett, P.; McDermott, K. P. eds. Raleigh, NC: Center for Transportation and the Environment, North Carolina State University.

Jacobson, R. B.; Primm, A. T. 1997. Historical land-use changes and potential effects on stream disturbance in the Ozark Plateaus, Missouri. U.S. Geological Survey Water-Supply Paper 2484. 95 p.

Jennings, M. E.; Thomas, W. O.; Riggs, H. C. 1994. Nationwide summary of U.S. Geological Survey regional regression equations for estimating magnitude and frequency of floods for ungauged sites, 1993. Water Resources Investigation Report 94-4002. Reston, VA: U.S. Geologic Survey. 38 p. Prepared in cooperation with FHWA and Federal Emergency Management Agency.

Johnson ,P.; Gleason, G.L.; Hey, R.D. 1999. Rapid assessment of channel stability in vicinity of road crossing. J Hydraulic Engineering 125(6):645-651.

Kattell, J.; Eriksson, M. 1998. Bridge scour evaluation: screening, analysis, and countermeasures. Gen. Tech. Rep. 9877 1207–SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

Lagasse, P. F.; Byars, M. S.; Zevenbergen, L. W.; [and others]. 1997. Bridge scour and stream instability countermeasures. Hydraulic Engineering Circular 23 (HEC-23). FHWA HI-97-030. Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

Lagasse, P. F.; Schall, J. D.; Johnson, F.; [and others]. 1995. Stream stability at highway structures. Hydraulic Engineering Circular 20 (HEC-20). FHWA HI-96-032. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 144 p.

Lane, J. 2002. Personal communication. U.S. Department of Agriculture, Custer National Forest, Billings, MT.

Leopold, L. B.; Wolman, M. G.; Miller, J. P. 1964. Fluvial processes in geomorphology. San Francisco, CA: W. H. Freeman & Co. 522p.

Leopold, L. B. 1994. A view of the river. Cambridge, MA: Harvard University Press. 298 p.

Lohnes, R. A.; Gu, R. R.; McDonald, T.; [and others]. 2001. Low-water stream crossings: design and construction recommendations. CTRE Project 01-78. Ames, IA: Center for Transportation Research and Education, Iowa State University.

Loomis, Grant. 2002. Personal communication. U.S. Department of Agriculture, Forest Service, Tonto National Forest, Phoenix, AZ.

Lydecker, Allen. 1973. Use of gabions for low water crossings on primitive or secondary forest roads. Engineering Technical Information Series, Field Notes, Volume 5, No 5 and 6, May-June 1973. Washington, DC: U.S. Department of Agriculture, Forest Service. pp. 13-16.

McCuen, R. H.; Johnson, P. A.; Ragan, R. M. 2002. Highway hydrology. Hydraulic design series No. 2. Pub. No. FHWA-NHI-02-001. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 424 p.

McCullah, J; Gray, D. 2005. Environmentally Sensitive Channel and Bank Protection Measures. National Cooperative Highway Research Program Report 544. Washington, DC: Transportation Research Board, National Research Council. 50 p. plus CD.

McDougal, L. A.; Russell, K. M.; Leftwich, K. N. (eds) 2001. A conservation assessment of freshwater fauna and habitat in the southern National Forests. R8-TP 35. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southern Region. 141 p.

McNemar, R.1983. Use of pre-cast concrete ramp planks for low-water crossings. Engineering Field Notes vol 15, April-June. Washington DC: U.S. Department of Agriculture, Forest Service.

Motayed, A. K.; Chang, F. M.; Mukherjee, D. K. 1982. Design and construction of low-water stream crossings. Report No. FHWA/RD-82/163. Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

Neiman, J. (2005) personal communication. Engineer, U.S. Department of Agriculture, Forest Service, Idaho Panhandle National Forest, Sandpoint Biotechnical Zone, Sandpoint ID.

Normann, J. M.; Houghtalen, R. J.; Johnson, W. J. 1985. Hydraulic design of highway culverts. Reprinted. Hydraulic Design Series 5. FHWA-NHI-01-020. Washington DC: U.S. Department of Transportation, Federal Highway Administration. 376 p.

Pence, L. M. 1987. A plastic ford—-you've got to be kidding. Engineering Field Notes. Washington, DC: U.S. Department of Agriculture, Forest Service.

Plocher, K. 2001. Skull Creek GEOWEB Crossing-Duck Valley Reservation. Humboldt-Toiyabe National Forest Construction Report. Reno, NV: U.S. Department of Agriculture, Forest Service Toiyabe National Forest.

Racin, J. A.; Hoover, T.; Avila, C. 1996. California bank and shore rock slope protection design—practitioner's guide and field evaluations of riprap methods. FHWA-CA-TL-95-10. Sacramento, CA: State of California, Department of Transportation.

Reid L. M.; Dunne, T. 1984. Sediment production from forest road surfaces. Water Resources Research. 20(11) 1753-1761.

Richardson, E. V.; Davis, S. R. 1995. Evaluating scour at bridges. Hydraulic Engineering Circular No. 18. Pub. No. FHWA-HI-96-031. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 204 p.

Ries III, K. G.; Crouse, M. Y. 2002. The National Flood Frequency Program, version 3: a computer program for estimating magnitude and frequency of floods for ungaged sites. Water-Resources Investigations Report 02-4168. http://pubs.usgs.gov/wri/wri024168/#pdf (9/12/06).

Rosgen, D. L. 1994. A classification of natural rivers. Catena. 22: 169-199.

Rosgen, D. L. 1996. Applied River Morphology. Pagosa Springs, CO: Wildland Hydrology. 354 p.

Sampson, H. 2002. Personal communication. Engineer. U.S. Department of Agriculture, Forest Service, Klamath National Forest, Yreka, CA.

Schall, J. D.; Richardson, E. V.; Morris, J. L. 2001. Introduction to highway hydraulics. Hydraulic Design Series No. 4. Pub. No. FHWA-NHI-01-019. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 214 p.

Skordinsky, Mary. 2005. Personal communication. U.S. Department of the Interior, National Park Service, Agua Fria National Monument, Phoenix, AZ.

Taylor, S. E.; Rummer, R. B.; Yoo, K. H.; [and others]. 1999. What we know and don't know about water quality at stream crossings. Journal of Forestry 97(8):12-17.

Theisen, M. 1997. The Expanding Role of Geosynthetics in Erosion and Sediment Control. GPD-SM-200. Chattanooga, TN: SI GeoSolutions.

U.S. Army Corps of Engineers. 1991a. Hydraulic design of flood control channels. EM 1110-2-1601. Reston, VA: U.S. Army Corps of Engineers. ASCE Press. 120 p.

U.S. Army Corps of Engineers. 1991b. HEC-RAS U.S. Army Corps of Engineers. http://www.hec.usace.army.mil/software/hec-ras/ (9/6/06).

U.S. Department of Agriculture, Forest Service. 1987. Forest Service Handbook 7709.56: Road Preconstruction Handbook. Washington, DC: U.S. Department of Agriculture, Forest Service.

U.S. Department of Agriculture, Forest Service. 1995. A guide for field identification of bankfull stage in the western United States. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Stream Systems Technology Center. 31-minute video.

U.S. Department of Agriculture, Forest Service. 1999. Road analysis: Informing decisions about managing the national forest transportation system. FS-643. Washington, DC: U.S. Department of Agriculture, Forest Service. 222 p.

U.S. Department of Agriculture, Forest Service. 2000. Water quality management for national forest system lands in California - best management practices. Vallejo, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region. 186 pp.

U.S. Department of Agriculture, Forest Service. 2001. Forest Service Handbook 7709.56b: Transportation Structures Handbook. Washington, DC: U.S. Department of Agriculture, Forest Service.

U.S. Department of Agriculture, Forest Service. 2003. Identifying bankfull stage in the forested streams in the eastern United States. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Stream Systems Technology Center. 46-minute DVD.

U.S. Department of Agriculture, Forest Service. 2005. Best management practices: water quality management for nonpoint source pollution. Draft. On file with: S. Hazelhurst, USDA Forest Service Water Quality Program Leader, Washington DC.

U.S. Department of Agriculture, Forest Service. 2005. Forest Service Manual 7720: Transportation System Development. Washington, DC: U.S. Department of Agriculture, Forest Service.

U.S. Department of Agriculture, Forest Service. 2005. Sign and poster guidelines for the Forest Service. EM 7100-15. Washington, DC: U.S. Department of Agriculture, Forest Service, Engineering.

U.S. Department of Agriculture, Natural Resources Conservation Service. 1996. Chapter 16, streambank and shoreline protection. Engineering field handbook. Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service.

U.S. Department of Agriculture, Soil Conservation Service. 1992. Chapter 18, soil bioengineering for upland slope protection and erosion reduction. Engineering field handbook. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service [Natural Resources Conservation Service]. 62 p.

U.S Department of Transportation, Federal Highway Administration. 1961. Design charts for open channel flow. Hydraulic Design Series 3 (HDS 3). Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

U.S. Department of Transportation, Federal Highway Administration. 1983. Hydraulic design of energy dissipators for culverts and channels. Hydraulic Engineering Circular 14 (HEC 14). FHWA EPD-86-110. Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

U.S. Department of Transportation, Federal Highway Administration. 2003. Standard Specifications for construction of roads and bridges on Federal Highway projects (FP 03-US Customary Units). FHWA-FLH-03-002. Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

Warhol. T. 1994. An evaluation of stream crossing culverts and low-water fords in the western Cascades of Oregon. Corvallis, OR: Oregon State University. Department of Civil Engineering. 64p. Thesis.

Warhol, T.; Pyles, M. 1989. Low-water fords: an alternative to culverts on forest roads. Proceedings of 12th Annual Council on Forest Engineering Meeting at Coeur d'Alene, ID. Corvallis, OR: Council on Forest Engineering. Pages unknown.

Webb, B.1994. Deep Creek low-water crossing, Osceola National Forest. Engineering Field Notes Vol. 26:3-6. Washington, DC: U.S. Department of Agriculture, Forest Service, Engineering.

Wilson, C. 2006. Personal communication. Director, Fisheries Experiment Station, Utah Division of Wildlife Resources. Logan UT.

Wilson, W. E.; Moore, J. E. eds. 1998. Glossary of hydrology. Alexandria, VA: American Geological Institute. 248 p.

Zeedyk, W. D. 1996. Managing roads for wet meadow ecosystem recovery. Gen. Tech Rep. FHWA-FLP-96-016. Albuquerque, NM: U.S. Department of Agriculture, Forest Service, Southwest Region. 76 p.

A

AASHTO	American Association of State Highway and Transportation Officials. This group is responsible for developing most of the bridge and highway standards used in America today.
Aggradation	The process by which sediment deposition builds up the channel bed so that it rises in elevation. Aggradation occurs when the supply of sediment to the stream exceeds the stream's ability to transport it.
Aggraded channel	A channel where sediment deposition has built the streambed up to a higher elevation.
Aquatic organisms	Species that live only or principally in the water.

B

Bankfull flow	The flow that just overtops the streambank as it begins to flow over the flood plain. It is the flow at which channel maintenance is most effective; that is, the discharge at which the stream is moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels. In many streams, bankfull flow has an approximate recurrence interval of 1.5 years (Dunne & Leopold 1978).
Baseflow	That part of the stream flow not derived from direct runoff from precipitation or melting snow. It is sustained by ground water inflows. (Wilson and Moore 1998)
Bedload	That portion of the total stream sediment load that is in transport along the bed. Particles moving as bedload (e.g., rocks, gravel, sand) roll or saltate (bounce or skip) along the streambed.

C

Channel-forming flow	A single discharge rate taken to represent the range of flows that determine channel parameters such as cross sectional geometry and meander wavelength. Because this flow rate is relatively high and occurs relatively frequently, it transports the most sediment and is also called effective or dominant discharge. It is often equated with bankfull discharge.
Channel function	Channel functions include transport of water and energy downstream and over the flood plain, erosion, transport and deposition of sediment debris and other watershed products, and provision of aquatic habitats.

Channel incision	The process by which a channel bed erodes vertically downward below the surrounding ground. Figure 3-2 b shows an incised channel. (See also degradation.)
Confined channel	A channel that is limited in its ability to move laterally across the valley floor. Generally a channel is confined because its valley is narrow and valley side slopes constrain the channel's ability to meander. Figure 2-1b shows a confined channel.

D

D_{50}	The median particle size in a streambed, generally determined by a Wolman pebble count (Harrelson 1994) or a sieve analysis. Fifty percent of streambed material is smaller than D_{50}.
Degradation	The lowering of the channel bed due to scour or headcutting.
Degrading stream	A channel undergoing degradation (downcutting).
Distributary channel	A divergent stream flowing away from the main stream and not returning to it, as in a delta or alluvial fan. It may be produced by stream deposition choking the original channel (Wilson and Moore 1998). On fans where sediment deposition is actively occurring, distributaries can shift their location frequently.

E

Embedded culvert	A culvert with the invert sunk beneath the streambed surface, so that streambed material is present throughout.
Entrenchment	The vertical containment of a river. An entrenched stream cannot spread very much as water level rises, either because it is incised in the valley floor, or because steep, valley slopes constrain it. See figure 2.1.
Entrenchment ratio	The ratio of the width of the flood-prone area to the surface width of the bankfull channel. (Rosgen 1996) The flood-prone-area width is measured at the elevation that corresponds to twice the maximum depth of the bankfull channel.
Ephemeral stream	A stream that flows briefly in response to precipitation events or other direct short-term water inputs.
Expected high water level	The level that water in a stream or river is expected to reach during a major storm event, such as a 50- to 100-year storm.

F

FP-03	Shorthand designation for the Federal Highway Administration's "Standard specifications for construction of roads and bridges on Federal highway projects" (Federal Highway Administration 2003). These specifications are currently used by the USDA Forest Service and FHWA. They are in customary U.S. units and in metric units.
Flood plain	A flat land area, adjacent to the stream that the river is building in the current climate. Planners and engineers also use the term to refer to any area inundated during a flood of a specific return interval. In this case, the 100-year flood plain is the area inundated by water during a 100-year flood (Dunne and Leopold 1978).
Floodprone area	The area submerged when flow depth is double the maximum depth of the bankfull channel. (Rosgen 1996)
Flow capacity	The volume of water that can pass through a structure, usually measured in cubic feet per second.
Freeboard	That part of the armored crossing structure that is above the water surface at the high design flow.

G

Gabions	Woven metal wire baskets, typically in multiple dimensions of a yard or meter, used to confine rock and form a footing, abutment, retaining wall, or offer streambank stabilization, or scour protection around structures. They are backfilled with 4- to 8-inch rock. They can be galvanized or provided with a plastic coating to minimize corrosion.
Geocells	A plastic (typically high density polyethelene) cellular confinement system used to confine sand or aggregate. They are used to armor roadways, fords, boat ramps, in retaining walls, and other structures. They come in variable heights, diameters, and are solid or perforated for drainage.
Grade control	Any natural or man-made structure that controls streambed elevation at a cross section (e.g., a dam, culvert, debris jam, rock, or concrete weir, etc.). Grade controls can prevent a headcut from migrating upstream.

H

HS 20-44	The designation for the structural load from a legally loaded, 80,000-pound semi-truck and trailer.
Headcut	A stream segment where the streambed is actively incising (downcutting). Depending on streambed materials, headcuts can be vertical or near vertical (resistant rock or clay), or the segment can simply be steeper than normal (sand and gravel). Headcuts move upstream with time as the steeper section erodes to the new streambed elevation and stabilizes.
High design flow	The high water level or flow volume that can be expected in relation to a structure being built into a stream channel. Generally, structures are designed large enough to pass the high design flow.

I • J • K • L

Improved ford	A stream crossing at or near streambed elevation that has been shaped and surfaced with any of a number of possible materials (rock, concrete, asphalt, etc.)
Incised channel	A channel that has downcut relative to the surrounding ground. Incised channels are generally entrenched.
Intermittent stream	A stream that flows for an extended period at certain times of year, such as during snowmelt or the rainy season. The term is commonly applied to streams that flow continuously longer than a month (Wilson and Moore 1998).
Jersey barrier	The common name for precast concrete beams used in highway medians or for temporary separation of lanes. They are typically about 3 feet high, 10 feet long, and taper from a foot-wide base to about a half-foot thickness on top. They are also called "K-rail."
Key in	To construct a wingwall, apron, or other scour protection measure to extend some distance back into the soil area (e.g., streambed, streambank) that it is designed to protect. The purpose is to ensure the structure will continue to function even if some erosion does occur.
Low-water bridge	A structure without a solid floor (i.e., built on spread footings or other foundation) that is designed to be overtopped at some frequency. This definition is not the same as that used by USDA Forest Service and Federal Highways Administration for bridge inventories, where any structure with a span wider than 20 feet is considered a bridge.

M

Maintenance level	The designation given to National Forest System roads to identify the standard of road, what type of vehicle it supports, and how often it is likely to receive maintenance work. Levels 1 through 5 are used in the Forest Service, with Maintenance Level 1 being a road closed to motorized vehicles, while Maintenance Level 5 roads are typically paved highways that accommodate all tvehicles.
Maximum expected high water level	See "expected high water level". This is the highest level to which water is expected to rise.
Mean annual flow	The total volume of water that passes through a stream location in a year divided by the number of seconds in the year. In the United States, the common unit of measure is cubic feet per second.

N • O • P • Q

Normal low-water level	(see baseflow)
Object marker	Plastic or carsonite markers that are placed at the entrance to bridges or fords to identify the corner of the structure. They typically have chevrons painted on them to help visually identify the traveled way.
Perennial stream	A stream or reach of stream that flows year round. The bed of a perennial stream is below the adjacent water table.
Q_{50}	The 50-year recurrence interval flow. The discharge that occurs on average once every 50 years. $Q_{½}$ is the flow expected to occur or be exceeded 2 times per year on average (i.e., the recurrence interval is ½ year). Q_2 is the 2-year recurrence interval flow, which is expected to be exceeded once every other year on average. In many streams Q_2 approximates bankfull flow.

R

Ramp up	Raising a roadfill up to a crossing structure that is higher than the ground surface because of the need to provide enough capacity for very large flood flows and debris. Ramping the roadfill up across a flood plain means the roadfill blocks some or all of the overbank flows on the flood plain.
Reno mattress	A large wire basket filled with cobble or gravel (gabion basket) placed on a streambed or banks to prevent scour. Baskets vary in width and length, but are typically only 1-foot thick.

Road-user costs	All costs that accrue to the road user while operating and maintaining his/her vehicle. These include vehicle operating and running costs, maintenance and depreciation, travel time, traffic delays, and accident costs.

S

Second-order stream	A stream with at least one tributary. A first-order stream has no tributaries. Where two first-order streams come together, they form a second-order stream. Where two second-order streams come together, they form a third-order stream. A second-order stream can have any number of first-order tributaries, and a third-order stream can have any number of first- and second-order tributaries. Where a third-order stream joins another third-order stream, they become a fourth-order stream.
Sediment load	The volume of sediment moving in the stream over a given time period, usually reported as weight per unit time.
Stormproofing	The process of making a road, structure, or watershed resistant to flood damage. Includes planning and design measures as well as physical onsite-mitigation measures. Examples are: providing adequate road drainage, designing crossings to avoid diverting flood flows down the road, strengthening revetments, adding riprap or other armor to erodible surfaces, etc.
Stream simulation	A method of designing road-stream crossing structures (usually culverts) in which the streambed is continuous through the structure. The goal is to create a selfsustaining streambed inside the structure that is as similar as possible to the natural channel. A stream simulation should present no more of an obstacle to aquatic organisms than the natural channel itself.

T • U

Terrace	Terraces are abandoned flood plains. As a stream downcuts, at some point it may abandon its flood plain; that is, at the new, lower elevation the stream is no longer able to overflow the flood plain on a frequent basis and is therefore no longer constructing it. The former flood plain is then termed a terrace.
Unimproved ford	Any stream crossing created by traffic only; that is, a crossing at streambed elevation that has not been graded, shaped, or hardened except by the action of traffic.
Unstable channel	A channel that is changing rapidly. It may be incising, aggrading, or shifting quickly enough to change its location, elevation, width, slope, or other major characteristic on an engineering time scale.

Unvented ford — A stream crossing structure without culverts or other provision for low flows to pass underneath. All stream flow must pass over the surface of an unvented ford.

V • W • X • Y • Z

Vent-area ratio — The ratio of the cross sectional area of the vent opening (e.g., culvert or box) in a vented ford to the cross sectional area of the bankfull channel.

Vented ford — A crossing structure where relatively frequent overtopping is expected, but where the driving surface is elevated some distance above the streambed. Culverts (vents) allow low flows to pass beneath the roadbed.

Wetted perimeter — That part of the cross section of a ford or stream that is submerged at any given flow. In ford design, it frequently means the portion of the structure submerged by the high design flow. Unit of measurement is feet.

Appendix A Table of Contents

Case Studies

Appendix A—Case Studies

Structures highlighted in BLUE in table A1 are similar to the numbered case study just above them. Their descriptions are included at the end of that case study under the heading Similar Structures in Other Locations.

Table A1—Case study index by structure type.

	Crossing Name	Forest	State	Structure Type
		Unvented Fords		
1	Red Clover	Plumas	California	Rock dip
2	20-mile Cr	Okanagan	Washington	Rock dip
3	Nurse Cr	Umpqua	Oregon	Large-rock fill
		Idaho Panhandle	Idaho	Vented rock fill structure
4	FR 732	Prescott	Arizona	Jersey barriers/riprap
	7-Springs Rd	Tonto	Arizona	Jersey barriers/gabions
5	Willow Cr	Plumas	California	Concrete planks
6	Fitzpatrick Cr	Coos Bay BLM	Oregon	Concrete blocks
	E. Fk. So. Tongue R; Copper Cr	Bighorn	Wyoming	Concrete blocks
7	Woodrock	Bighorn	Wyoming	Geoweb
	Little Brush Cr	Ashley	Utah	Geoweb
8	Agua Fria R	Tonto	Arizona	Concrete slab
	Ashdale Admin Site	Tonto	Arizona	Concrete slab
		Vented Fords		
9	Messman	Fremont	Oregon	Concrete slab with slot
10	Black Canyon	Clearwater	Idaho	Concrete planks with culvert
11	Babcock	Plumas	California	Concrete w/culverts
	Harris Creek	Ouachita	Arkansas	Concrete w/culverts
12	Grubbs	Plumas	California	Concrete slab with grated top vent
13	N Fk Consumnes R	Eldorado	California	Concrete box w/grated top
14	Rocky Cr	Ouachita	Arkansas	Concrete box w/curbs
	FR 512	Ouachita	Arkansas	Embedded concrete boxes
15	Moonlight	Plumas	California	Concrete box w/fish ladder
16	Sibley Cr	Mt Baker Snoqualmie	Washington	Concrete box-removable top
	Catherine Cr	Industrial land	British Columbia	Large-rock fill
17	Stoney R	Superior	Minnesota	Embedded timber boxes
18	French Cr	Plumas	California	Embedded concrete boxes
19	Mill Cr	Mark Twain	Missouri	Embedded concrete boxes
	Kincaid	Shawnee	Illinois	Embedded concrete boxes
		Low-water Bridges		
20	Deep Cr	Osceola	Florida	Double T-sections w/concrete deck
21	Capps	Eldorado	California	Concrete piers; cattleguard
	Jones Wreckum	Eldorado	California	Concrete piers; cattleguard

Appendix A—Case Studies

Introduction to the Case Studies

Traffic use, hydrologic regime, available materials, channel type, stability, and aquatic species passage needs are all critical variables affecting the choice of structure type at a site and its success. Each crossing situation involves a unique combination of these variables, so each site is an individual engineering challenge. The following case studies illustrate a variety of structure types in different hydrogeographic areas around the country. Studying examples like these is the best way to learn from other people's experience, and the case studies should help you generate ideas for fitting new structures to individual sites.

Most of the structures described here are compromises, because the fit of the structure to the road, landform, or stream is rarely perfect. The structures are of very different ages, representing the development of low-water crossing design over the past few decades. Some demonstrate popular designs that have worked well in the past from a transportation or road-use perspective but which caused channel erosion and blocked aquatic species. Many have required repairs or improvements to make the structure functional today. Few achieve all the goals we would set for new structures. However, both their flaws and their successes demonstrate important points about locating, designing, and constructing low-water crossings. Use them as a resource to help you learn from, rather than repeat, the experiences of others.

About the case studies:

- The "Crossing Description" section, at the beginning of each case study, highlights the key points about the structure and is intended as a summary for people browsing through the appendix.
- Ecological unit information, under the "Setting" heading in each case study, comes from McNab and Avers' (1994) descriptions of the ECOMAP sections, shown on the map "Ecoregions and Subregions of the United States." In some instances, where forests have completed landtype mapping, the sections include more details.
- We frequently cite Rosgen's (1996) channel types. Because we identified the channels only visually, consider our classifications as estimates.
- Information was available in different levels of detail. We have attempted to be as consistent as possible in describing and evaluating the structures. However, in some cases, information supporting an informed judgment about performance was not available.

Appendix A—Case Studies

The case study index (table A1) is arranged by structure type. Table A2 lists the case studies by channel characteristic, so that users confronted by a certain channel type can see which structures have or have not worked in a similar channel. We also list flow regime (perennial, intermittent, ephemeral) and special site considerations that pertain to each case study.

Table A2. Case studies indexed by channel characteristics and streamflow regime.

Channel Characteristic	Flow Regime	Fishery	Structure Type	Name	Case Study Number	Special Design Considerations
Unentrenched	Intermittent	Y	Unvented ford	20-mile	2	Spring trout spawning; seasonally closed road
	Perennial	Y	Unvented ford with slot	Messman	9	Juvenile trout passage in summer; headcut control
	Perennial	Y	Vented ford	Mill	19	Debris-jamming hazard (wood)
	Perennial	Y	Vented ford	French	18	Wide floodplain; high stream power; debris
	Perennial	Y	Low-water bridge	Deep	20	Very low gradient; wide floodplain; soft soils
Moderately Entrenched	Ephemeral	N	Unvented ford	Red Clover	1	Discontinuous, poorly defined channel
	Ephemeral	N	Unvented ford	732 Road	4	Flow diversion down riparian road; channel downcutting
	Perennial	Y	Unvented ford	Woodrock	7	Compressible stream-bank soils; RVs and ATVs
	Perennial	Y	Vented ford	Stoney	17	Damming (ice); scenic values
	Perennial	Y	Vented ford	Rocky	14	Summer passage for weak-swimming fish; debris
	Perennial	Y	Vented ford	Babcock	11	Trout passage; reservoir releases
	Perennial	Y	Vented ford	Grubbs	12	Trout passage; very high stream power; coarse sediment
	Perennial	Y	Vented ford	North Consumnes	13	Juvenile trout passage; debris flow deposition zone
	Perennial	Y	Low-water bridge	Capps	21	Pre-existing channel damage—widened channel

Appendix A—Case Studies

Table A2. *Continued.*

Channel Characteristic	Flow Regime	Fishery	Structure Type	Name	Case Study Number	Special Design Considerations
Entrenched	Perennial	N	Unvented	Nurse	3	Steep, high energy stream
	Perennial	Y	Unvented	Willow	5	Trout passage; channel incision at tributary junction
	Perennial	Y	Vented	Fitzpatrick	6	Aquatic organism passage; large woody debris
	Perennial	N	Vented	Black Cyn	10	Snow avalanches
	Perennial	N	Vented	Sibley Cr	16	Debris torrents
Laterally Unstable	Intermittent	Y	Unvented	20-mile Cr	2	Spring-spawning steelhead, seasonally closed road; alluvial fan
	Perennial	Y	Vented	French	18	Potential for channel shift if blocked during flood
	Perennial	Y	Low-water bridge	Capps	21	Pre-existing channel and floodplain damage
Vertically Unstable	Perennial	Y	Unvented	Mesman	9	Grade control, fish passage
	Perennnial	Y	Vented	Moonlight	15	Grade control, fish ladder
	Perennial	Y	Vented	North Consumnes	13	In depositional zone

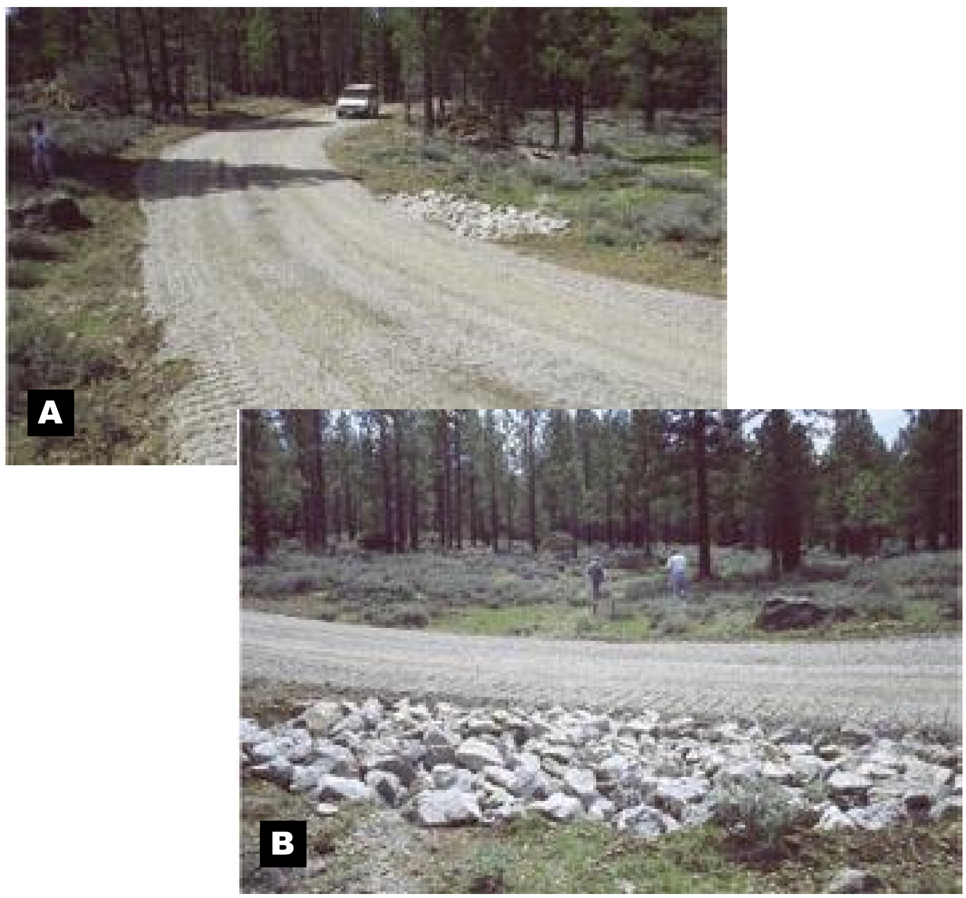
Case Study 1 Red Clover Rock Ford

Location

Northeastern California. Plumas National Forest. An unnamed tributary to Red Clover Creek in McReynolds Valley, 5 miles north of Lake Davis, CA. Forest Road 25N05, Station 82+10 (Red Clover Timber Sale).

Crossing Description

This ford was constructed in 2001 as a simple rock-armored ford across an unnamed ephemeral draw on a road constructed to access a timber sale. The ford is a simple, elongated rolling dip with a riprap-reinforced subgrade with aggregate surfacing and a riprap-armored outlet (figures A1a and A1b). The road is 12 feet wide and the armored portion of the ford is 30 feet long. The entire roadway surface through the dip is approximately 120 feet long. The structure is relatively new so it has only been through two mild winters. This design is the "standard" simple, rock ford.



Figures A1a and A1b. Red Clover rocked dip. Figure A1a. Flow is from left to right across the dip. Figure A1b. View is upstream.

Setting

Eastern Sierra Nevada. The area has broad valleys between granitic and volcanic mountains. This east-side forest area has a light cover of pine and sagebrush at an elevation of 5,410 feet.

Appendix A—Case Study 1

Why Was This Structure Selected?

This structure was chosen because of its minimal cost and because the crossing site is an ephemeral draw that flows only during the early spring, typically before any road use. Traffic volume and type are such that rare interruptions are acceptable. A culvert was considered but not selected due to its higher cost. Maintenance costs are anticipated to be low. This structure was designed and constructed by the Plumas National Forest.

Crossing Site History

This road previously had an unreinforced dip that would either wash out or become soft and rut in the springtime.

Road Management Objective

It is maintained for logging or pickup trucks (USDA Forest Service maintenance level 2), with some sections that are native- and some gravel-surfaced. Annual average daily traffic is 10 vehicles or less, mostly during the summer months. During a timber sale, road use is a mix of logging traffic and USDA Forest Service administrative traffic, with occasional other public use.

This road provides access from lower Red Clover Valley through McReynolds Valley to Squaw Queen Valley and the east side of the forest. The through route is closed during the winter. During the summer, traffic interruptions might occur up to two times per year during intense thunderstorms. These floods can last approximately 4 to 8 hours.

Stream Environment

Hydrology: Average annual precipitation—predominately snow—is approximately 30 inches. The stream is ephemeral, draining approximately 140 acres. The 100-year flow for this very small, flashy watershed is estimated at 75 to 115 cubic feet per second.

Channel Description: The channel is only slightly entrenched with banks that are relatively flat and stable except for local scour at some bends (figure A2). Bank vegetation is coniferous trees, shrubs, and grasses. The channel varies from 4 to 10 feet wide near the site and channel slope is about 3 percent. The substrate is a poorly graded mixture of clayey sands, some gravels, and occasional volcanic rocks.

Figure A2. Measuring bankfull channel dimensions on the ephemeral channel upstream of dip.

Aquatic Organisms: None known.

Water Quality: Sediment delivery and movement in this watershed is a moderate concern since the larger watershed produces significant amounts of sediment. The armored dip is being used to prevent the production of sediment as vehicles drive across this drainage.

Structure Details

Structure: The Plumas National Forest designed this structure as part of the Red Clover Timber Sale road package. The timber purchaser accomplished the road construction. The project took approximately 2 days to construct and required a total of 50 cubic yards of rock. The design involves a simple 1-foot thick reinforced bed of Class II riprap, covered with a 0.4-foot-thick layer of Class II crushed aggregate. A layer of geotextile separates the native soil and Class II riprap (figure A3).

Bank and bed stabilization, and approaches: The outlet to the crossing is armored with several cubic yards of Class VI riprap to prevent downslope scour and serve as an energy dissipator where flow returns to the natural stream channel.

Cost: Cost was estimated at $2,000 in 2001.

Safety: The structure is at grade with the natural stream channel so it presents no more safety hazard than any other part of the road. Crossing of the drainage during high flows is very unlikely because of the low road use.

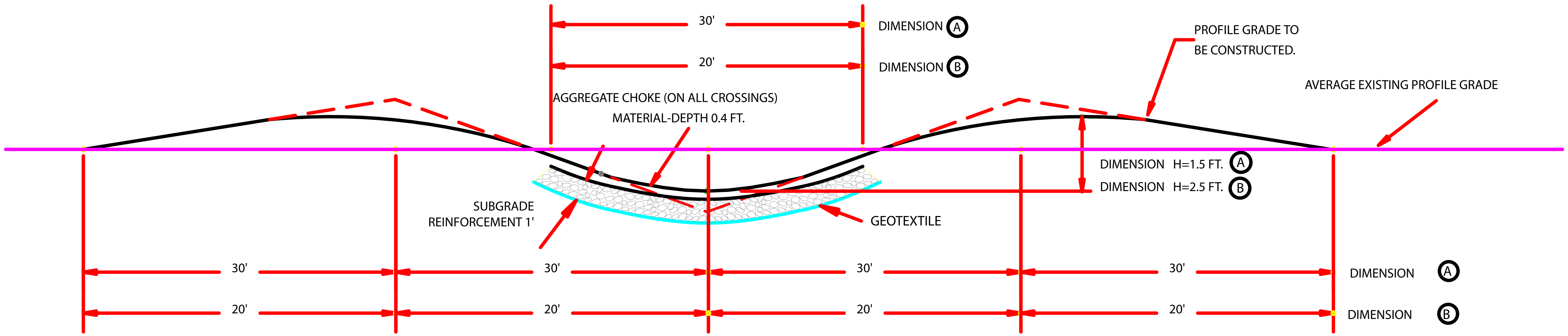
Flood and Maintenance History

The crossing has not yet experienced a large runoff event. The road is bladed once every other year or during periods of intensive use, such as a timber sale. The crossing will require maintenance after high flows, which are expected to remove the aggregate surfacing (choke) material.

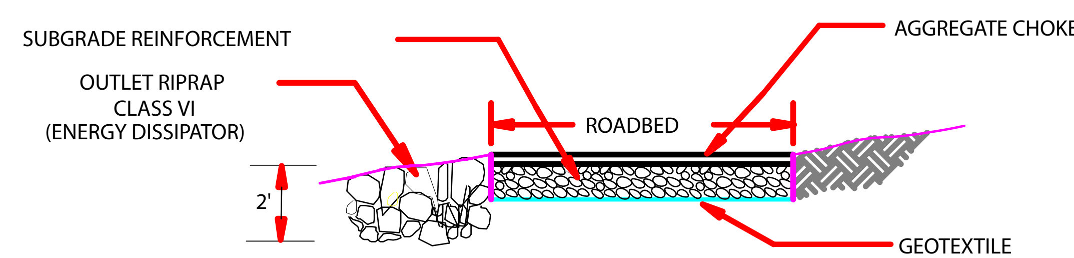
Summary and Recommendations

The Red Clover simple rock ford is an example of a very cost-effective drainage crossing structure for locations with ephemeral channel flows and low road use. Maintenance will be needed across the structure after high flows to replace the aggregate surfacing. The at-grade structure and downstream riprap should prevent scour and sediment loss from the site.

Charlie Carter, design team leader on the Plumas National Forest (retired), designed the structure and provided information for this case study.



PROFILE VIEW



CROSS SECTION VIEW

NOTES:

CONSTRUCT LOW WATER CROSSING AT LOCATIONS SHOWN ON THE DRAWINGS.

ANY BORROW MATERIAL REQUIRED OR EXCESS MATERIAL TO BE WASTED SHALL BE GENERATED OR DISPOSED OF WITHIN 200 FT. ON THE ROAD SURFACE.

OUTLET DIMENSIONS WILL VARY TO CONFORM WITH NATURAL DRAINAGE ELEVATION.

THE MINIMUM SLOPE OF DRAIN SHALL BE -5%.

SUBGRADE REINFORCEMENT ROCK SHALL BE CLASS II RIPRAP WITH AGGREGATE CHOKE, CRUSHED AGGREGATE BASE CLASS GRADATION 2.

IF OUTLET RIPRAP IS SPECIFIED IT SHALL CONFORM TO THE DIMENSIONS SHOWN ON THE ROLLING DIP TYPICAL.

UNLESS SPECIFIED OTHERWISE, SUBGRADE REINFORCEMENT FINISHED WIDTH SHALL BE EQUAL TO THE FINISHED ROADBED WIDTH SHOWN ON DRAWINGS.

GEOTEXTILE IS SPECIFIED, FURNISH AND INSTALL, FUNCTION F, TYPE 3, SECTION 720 SUBGRADE REINFORCEMENT ON ALL LOW WATER CROSSINGS.

LOW WATER CROSSINGS CONSTRUCTED UNDER SECTION 203 SHALL USE TOLERANCE CLASS "A"

(A) DIMENSION: ROAD# 25N05

SEG. I

STA. 32+00
STA. 50+85
STA. 82+10
STA. 101+97

SEG. II

STA. 83+20

(B) DIMENSION: ROAD# 25N05

SEG. I

STA. 23+13

SEG. II

STA. 2+40

U.S. DEPARTMENT OF AGRICULTURE
FOREST SERVICE
PLUMAS NATIONAL FOREST
QUINCY, CALIFORNIA

RED CLOVER
25N05

LOW WATER CROSSING
WITH REINFORCED SUBGRADE

DESIGNED: J.MUNN DATE: 4/01
DRAWN: J.MUNN DATE: 4/01
CHECKED: C.CARTER DATE: 4/01

DATE REVISION BY

DRAWING NAME
LWCTYP.DWG

SHEET 7

Figure A3. Red Clover design drawing.

Case Study 2: Twenty-mile Creek Rock Fords

Location

Washington. Okanagan National Forest. Methow Valley Ranger District. Chewuch river basin, 20-mile Creek or East Chewuch Road.

Crossing Description

The Twenty-mile Creek alluvial fan is a very active depositional zone at the edge of the main Chewuch River valley. In addition to the main channel descending the fan, there are several distributary channels, which are expected to move around frequently. The East Chewuch Road crosses all these channels on the lower part of the fan. The hardened rock fords on distributary channels are inexpensive, low maintenance, and easy to replace if the channels do move. These channels lead to spawning habitat for steelhead at the fan head, and fish have been observed successfully passing on their way upstream. The fords approximate natural channel size and shape and have not required major maintenance since construction in 1999. An old concrete vented ford, believed to block adult steelhead, crosses the main channel.

Figure A4. Hardened rock ford on East Chewuch Road.

Setting

Eastern Cascades (M242-C). Continentally glaciated mountains with steep canyons that end in alluvial fans as they enter the flatter valleys or the larger rivers. Silver fir and Douglas fir communities.

Why Was This Structure Selected?

The dynamic conditions of this alluvial fan site require structures that are easily maintained and inexpensive to replace. Downstream water quality is protected better by a crossing that can pass large debris and rocks than by a culvert prone to plugging. The structure conforms to channel shape and slope, permitting the channel to maintain its natural form and function. The structures allow fish passage during the spawning migration.

Crossing Site History

The original structure in the main fan channel was an 8-foot culvert that was washed downstream in a 1972 flood. At that time, the fan was functioning normally, and bedload and debris deposition at the fanhead frequently caused the main flow to shift location, such that the crossing was at times useless. After the washout, the main channel was straightened and leveed to avoid overflows and to fix the channel in place (figure A5), and the crossing was replaced with a vented ford. The channel modification increased water velocity and the pipe on the ford plugged (figure A6) causing water to divert down the road (figure A7). The modification also impaired the natural water and sediment storage functions of the fan, causing more rapid water and sediment delivery to the Chewuch River during floods. This contributed to a reduction in water quality and, possibly, quantity during low summer flow, which is critical for downstream irrigation and fish habitat.

Figure A5—Twenty-mile creek was channelized near the top of the alluvial fan. Note levee at right of photo.

To reduce sediment input to the Chewuch, and to increase water storage on the fan, the district in cooperation with the Pacific Watershed Institute undertook a channel restoration project in 1999. The levees were breached, and flow was allowed to disperse into several distributary channels down the fan, more closely simulating natural flow patterns. To permit fish passage up the secondary channels, culverts were replaced with the hardened fords described here.

Figure A6—Vented ford plugged with boulders.

Figure A7—Plugged culvert causes water diversion down road before construction of rock fords.

Road Management Objectives

Twenty-mile Creek is an aggregate-surfaced road used principally for hunting, dispersed camping, and recreational driving as part of a recreational loop road. It is gated during spring runoff when the steelhead are migrating. The road is maintained for high-clearance vehicles that can negotiate the moderately steep approaches to the low-water crossings and the large riprap in the bottom of the fords. Constructing the dips resulted in a change of design vehicle from passenger cars to higher clearance vehicles.

Stream Environment

Hydrology: Twenty-mile Creek is a perennial tributary to the Chewuch River with a watershed area of 5.5 square miles. Peak flows occur during spring snowmelt runoff, and less frequently during summer thunderstorms. Since the restoration project, summer flows in the main channel sometimes sink into the fan, while a couple of the secondary channels maintain perennial flow.

Channel Description: Twenty-mile Creek begins as a low gradient channel in high-elevation meadows. It descends through a steep canyon before dropping much of its bedload on the alluvial fan. Before the restoration project described above, the slope of the main fan channel exceeded 3 percent, bankfull width was 30 to 40 feet, and the substrate was small to large boulders arranged in cascades and large steps. Fines were being swept through the system and deposited in the mainstem Chewuch River. After the levees were breached and distributary channels began functioning again, the main channel has gained sinuosity, reduced slope, and is retaining more fines. The distributaries are slightly to moderately entrenched (figure A8). They are about 15 feet wide or less, with slopes of around 3 to 4 percent in the vicinity of the road.

Figure A8—Looking upstream along a distributary channel (hardened dip in foreground).

Aquatic Organisms: Two Upper Columbia Basin endangered species—spring chinook salmon and steelhead trout—as well as redband trout (a sensitive species) use this stream for spawning and juvenile rearing. Resident bulltrout (threatened), west slope cutthroat, and redband are thought to use 20-mile Creek for foraging.

Water Quality: Alluvial fans are dynamic systems, where streamflow infiltrates at the fan head, storing water for later slow release during the summer. Bed material and woody debris also deposit on the fan, causing channel locations to change during high flows. The objective of the restoration project was to reestablish these natural channel processes and alluvial fan functions. The desired end result was to reduce sediment transport to the main stem, increase water storage and summer release, and maintain or enhance fish passage and habitat diversity. Successful accomplishment of these goals should improve water quality in the Chewuch River by reducing sediment and floodwater inputs, and by increasing cool water releases in summer.

Structure Details

Structure: These rock dips are designed to mimic channel dimensions and slope so that water and sediment are transported through the crossing and so that fish can move up through them. The vertical curve is also designed to prevent stream diversion down the road during the 100-year flood (figure A9a). The dips are outsloped at 3 to 5 percent, similar to the slope of the channels. Riprap on the ford surface (a dense mix of Class III and V riprap) is sized to stay in place during the 100-year flood. Although the U.S. Army Corps of Engineers Hydrologic Engineering Center – River Analysis System (HEC-RAS) was not used for this design, it has been used for subsequent ones to make sure the riprap, boulders, and ford width and depth are sized appropriately for the velocity in the stream.

A line of embedded rounded boulders is placed on the downstream shoulder of the ford to maintain the dip shape and to help hold the riprap of the ford surface material in place. The boulders are spaced to trap smaller material from the road but not so close together that they would be a fish passage barrier.

Because the culvert that had been at this site had caused some downcutting downstream, boulders were placed there to trap sediment and raise the channel bed to its original elevation (figure A9b). Again, the rock was sized to mimic the larger rocks in the natural stream channel. The approach appears to be working well.

Cost: Total cost in 1999 (including installation) for the 2-dip project was $18,275.

Safety: No information provided.

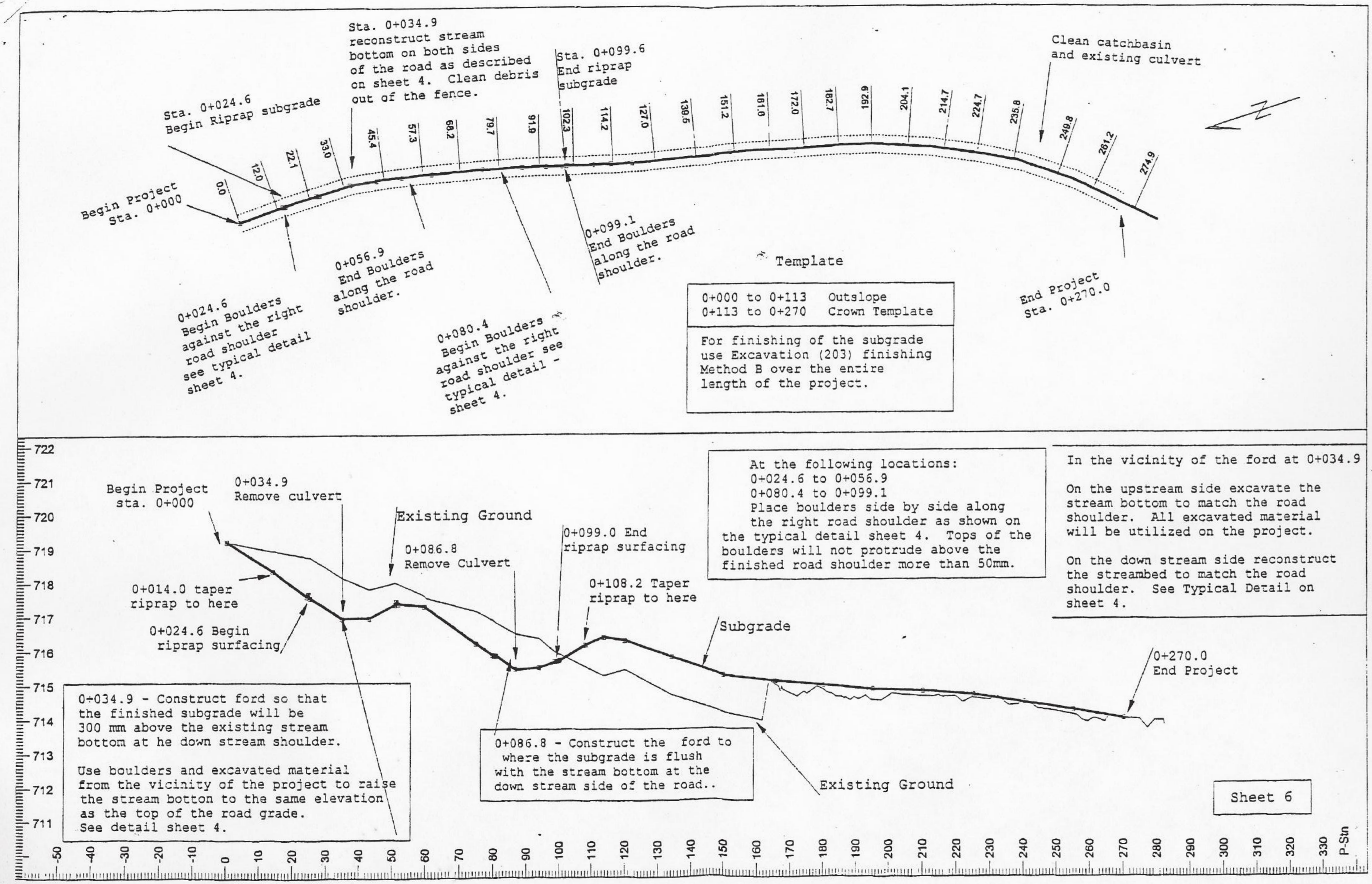


Figure A9a. Ford profile.

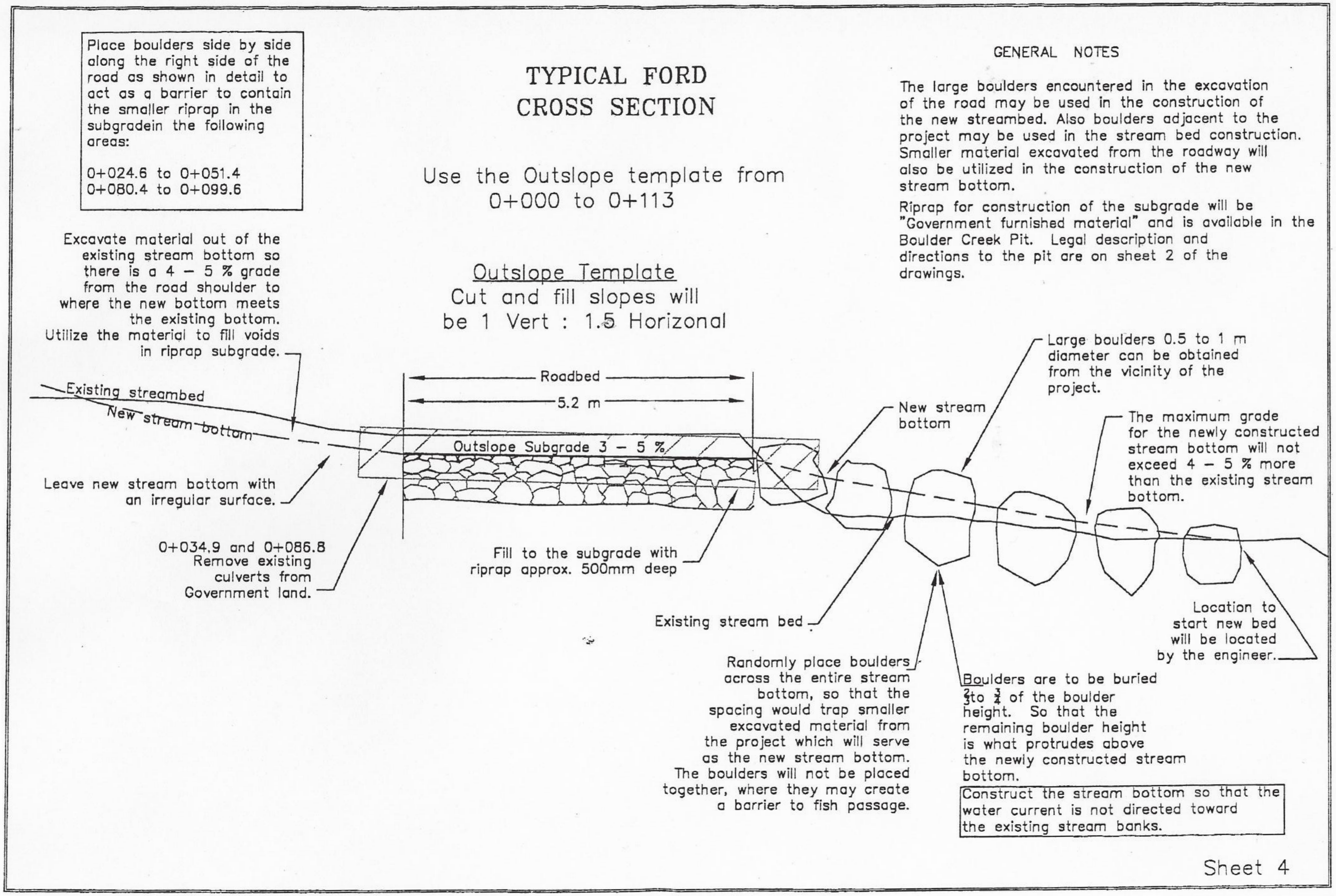


Figure A9b. Cross-section drawings.

Flood and Maintenance History

The structures were built in 1999. They have not experienced a major event and maintenance has been limited to minor reshaping of the approaches. No sediment has required clearing from the roadway. Fish are spawning in the ford, which means the road must remain closed for longer periods in the spring (2 to 3 months).

Figure A10. Hardened dip on East Chewuch Road.

Summary and Recommendations

This example shows the importance of looking at offsite watershed conditions when designing road crossings. Previous channel straightening and confinement with levees had caused significant channel erosion that plugged the vented-ford crossing. Some of the alluvial fan functions that support high water quality and maintain fish habitat were also lost. Restoration required breaching the levees and allowing flow down distributary channels. The rock dips on the distributary channels are a simple, inexpensive way to provide vehicle access in summer without creating a barrier to fish passage. Fish passage is maintained by mimicking natural channel width and slope and by using rock surfacing that is rough enough to keep flow velocities within the range fish can negotiate. Rock dips are also appropriate here because they can be rebuilt easily should channel location change due to depositional patterns at the fan head.

Recommendations from the design engineer:

1. Work with your local hydrologist to estimate stream flows and velocity and do a run with HEC-RAS.

2. Changing this road from one maintained for passenger cars to one maintained for higher clearance vehicles required an adjustment both for public and administrative traffic. In cases such as this, good communication with all affected parties should be considered an essential part of project planning and implementation.

Jennifer Molesworth, fishery biologist on the Methow Valley Ranger District, and David McCormack, engineer on the Okanagan National Forest provided information and photos for this case study.

Case Study 3. Nurse Creek Rock Fill Ford

Location

Southwest Oregon. Umpqua National Forest, Diamond Lake Ranger District, north of Toketee Ranger Station. Nurse Creek, tributary to the North Umpqua River.

Crossing Description

This ford was constructed in 1981 on Nurse Creek, a perennial tributary to the North Umpqua River. To create an acceptable vertical curve crossing this steep, entrenched channel, the channel was filled with large angular rock. Water flows over and through the rock fill. The large riprap necessary for this structure was obtained from nearby roadcuts. The crossing is on a closed road, and has needed no maintenance since it was built.

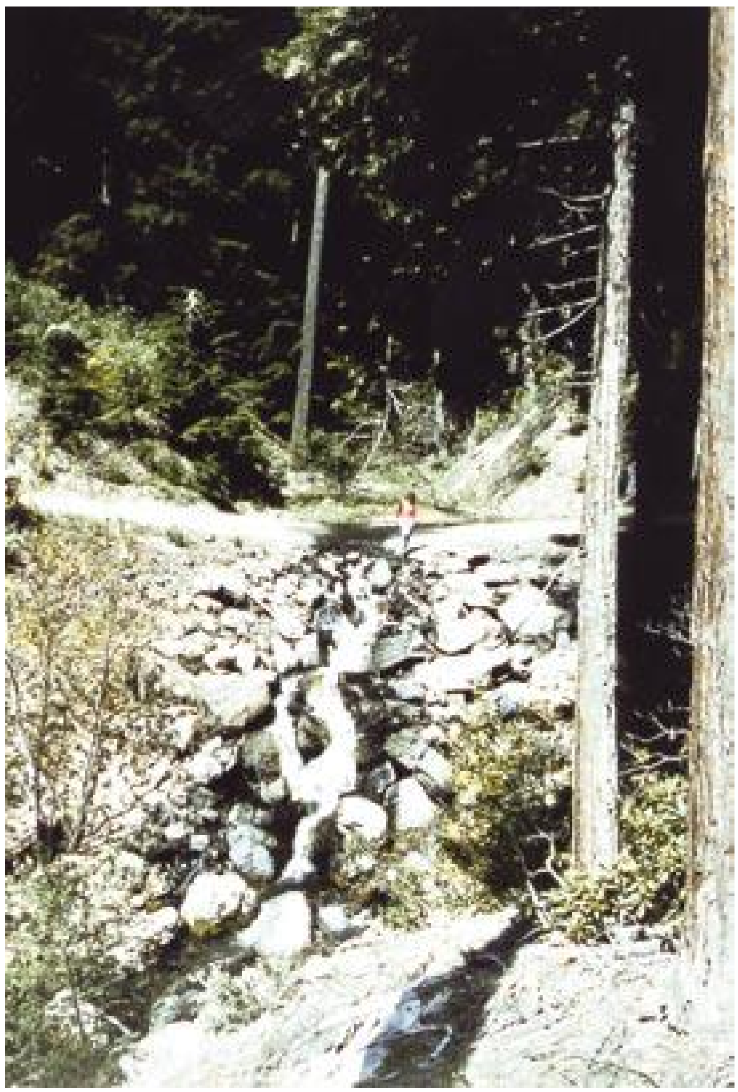


Figure A11. Nurse Creek rock fill ford in 1988

Appendix A—Case Study 3

Setting

Western Cascades Section (M242-B). The section is an uplifted sequence of volcanic and volcanoclastic rocks, interspersed with intrusives that have been dissected by large order riverine systems such as the Umpqua River. Soils have organic matter rich topsoil, and contain volcanic ash. The predominant forests are silver fir-Douglas fir and fir-hemlock. Western red cedar occurs in drainages. This area is about 35 air miles northwest of Crater Lake.

Why Was This Structure Selected?

This structure was selected for low maintenance and to protect downstream water quality and fish habitat. If the structure should wash out, there is no fine sediment in the fill to damage fish habitat in the North Umpqua River.

Crossing Site History

The previous structure at this location, an under-sized corrugated metal pipe, had been overtopped and was washing out.

Road Management Objectives

This road is closed to all motorized use (maintenance level 1). After the timber sale that reconstructed this crossing, the road was gated. No further activities are planned in the area in the foreseeable future.

Stream Environment

Hydrology: Nurse Creek is a perennial stream tributary to the North Umpqua River. The watershed above this crossing location (3,520 feet elevation) is approximately 353 acres (0.55 square miles). Peak runoff occurs during snowmelt. Calculated discharges for the 25-, 50-, and 100-year events are 103, 119, and 136 cubic feet per second respectively.

Channel Description: This is a steep drainage. It is a Rosgen channel type Aa+, with an estimated slope of 15 percent. Banks are stable and riparian vegetation includes brush and conifers. The channel is moderately confined between valley walls, and is both vertically and laterally stable. Basaltic bedrock outcrops occur in the channel and along one bank a few hundred yards above the ford.

Aquatic Organisms: Nurse Creek is too steep to provide fish habitat, so fish passage is not an issue at this crossing. Passage for amphibians may be possible through and over the wet rocks, but this is unknown. A small pool at the upper end of the structure provides habitat for wildlife.

Water Quality: Water quality in the stream is high and this structure probably does not affect it at all. Large riprap and the 1.5-inch minus open-graded surfacing material do not contribute fine sediment. The road itself is aggregate-surfaced and outsloped, minimizing sediment delivery to the stream.

Structure Details

Structure: To construct this rock fill ford, 6 to 8 feet of the previously existing road surface were excavated and replaced with large riprap. The large rock was placed all the way down the fillslope to protect against undercutting. The splash apron also covers the approach fillslopes as they wrap around the steep drainage, so that high flows are focused back to the channel. The dip is designed to contain flows with return intervals exceeding 100 years.

Cost: The ford cost less than $10,000 to construct in 1981.

Safety: The road is closed with a metal gate about 250 feet before the crossing.

Flood and Maintenance History

This structure went through large floods in 1996-97 with little or no damage. After more than 20 years and almost no maintenance, water still flows where it was designed to flow and vegetation has grown up all around the ford. Recently, a snag fell over the ford without damaging its function in any way (figure A12). A beaver has taken up residence in the pool at the inlet.

Figure A12. Snag fallen across the ford August 2004. Note beaver dam at upstream end of roadway.

Summary and Recommendations

The structure is serving its intended purpose well. It is self-maintaining, and transmits high quality water to a downstream fishery stream. For long-term road closures and very steep streams where fish habitat is not an issue, this type of structure appears to fit the geomorphic and biologic environment well. It is clearly a highly stable choice. Figure A13, taken in August 2004 shows the foreslope riprap covered with moss and debris. If the crossing were a big culvert with a big fill, plugging due to the snag's fall could have caused overtopping and fill failure. Even if the existing rock structure should fail, the materials used in construction would not degrade either Nurse Creek or the North Umpqua River.

Figure A13. Stable, moss-covered rocks on the splash apron with pieces of fallen snag. Dashed line indicates approximate road surface.

Steve Nelson, supervisory forester on the Diamond Lake Ranger District, Umpqua National Forest, provided information and photos for this case study.

Similar Structures in Other Locations

Rock fill fords have also been used successfully on the Klamath National Forest in steep drainages moving considerable woody debris after forest fires. Traffic delays and fish passage were not issues in those situations. Passage for other aquatic organisms was not considered when the fords were built, and it is unknown whether they are barriers or not. With time the voids between the rocks tend to plug so that less and less water filters through the structure and more water flows over the roadway (Harry Sampson, personal communication).

Figure A14 shows a similar rock structure built by the Idaho Panhandle National Forest in about 1996 to replace a culvert that washed out during a flood. The objective was to fortify the crossing to withstand culvert plugging and subsequent overflows. The fill is high and the structure is not considered a vented ford, but it is designed to withstand overflow (Jim Neiman, personal communication).

The Idaho Panhandle National Forest used a similar design to retrofit an undersized culvert that could not be replaced immediately (figure A15). Again, the goal was to prevent a catastrophic culvert failure during large floods that characteristically plug culverts with woody debris (Gary Harris, personal communication 2001). Plans called for removing fill to create a driveable dip over the culvert, and sizing the dip to contain the 100-year flow (assuming the culvert plugs). The roadway is outsloped over the dip, and up- and downstream fillslopes are riprapped with class V rock (maximum size 26 to 28 inches).

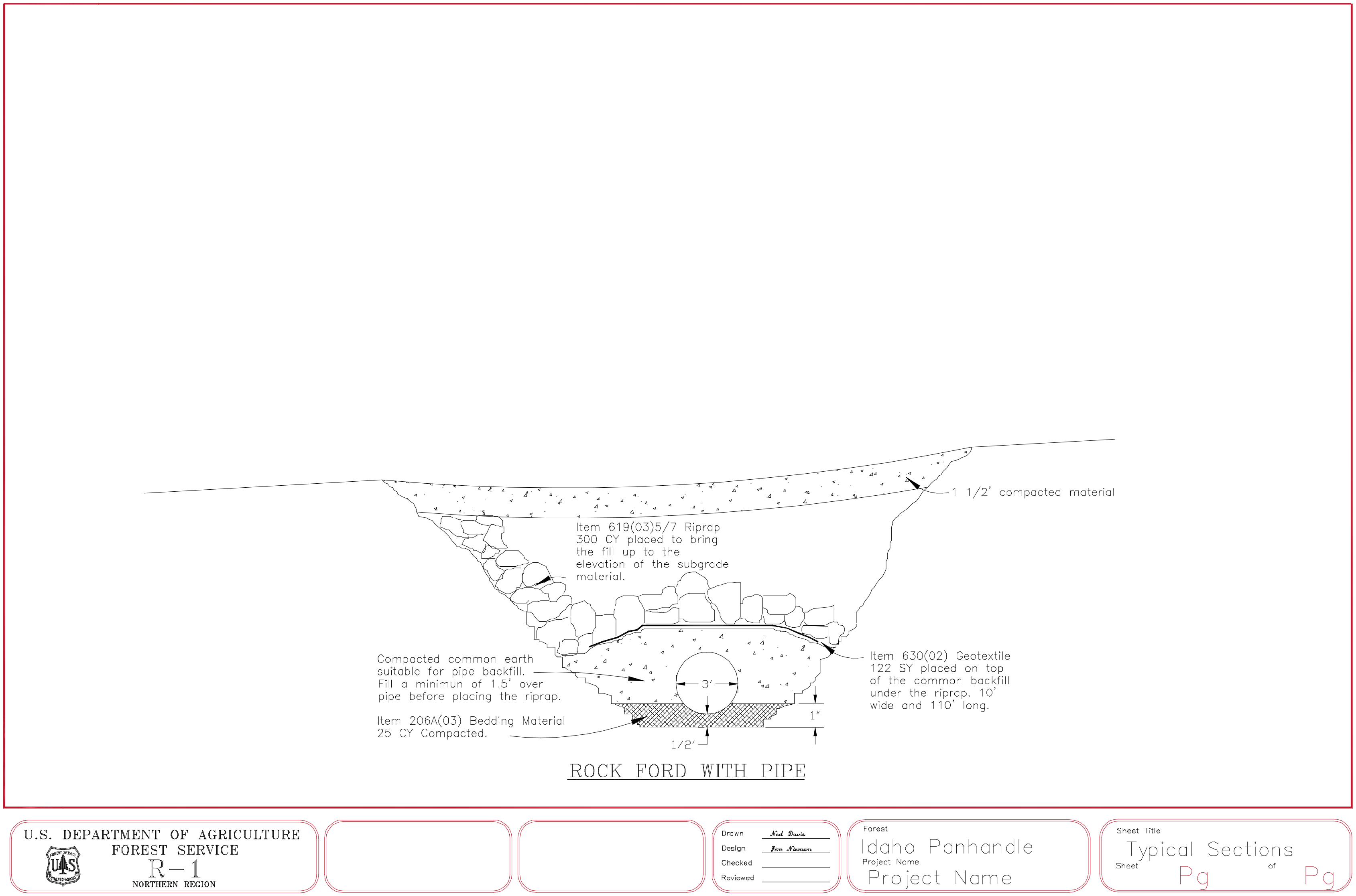


Figure A14. Rock ford with culvert, Idaho Panhandle National Forest.

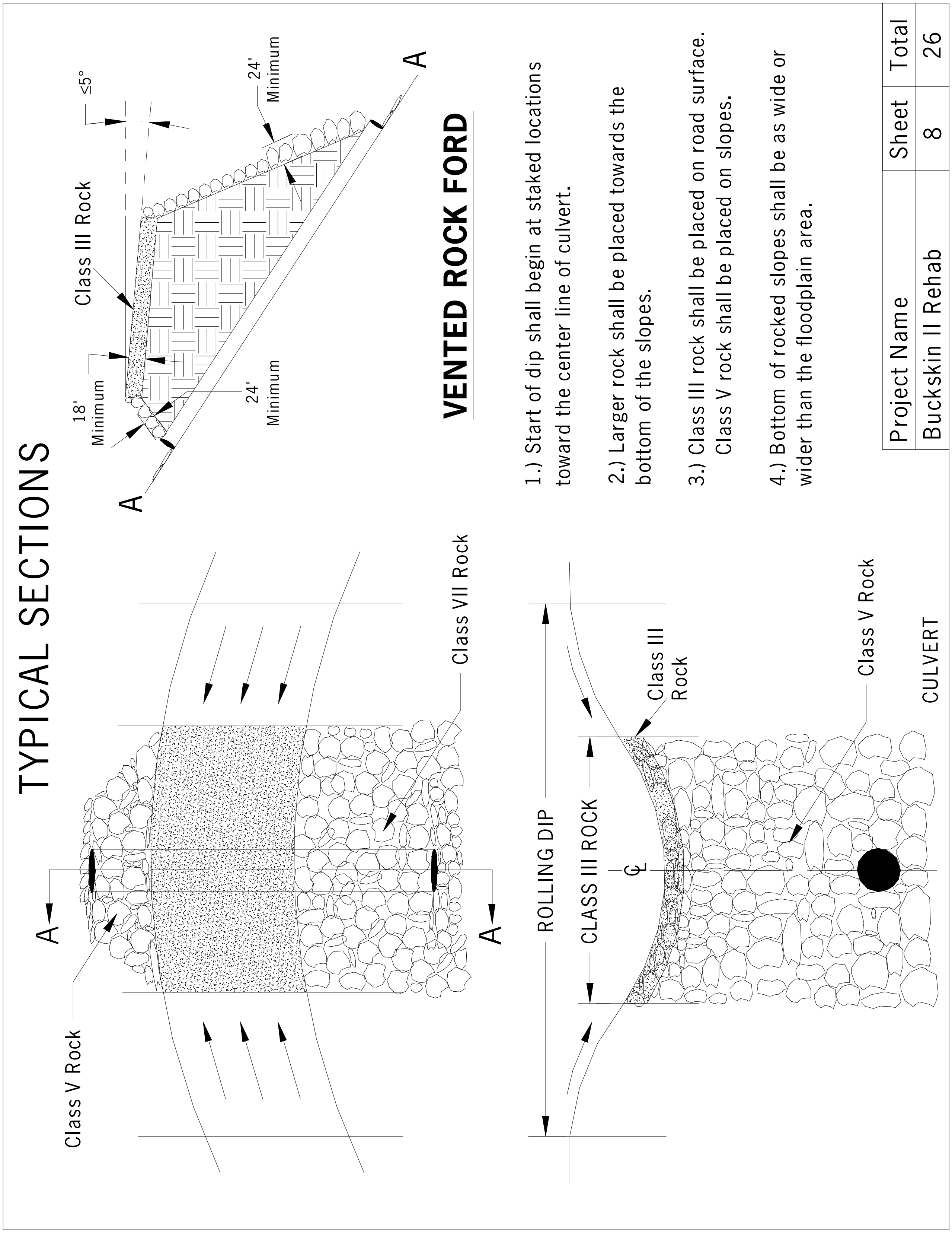


Figure A15. Vented rock ford, Idaho Panhandle National Forest.

Case Study 4. Forest Road 732 Jersey Barrier Fords

Location

Northern Arizona. Prescott National Forest. Verde Ranger District. Cienega Creek. Forest Road 732, Squaw Peak Road.

Crossing Description

These crossings are unvented fords on an ephemeral channel that transports up to boulder-sized rock during floods. Jersey barriers and large riprap support the downstream edge of the road. The jersey barriers also function to trap sediment and prevent channel downcutting occurring due to land use in the area.

Setting

Tonto Transition Section (313-C). Rock types are lava flows, plugs, dikes, and relatively flat sedimentary deposits. Vegetation in this area is pinyon, juniper, and chaparral.

Figure A16. Jersey barrier ford, FR 732.

Why Were These Structures Selected?

Channels in this area flood 4 to 5 times each year during summer thunderstorms and are dry the rest of the time, making unvented fords feasible structures. Jersey barriers act as a retaining structure, providing support for the road. They also work to control channel downcutting. These structures are simple, easy, and inexpensive to construct with road maintenance equipment, and they have low maintenance requirements.

Appendix A—Case Study 4

Crossing Site History

Originally, this road accessed mines and ranches in the Cienega Creek area, and the alignment followed the wash, so that flood flows tended to divert down the road. After a major flood event in 1993, the road was relocated away from the channel, and crossings were realigned to eliminate the diversion potential. Crossings were also stabilized with jersey barriers to keep water in the channel and to control channel downcutting. Previous crossing structures on this road were culverts, which were overtopped and began washing out in 1993.

Road Management Objectives

This road is part of the Great Western Trail system, an off-road system stretching from the Mexico to the Canada border. It is maintained for high-clearance vehicles (maintenance level 2), and receives moderate mostly recreational use. Approximately 5 to 20 vehicles use the road per day, with the higher number occurring during hunting season. Traffic is interrupted about 3 to 4 days per year, 2 hours at a time by flooding.

Stream Environment

Hydrology: Annual precipitation is about 16 to 20 inches, falling as winter snow and rain during summer thunderstorms. Cienega Creek is a tributary to Ash Creek in the Agua Fria River watershed. There is naturally low ground cover and high runoff.

Channel Description: The channel is poorly defined immediately above and below the structure, although most of the channel is confined. Channel slope is around 2 to 3 percent and substrate is large cobbles and small boulders with gravel infill.

Aquatic Organisms: Providing passage for aquatic species is not an issue at this location.

Water Quality: Channels are downcutting in this area because the natural vegetative cover was modified by overgrazing, which increased surface runoff and erosion during rainstorms. The 1993/94 flood restoration project aimed to stabilize the channels with jersey barriers. There is a naturally high sediment load due to the large amount of granite in the watershed.

Structure Details

Structure: Jersey barriers (usually seen on freeway medians) act as a retaining structure supporting the roadway. Barriers are set to mimic channel width and shape (figure 18a) and the ends of the structure (at channel edges/road approaches) should extend above the elevation of the largest expected flood. Figure 18b shows how they can be connected.

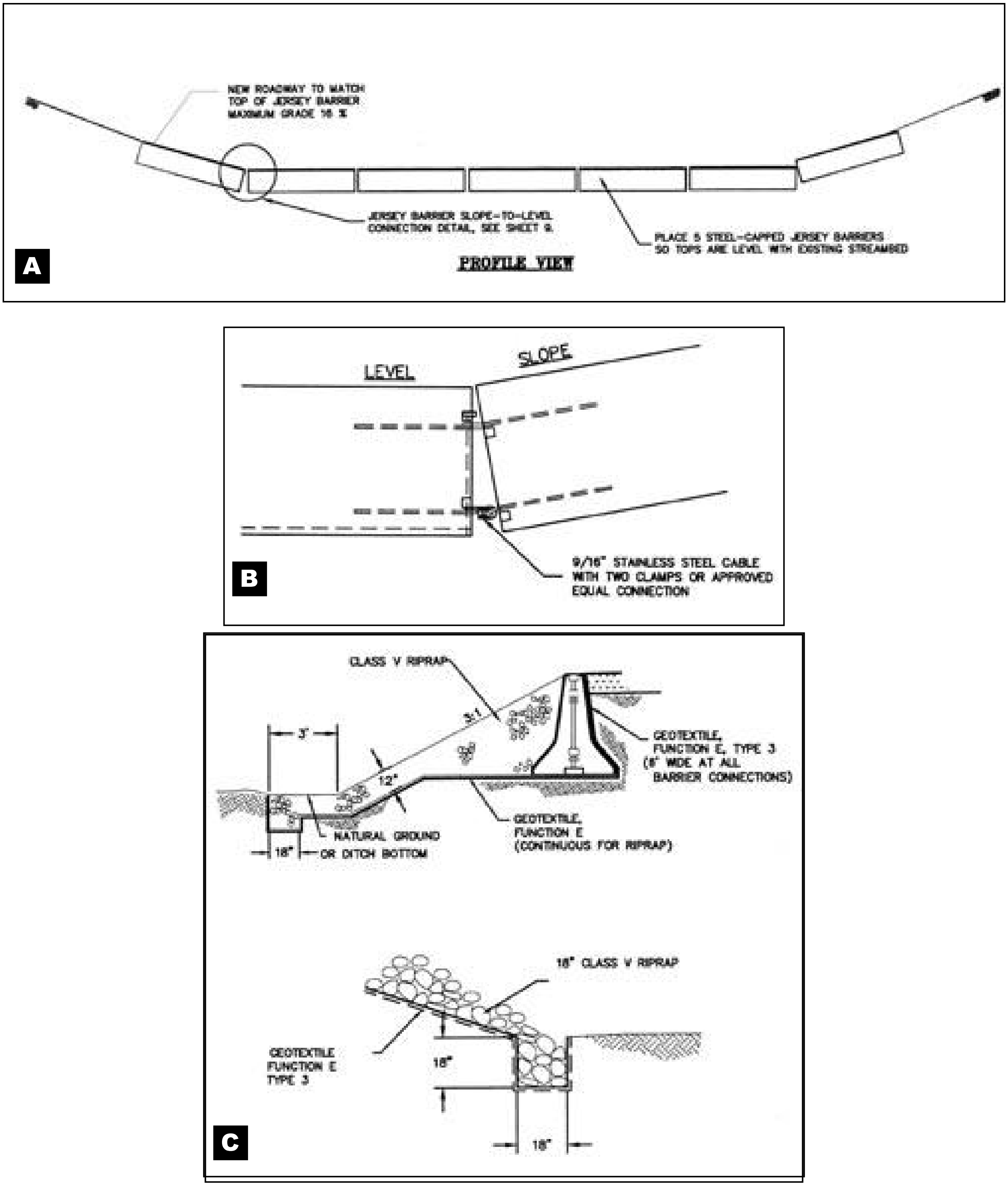
The fords are backfilled with native rock material and large riprap is usually placed downstream to prevent scour (figure A17). Experience has shown that the downstream edge of the jersey barriers should be protected from scour by gabions or an engineered riprap fill (figure A18c) unless the channel is highly resistant to erosion.

Figure A17. Looking upstream across another jersey barrier ford on FR 732. Sloped road approaches prevent diversion and large rock is placed downstream to prevent scour.

Bank stabilization and approaches: Road approaches slope down into the crossing to prevent diversion down the road.

Cost: Cost was minimal due to the use of off-the-shelf technology and small equipment. The barriers had been used in a previous Arizona Department of Transportation project, and were inexpensive to buy from a contractor.

Safety: This type of crossing is appropriate on the 732 road, which is designed for high clearance vehicles and meant to be driven at low speed. The crossings are not signed.



Figures A18a, b, and c. Typical jersey-barrier installations from the Tonto National Forest. (a) profile view (channel cross section view); (b) jersey barrier connections detail; (c) riprap fill detail.

Flood and Maintenance History

No significant flood events have occurred since these structures were installed in 1993, and no maintenance has been done. Some of the structures are now showing the need for repair. For example, in figure A19 the jersey barriers were not extended high enough to control high flows, and water has gone around the ends of the barriers. Part of the reason for this could also be that sediment has been deposited and revegetated upstream of the crossings.

Figure A19. High flows have outflanked one of the ford structures.

Summary and Recommendations

This structure type is a good choice at this site because of the hard, rocky substrate, flashy ephemeral flow regime, and the risk of culvert plugging by boulders moving during floods. The fords are working both as channel rehabilitation and crossing structures.

Some of the information for this case study came from field notes from an August 1999 visit to the Prescott National Forest by the Riparian Roads team from the San Dimas Technology and Development Center. Notes were written by Lisa Lewis, Jim Doyle, and Mary Lee Dereske. Other information was supplied by Doug MacPhee, retired Prescott National Forest team leader for Range, Soils, Water and Ecology, and Tim Mabery, Prescott National Forest range technician.

See also Mendenhall, Rod (1983). The use of jersey barriers as ford walls. USDA Forest Service Engineering Program, Engineering Field Notes v15 (January – March):3-7.

Similar Structures in Other Locations

The Prescott National Forest has used the same design on crossings in the Copper Canyon drainage (FR 136). Concentrated runoff from Interstate 17 drains directly into the canyon, and was accelerating channel downcutting. In 1991, Jersey barrier fords were installed in a series at several stream crossings that had been unarmored natural fords. The fords have worked well to retain sediment and foster the growth of riparian vegetation (figure A20). They are working both as stream crossing structures and as riparian improvements.

Figure A20. Jersey barrier ford on FR 136 has helped control channel downcutting and restore the riparian area in Copper Canyon. Photo is looking upstream at the ford.

The Tonto National Forest, just south of the Prescott, also uses jersey barrier fords, sometimes adding gabion basket energy dissipators to control downstream scour (figure A21). Jersey barrier fords generally create a downstream drop, and require scour protection to avoid being undermined. When they fail, it is often because of downstream degradation or outflanking when floodwaters rise above the protected approaches. Upstream aggradation can exacerbate problems with outflanking, and care is required to create enough sag and armor the approaches high enough to avoid it.

Figure A21. This jersey barrier-gabion ford on the 7-Springs Road on the Tonto replaced a bridge washed out in a flood.

Case Study 5. Willow Creek Concrete Plank Ford

Location

Northeastern California. Plumas National Forest. Willow Creek. 5 miles northwest of Portola, CA, on Spur Road 23N97Y off Forest Road 24N12, (Smith Peak Lookout Road).

Crossing Description

This unvented ford, constructed in the mid 1980s, is on a perennial fisheries stream. Concrete planks form the driving surface. The structure is 31 feet long and the driving surface across the planks is 14 feet wide. There are 21 concrete planks, which are each 12 inches wide, with a 6-inch space between planks. The spaces allow passage of low flows. The planks are set into the streambed 2 inches and rest upon a bed of coarse streambed material and Class IV riprap. The outlet of the structure spills onto Class X riprap. Grades into the ford vary from 7 to 9 percent on both approaches, and the middle of the ford is flat.

Figure A22. Willow Creek concrete plank ford.

Setting

Sierra Nevada Section (M261-E). Elevation 5,130 feet. Variably weathered granitic mountains capped with tertiary volcanic (pyroclastic) flows. Vegetation is mixed conifer.

Appendix A—Case Study 5

Why Was This Structure Selected?

This structure was chosen for its ability to pass large rocks without damage, and for its easy maintenance and low cost. The large concrete planks are large enough to resist movement if properly bedded.

Crossing Site History

This site was originally a native rock ford. The concrete plank structure was built by the Plumas National Forest in 1985 to improve the road for a timber sale.

Road Management Objectives

This is a native-surface road maintained for high-clearance vehicles (maintenance level 2). It provides access only to the local area, and average daily traffic is about 10 vehicles. The road is closed during the winter. Occasional interruptions are acceptable as traffic volume is low. Traffic interruptions occur several times each year, particularly during the springtime, and last approximately 12 to 24 hours each time. Road use is a mix of occasional logging traffic during a timber sale, Forest Service administrative traffic, and occasionally the general public.

Stream Environment

Hydrology: The Willow Creek watershed drains approximately 7 square miles on the south side of Smith Peak. It is a perennial stream fed with snowmelt, and both rain-on-snow and summer thunderstorms cause occasional floods. Annual precipitation in this location is 40 inches. Summer low flows are less than 1 cubic foot per second. The 2-year flow is 110 cubic feet per second, and the estimated 100-year flood is 1,500 cubic feet per second. Flood flows inundate the entire structure 1 to 2 feet deep. Maximum flood flow velocities of 10 to 12 feet per second are expected.

Channel Description: Channel slope is about 3 to 5 percent at the crossing. There is a drop in the channel bottom elevation of 3.5 feet just downstream of the crossing. This is partially due to scour, but also to an old wooden diversion structure that failed and caused channel cutting. A tributary also enters the stream immediately downstream of the road-crossing (figure A23—upper right). Sloping streambanks are 1 to 2 feet high and quite stable with boulders and riparian vegetation including willow and fir trees. Bankfull width is approximately 15 feet, with a bankfull depth of 2.5 feet. The substrate is a mixture of cobbles, some gravels, and large boulders.

Figure A23. Looking downstream: ford is just above a tributary junction where an old diversion structure blew out and caused streambed to degrade.

Aquatic Organisms: Several species of trout are resident in this stream, including rainbow and brown trout. Fish have been observed moving across the structure at high flows. However, at low flows, the riprap cascade immediately downstream of the structure prevents fish from accessing it. Passage for other aquatic species is unknown, but it seems likely that some crawling species could negotiate the gravel-floored spaces between the planks.

Water Quality: Water quality in this drainage is relatively high. Thus, the armored surface was selected to prevent driving directly through the creek most of the time. However sediment is added to the channel from the unsurfaced approaches.

Structure Details

Structure: The driving surface of the ford is made of steel reinforced concrete planks 12 inches wide by 12 inches high and 15 feet long. They are spaced 6 inches apart and held in place with metal brackets between the planks (figure A24). Each plank is tapered at each end. Twenty-one planks form the 31-foot-long reinforced driving surface. The planks are set onto a smooth bed of small riprap. Additional large riprap was placed along the downstream edge of the structure for scour protection.

Protection of the planks against scour and movement of the material beneath the planks is a key design detail. The bed must be carefully prepared to be smooth, yet made of coarse enough material to resist movement during storm flows.

Figure A24. Detail of planks and metal brackets.

Bank stabilization and approaches: Large riprap was added to stabilize the downstream area from the effects of the drop downstream (figure A22). Road approaches dip down into the crossing at 7- to 9-percent slope (see site sketch, figure A25).

Cost: Initial construction cost in 1985 was $10,000. Repair costs in 1998 were $21,500, including replacing several planks. Most of the cost in 1998 was in casting new concrete planks for two sites ($17,000).

Safety: This structure is not signed. The entire structure has a very low profile, and it is on a low velocity road. Also the site is on a relatively straight part of the road with good sight distance. Thus safety issues are minimal.

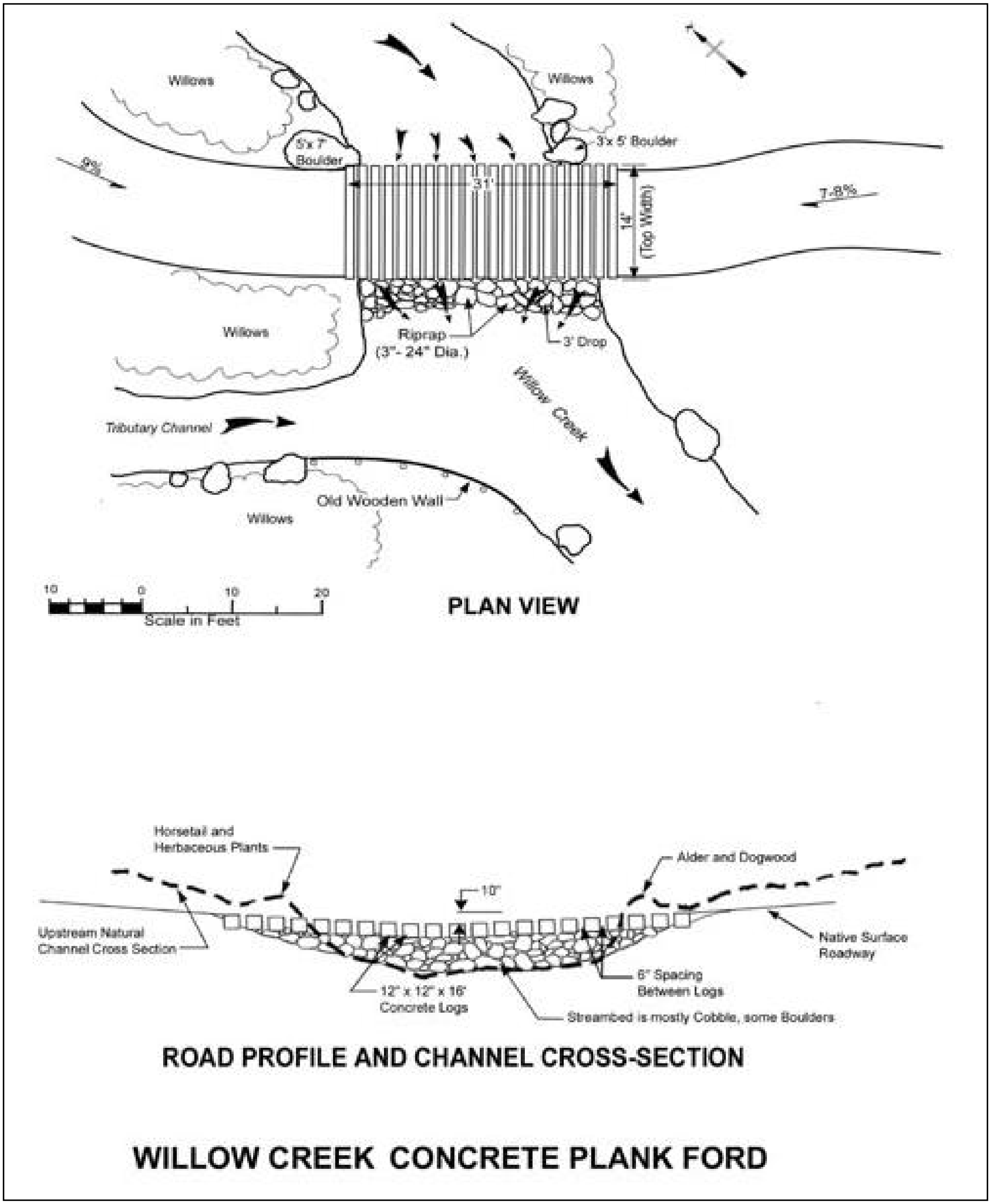


Figure A25. Site plan view and cross-section sketch.

Appendix A—Case Study 5

Flood and Maintenance History

The structure received only minor damage in the large storms of 1986 and 1995. However, during the major 1997 flood (local storm of record), some of the concrete planks were cracked and steel was exposed (figure A26). Repairs included replacing some concrete planks, rebedding most of those in the middle of the channel, and adding riprap scour protection at the downstream outlet of the structure.

Figure A26. The crossing was damaged in the 1997 flood by scour of fine bedding materials under the planks. The planks had to be reset into coarser materials and the downstream edge protected with riprap.

Summary and Recommendations

The Willow Creek concrete plank ford has the advantage of forming a stable road surface that is resistant to damage from boulders moving in the stream. Its open cross section permits free transport of rock and debris. The stream is fairly small and streambed material is coarse enough that the concrete planks can be well-bedded and resist movement. Large boulders placed under the downstream toe of the planks help resist scour and movement in this area. Careful preparation of the bedding for the planks is likely the most important construction detail. The large, heavy individual concrete blocks have the ability to resist fast stream velocities, so long as the material beneath the planks does not move.

Two disadvantages of this design are that, during large floods, it is susceptible to scouring underneath the structure, and it allows only partial aquatic organism passage. If the structure were slightly backwatered at lower flows, fish passage would be improved.

Possible changes to improve fish passage include: lower the structure or build step pools downstream; increase the outslope of the structure to no more than 5 percent; extend structure approaches; reconstruct the approaches to create a more defined dip, and armor the steeper approaches with gravel or pavement to minimize sediment movement.

Charlie Carter, design team leader on the Plumas National Forest (now retired), designed the structure repairs after the flood, and provided information and photos for this case study.

Case Study 6. Fitzpatrick Creek Cable Concrete Block Mat Ford

Location

Southwest Oregon. Bureau of Land Management Coos Bay District. Fitzpatrick Creek. BLM road 23-8-11.0.

This ford was constructed in 2000 on a deeply incised perennial stream where passage for salmon/steelhead and woody debris are major issues. Cable concrete block mats and riprap were used to make a stable driving surface that mimicked natural channel characteristics as closely as possible. The crossing is outsloped at approximately the same grade as the stream (4 percent), and the mat was set just under the final streambed elevation, with the expectation that a low-flow channel would develop to promote juvenile fish passage across the structure. Traffic use at this site is low, and occasional log haul is restricted by agreement with the National Marine Fisheries Service.

Figure A27. Fitzpatrick cable concrete mat ford.

Setting

Oregon and Washington Coast Ranges Section (M242-A). Highly dissected low mountains; moderately deep soils. Riparian vegetation is predominately red alder and big leaf maple with Douglas fir, western red cedar, and hemlock.

Appendix A—Case Study 6

Why Was This Structure Selected?

Key objectives that led to selection of this structure type were to: provide free passage for all aquatic organisms; floodproof the crossing: avoid blocking large woody debris that could cause the structure to fail during floods or require maintenance afterward; and handle only minor summer recreational and occasional log haul traffic.

The extremely low traffic volume reduces concern for public safety and for vehicle impacts on water quality and aquatic organisms. The cost of this structure is much less than the other possible structures, such as a bridge or open-bottom arch.

Crossing Site History

Two earlier culvert installations had washed out at this site. The second one—a 10-foot multiplate pipe installed in 1979—blew out after being plugged with debris during the 1996 floods.

Road Management Objectives

This crossing accesses both BLM and private forest land, but there are no residences or developed recreation sites. It receives little use, most of it during the autumn hunting season. However, the crossing must accommodate intermittent log and equipment haul as well as the low volume of summer and fall recreation traffic. It was anticipated that a private timber sale would occur not long after construction, and future BLM thinning projects were envisioned.

Stream Environment

Hydrology: Fitzpatrick Creek is a perennial stream. Rain on snow can produce large midwinter to spring floods. There is substantial large woody debris and gravel/cobble bed material transport during high flows. Summer low flows are on the order of 1-foot wide and a few inches deep at the site.

Channel Description: The channel is a Rosgen A3, with a 4-percent slope and low sinuosity. It is confined between stable 25-foot-high slopes that are well-vegetated with deep-rooted shrubs and trees (figure A28). Debris jams are not uncommon. The crossing is located immediately upstream of a bend.

Figures A28a and A28b. Channel character (a) looking upstream (b) looking downstream.

Aquatic Organisms: Fitzpatrick Creek is a spawning stream for two endangered species: coho salmon and steelhead, and passage for both spawning adults and juveniles is required. The stream also provides habitat for searun cutthroat trout, resident cutthroat, pacific lamprey, and pacific giant salamander.

Water Quality: Downstream habitats and water quality must be protected. Because the stream is well-confined, road approaches to the crossing are long and steep and if not treated, could be a potential source of sediment. This was dealt with by paving the approaches and the ditches with rock. Vegetation is now growing up through the rock in the ditch.

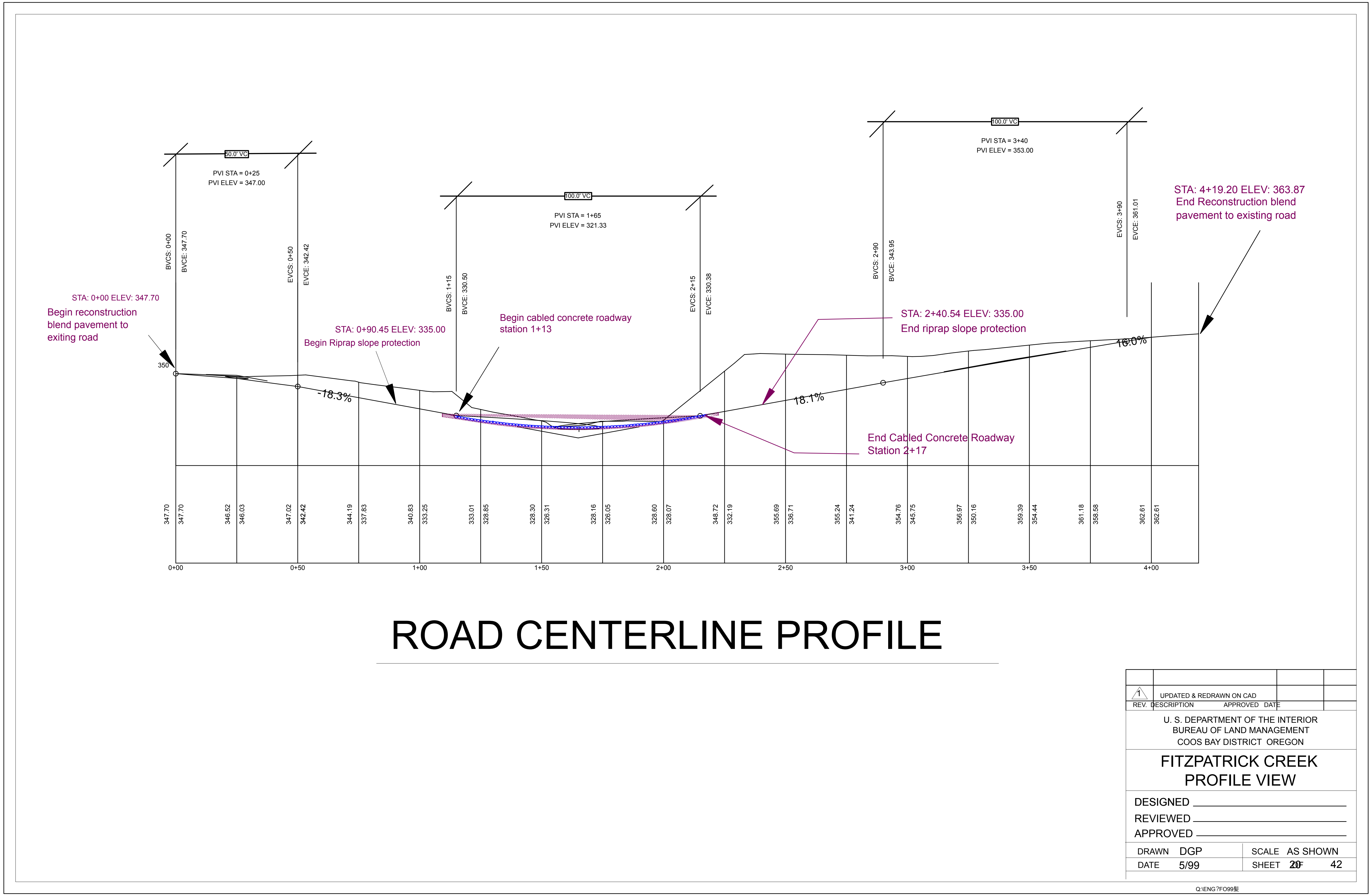


Figure A29a. Road profile through crossing.

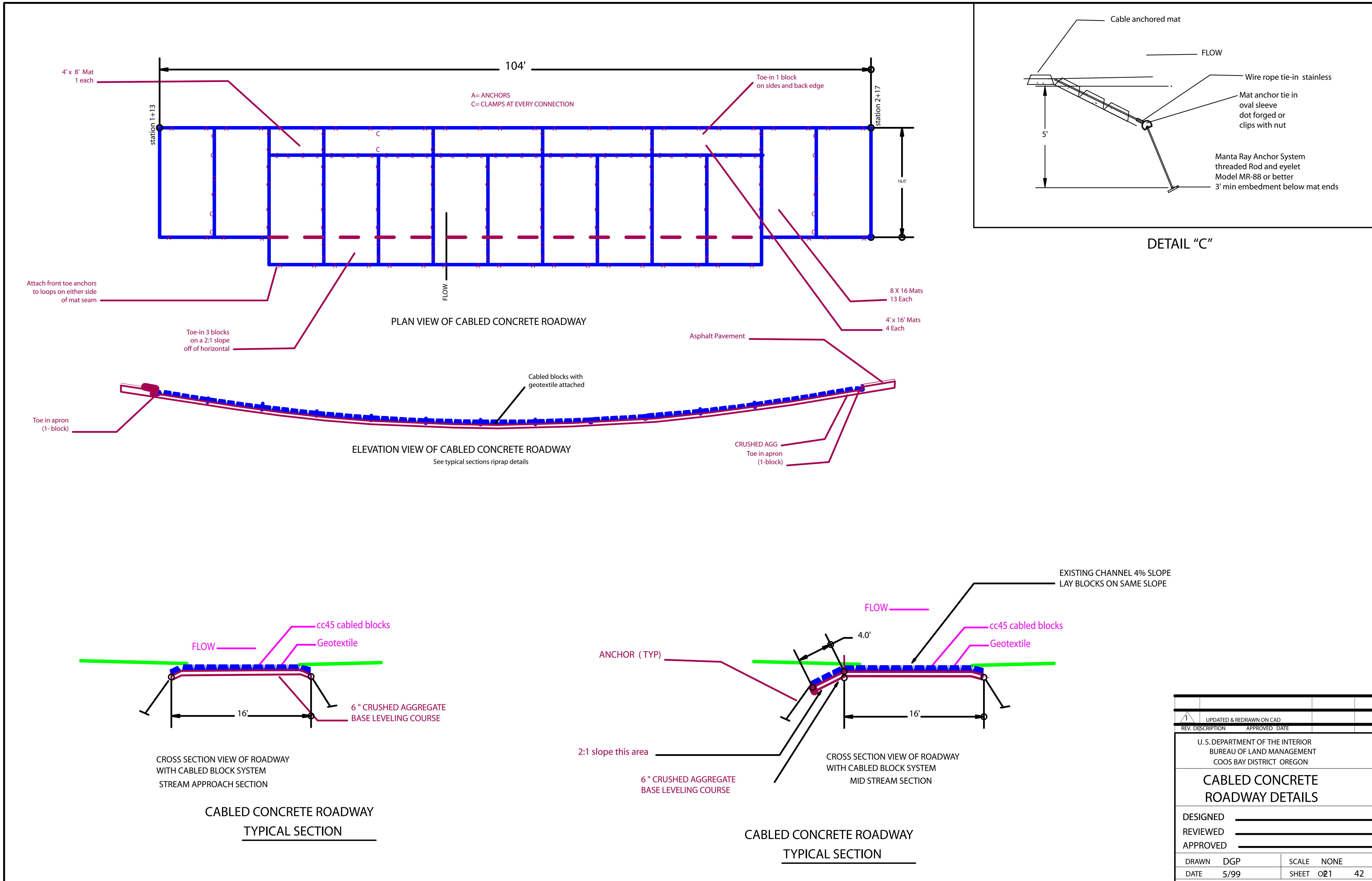


Figure A29b. Roadway cross sections and plan view.

Structure Details

Structure: The cable concrete mat is 16 feet wide and 104 feet long, extending to approximately the elevation of the 50-year flood (figure A29a). The blocks are sized for the 100-year event, according to manufacturer recommendations. Mats are fabricated with stainless steel cables embedded in the blocks to link them together in both directions. Geotextile fabric is attached to the bottom of blocks to prevent blocks from sinking into soft subbase, and to avoid erosion of fine material from the base. Mats were laid out on a 6-inch base of 1½-inch crushed aggregate to provide both support and a level surface (figure A30).

Figure A30. An excavator installs the mats with geotextile backing.

The mats were backfilled with ¾-inch clean gravel to help bed them and prevent movement, and to make driving easier over the 4- to 5-inch gaps between the blocks. A row of blocks was keyed in on the upstream edge of the structure to prevent scouring (figure A29b). Riprap was placed adjacent to the upstream and downstream edges to a depth just below the top of the blocks to prevent undermining. Earth anchors were driven 4 feet into the ground with a manual pile driver to hold the mat down under stresses expected from up to a 100-year event (Detail "C", figure A29b).

Bank stabilization and approaches: Riprap was placed to the 100-year flood elevation, or approximately 10 feet above structure height, for a distance of 23 feet up- and downstream. The road approaches of 17 to 18 percent on each side were paved with asphalt, and sloped to drain to a rocked ditch. Ditch water then filters through the riprap blanket.

Cost: The ford cost $60,000 in 2000 and was less expensive than either of the other alternatives, a large open-bottom culvert or a bridge.

Safety: There is no signing at this site.

Flood and Maintenance History

The structure has not yet gone through a large flood and no log haul has occurred. So far, the crossing has needed no maintenance.

Summary and Recommendations

The structure is performing well. As expected, sediment is deposited on the structure during high flows. The channels between the blocks are filled with streambed sediment and allow free fish and amphibian passage even at low flow. Vegetation is growing in the rock-lined ditch along the approaches. Some blocks have tilted slightly, pointing to the need to compact the entire surface before block installation.

There was a slight curve in the road approaching the crossing, and it was not possible to install the mat on a bend. The district used asphalt paving at that location to accommodate the curve. In general, mats are not suitable for installation on curves.

Installation Concerns: Uniform, well-compacted bedding material coarse enough to resist scour is needed as a foundation for the mats. In retrospect, to support future log haul the engineer recommends a thicker layer of larger rock than was used here.

Figure A31. The ford permits low flow passage for aquatic species even though the blocks have settled unevenly.

As originally laid down, the Fitzpatrick Creek mat was uneven. The installers were able to smooth it by running over it with the excavator, but as figure A31 shows, some of the blocks sank unevenly and disrupted the driving surface at the edge of the structure. The Big Horn National Forest sites (see below) are more severe examples of this problem.

Other Comments: Because vehicles drive through water on this crossing, the National Oceanic and Atmospheric Administration's National Marine Fisheries Service and the U.S. Department of the Interior Fish and Wildlife Service required restrictions on timing and conditions when commercial hauling would be allowed over this structure. The district is monitoring the structure to see if there is any channel readjustment and to evaluate structure performance over time.

Don Porior, project designer (now of Porior Engineering), and Brian Thauland of the BLM Coos Bay District provided information and photos for this case study.

Similar Structures at Other Locations

The Bighorn National Forest in Wyoming has used cable concrete mats in several locations with variable success. At one site on the East Fork South Tongue River, soil consolidation after the mat was installed caused the ends of the mat to sink lower in elevation, so that the stream runs around the ends even at low flow (figure A32). Without a firmly compacted base and secure anchoring, the mat has settled unevenly and some of the connecting cables are exposed. Horse and recreational-vehicle trailer hitches tend to catch on the cables. As a result, drivers choose to drive next to the mat rather than on it, and in this wide grassy flood plain there is nothing to restrict that access. Given the high-value fishery in this perennial river, this is an unacceptable situation, and the forest is considering a culvert replacement to disconnect the road from the stream. The tradeoff will be the need to either reroute the road or construct an elevated roadfill across this very wide, active flood plain.

Figure A32. East Fork South Tongue River cable concrete block mat crossing. Note tilted blocks, exposed cables, and short mat length. Traffic is driving around the mat and the river has outflanked it.

On Copper Creek, a much smaller stream with very low summer flow (figure A33), cable concrete mats are considered more successful. Again, the lack of a firmly consolidated base caused the blocks to tilt, making an uneven driving surface, and exposing cables that were then snagged and broken. Even so, the blocks remain in place and functional. At Copper Creek, the mat does extend high enough to contain bankfull flows, and there are no problems with water outflanking the structure (figure A34). The forest considers this a successful crossing in this situation where the road is used mostly by hunters in the fall. It has required no maintenance since construction in 1999.The structure is well-suited to the wide, flat valley site because it does not require a roadfill that would interrupt flows on the flood plain during the extended snowmelt season. This means that overbank flows are more naturally distributed. Flood-plain water storage processes and riparian vegetation are fully maintained, and erosion due to floodwater concentration through a constricted structure such as a culvert is minimized.

One change the forest would make for improvement is to stabilize the exposed streambanks. They are susceptible to erosion by wave action when vehicles drive through deeper water.

Figure A33. Copper Creek tributary, Bighorn National Forest. At this drier site with less traffic, the mat is considered the best crossing option because of its low maintenance requirement and installation cost.

Harold Golden, fishery biologist, and Bryce Bohn, hydrologist, of the Bighorn National Forest, provided information for the Bighorn sites.

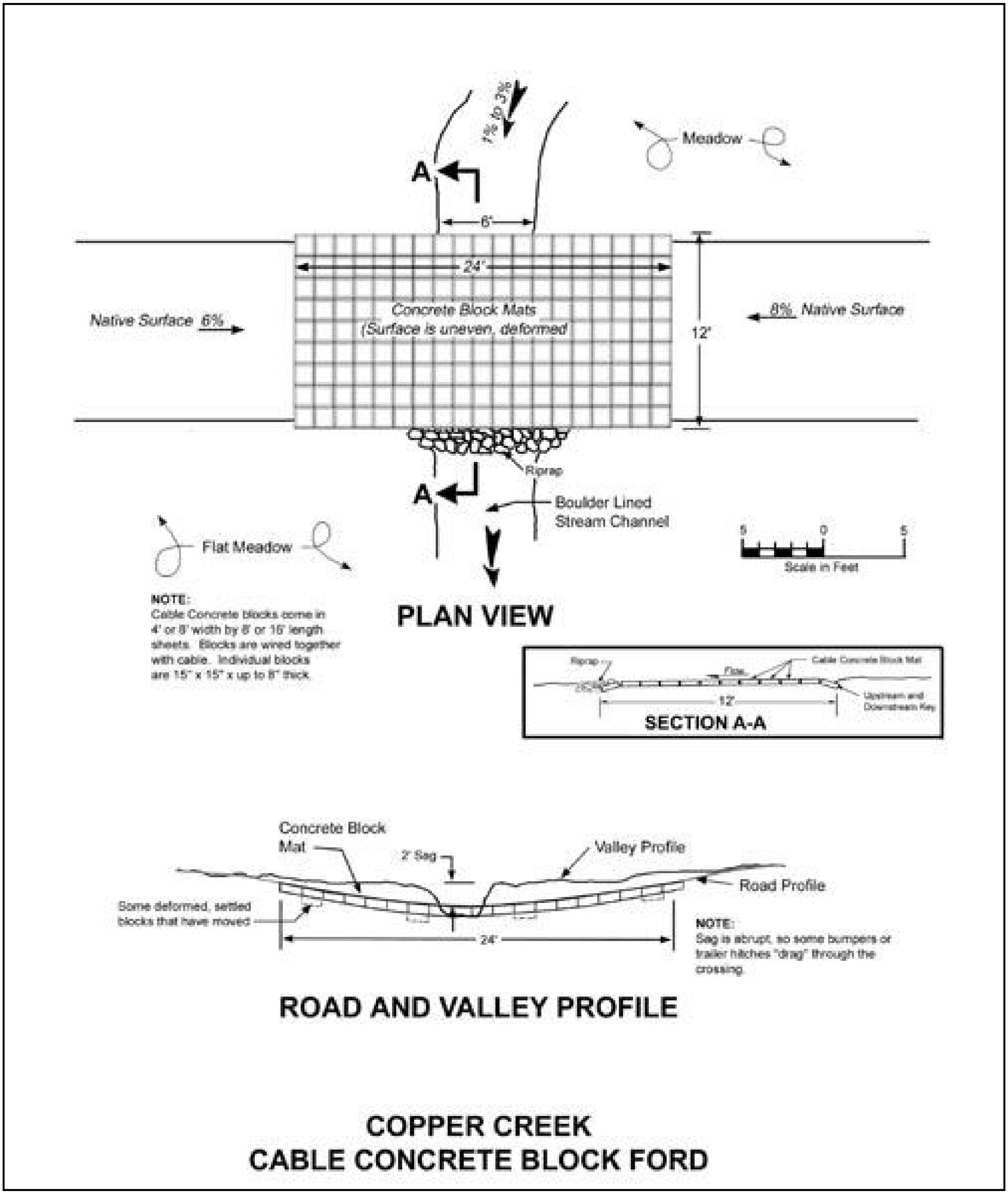


Figure A34. Copper Creek tributary site sketch.

Case Study 7. Woodrock Guard Station GEOWEB Ford

Location

Central Wyoming. Bighorn National Forest. West Fork of the South Tongue River. 20 miles southwest of Sheridan, off Forest Highway 26 (East Fork South Tongue River Road).

Crossing Description

This unvented ford is on a perennial brook trout stream where fish passage is a concern. The ford was constructed in 1997 with GEOWEB (high density polyethylene geocell) cellular confinement material backfilled with gravel to form a natural looking armored driving surface. A constructed boulder and cobble cascade armors the structure's downstream edge (figure A35). The site is in a broad meadow with an active flood plain and soft, compressible soils. Although traffic use is light, continued consolidation of the road approaches has caused the ford to spread laterally. The forest plans to replace this ford with an open-bottom arch matching bankfull width.

Figure A35. A boulder cascade was constructed at the downstream edge of the ford to control scour caused by placing the GEOWEB very slightly above streambed elevation.

Appendix A—Case Study 7

Setting

The West Fork South Tongue River valley is a wide, moderately sloping valley in the Bighorn Mountains (Section M331-B) at 8,440 feet. The Bighorn Mountains are composed of a highly weathered granitic batholith capped by limestone on the east and west. It is a cold continental climate, with fir and pine forests mixed with shrub-steppe vegetation.

Why Was This Structure Selected?

The GEOWEB structure was a relatively inexpensive way to provide a hardened surface through the creek for recreational traffic while allowing for fish passage. It was also expected to be easy to construct.

Crossing Site History

Before the GEOWEB was placed in 1997, this crossing was a natural ford; that is, there was no designed structure. The replacement was done as a watershed improvement project to stop bank erosion caused by waves from vehicles driving through, and to confine vehicles to a single crossing area.

Road Management Objectives

This road is maintained for high clearance vehicles (maintenance level 2) and is closed in winter. Traffic use is considered light recreational. The road accesses a campground and is used by all-terrain vehicles, recreational vehicles and 4-wheel drive trucks with trailers.

Figure A36. Ford is used by vehicles ranging from ATV’s to motor homes.

Stream Environment

Hydrology: The West Fork South Tongue River is perennial with summer flows about 1-foot deep. Peak flows occur during snowmelt and are usually sustained for 1 to 2 weeks. The runoff regime is fairly moderate, and catastrophic floods are very unusual. However, this is not a low-energy stream; slope was estimated at 2 to 3 percent in the vicinity of the crossing.

Average annual precipitation is approximately 20 inches. Ice plugging is a frequent problem with culverts in this area.

Channel Description: The stream is moderately entrenched in a flood plain about 40 to 50 feet wide, and the bankfull channel is 25 feet wide and 2 feet deep. It is probably a Rosgen B3 or B4 channel with some medium and large boulders. The wider valley surface is a grassy terrace about 2-feet above the flood plain (see figure A37). Streambank material is a highly organic sandy loam, and bank stability is generally high due to root masses of willow, bog birch, sedge and grass. The crossing has widened significantly since the structure was installed, apparently due to the compaction of the moist sandy loam valley soils.

Aquatic Organisms: The West Fork is a brook trout fishery.

Water Quality: Maintaining good water quality was one of the reasons the ford was originally armored. However, waves caused by vehicles driving through the fairly deep water wash the approaches, and the road is not surfaced well enough to prevent erosion and transport of material into the stream. Because vehicles are driving directly through the water and sediment is being produced, the forest intends to replace this ford with a culvert.

Structure Details

Structure: To construct this ford, large rocks were removed from the existing crossing and it was excavated to a depth equal to the height of the GEOWEB, 6 inches. This was done during low flow, but without diverting flow, so compaction was probably not achieved. The geotextile and GEOWEB were stretched out, anchored with rebar and hooking clips, forming a 16 foot by 48 foot layer, and the cells were filled to the top with 1½-inch to 4-inch crushed rock. To prevent undercutting, the upstream edge was bent down into a deeper trench that was later filled with large rock. Four to 6 inches of clean 1½-inch to 4-inch rock cover most of the ford.

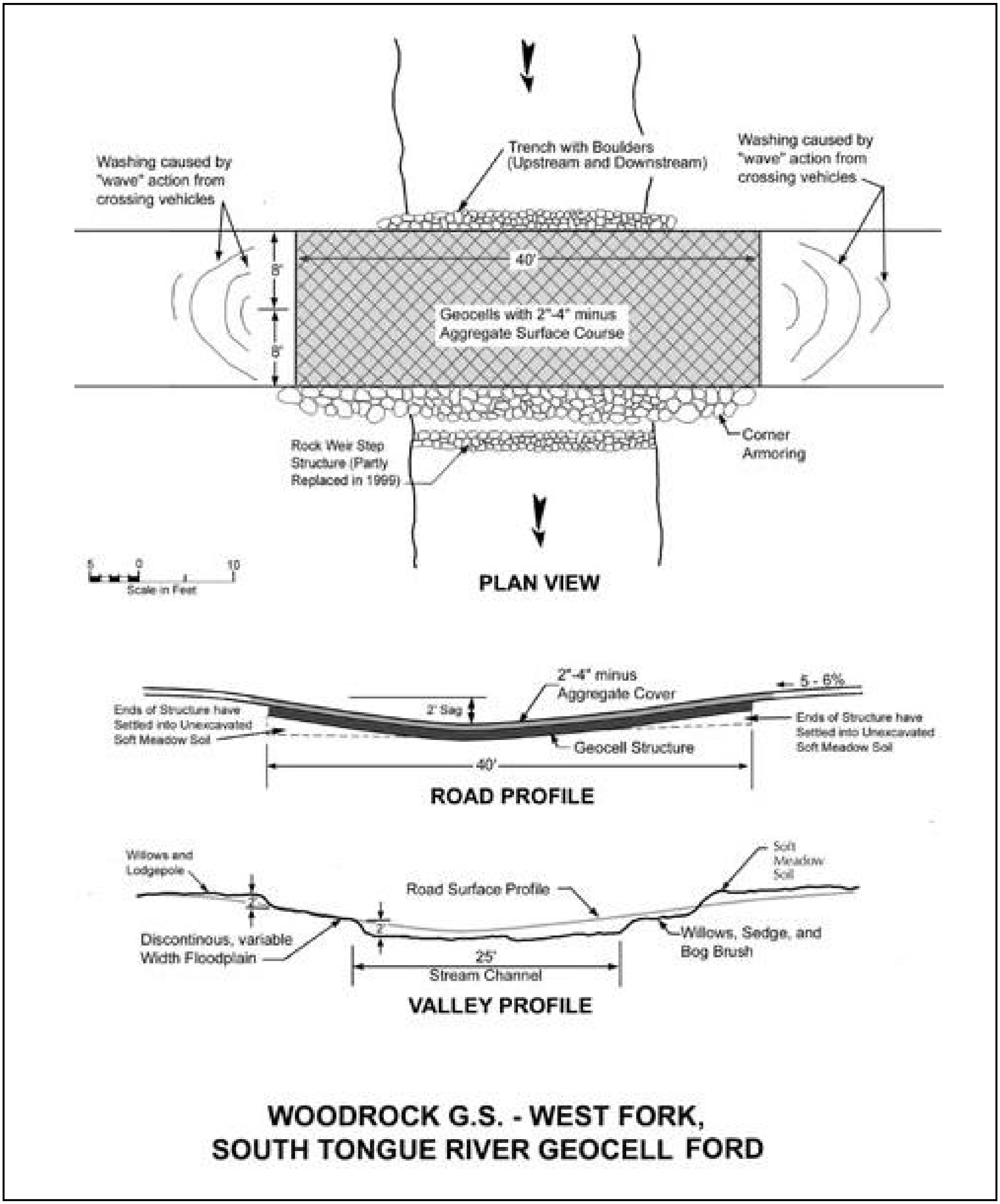


Figure A37. Plan view with valley and road profiles.

The original intent was to install the GEOWEB to the elevation of the 100-year flood. As can be seen in figure A38, although the GEOWEB originally extended higher, it has settled under traffic loads and probably does not fully cover the bankfull cross section. The stream widens out substantially at the crossing.

Figure A38. Soil compression on the approaches to the ford causes the stream to widen and lowers the elevation of the ends of the GEOWEB mat. Currently the geocell mat protects only part of the crossing during high flows.

The intent was to set the surface of the filled GEOWEB cells at the level of the finished streambed, matching stream slope. However, this is very difficult to do without diverting streamflow. The downstream edge of the GEOWEB protruded an inch or two, so a rock energy dissipator was placed there. Scour occurred despite this, and in 1999 a larger boulder cascade control was constructed. This support structure creates a berm that backs water up on the crossing so that vehicles drive through deeper water than would otherwise be necessary.

Bank stabilization and approaches: The road approaches slope into the crossing at about 5 to 6 percent. Even though 10 cubic yards of rock have been added to the approaches to raise the road grade, figure A38 shows that it is substantially wider than the natural channel. Riprap is placed downstream where the approaches cut into the streambanks.

Cost: $3,050 in 1997.

Safety: There is no signing for this structure, but the valley is wide and flat on the approach to the structure, making it easily visible.

Appendix A—Case Study 7

Flood and Maintenance History

There have been no major floods since the GEOWEB was installed. As noted above, scour due to the fact that the GEOWEB did not perfectly match stream grade necessitated construction of a boulder weir that now backwaters the ford. Erosion and consolidation of the approaches required the addition of rock, but compaction continued, and the crossing shape could not maintain itself. The boulder weir helps to retain the gravel surfacing necessary to protect the surface, but in many places, tire action appears to spin the gravel out of the top of the cells allowing the material to degrade (figure A39).

Figure A39. GEOWEB exposed, probably by tire action.

Summary and Recommendations

Geocell fords are attractive for low-traffic and light-vehicle uses because they are inexpensive and quick to install. However, they require the same attention to foundation leveling and compaction as heavier structures do. In this case, construction without diverting the stream may have been responsible for the difficulty with matching stream slope, which then required building a downstream weir and backwatering the structure. The risk of losing the crossing shape because of traffic compressing the soft flood-plain soils also was not recognized. Those soils should have been compacted or over-excavated and replaced with firm material.

The final elevation of the geocells plus cover material is critical to the design. Initially the site should be overexcavated to the depth of the cells plus the anticipated depth of cover aggregate. Four to 6 inches of coarse, clean cover aggregate is recommended. Since this material will likely be removed during high flows, some cover aggregate will periodically have to be replaced.

Carefully weigh the speed and economy of installation against the drawbacks specific to this structure type. The geocells are damaged by traffic if not protected by a layer of gravel, and after high flows the gravel surfacing will need maintenance or replacement (see also Figure A41 below). Generally, this design is not preferred for streams that experience high velocity flows or substantial traffic volume. The forest plans to replace this structure with one that will keep vehicles out of the water for at least most of the year.

Harold Golden, fisheries biologist, and Phil Fessler, engineer, Bighorn National Forest provided information for this case study.

See also Pence, Lester M. (1987). A plastic ford—-you've got to be kidding. USDA Forest Service Engineering Program, Engineering Field Notes v19 (January-February):27-33

Similar Structures in Other Locations

The Ashley National Forest has a successful temporary geocell (similar to GEOWEB) installation on Little Brush Creek (figure A40). The material used for this ford is called "TerraCell". The mats are 8-foot by 20-foot by 6-inches deep. Two mats were installed lengthwise across the stream.

The crossing accesses a road planned for storage within a few years, so the structure needed to last only 3 to 5 years. Traffic is mostly administrative and recreational, and is primarily 4-wheel drive vehicles such as light duty trucks, all-terrain vehicles, and sports utility vehicles. As the photo shows, after only one year, some of the 4-inch minus surfacing had been lost from the geocells on one side of the structure, and the material was deteriorating. Rock was added during the summer of 2002. Nonetheless, in 2004 the site was in a similar condition (figure A41). More material has eroded out from the geocells on one side of the ford and the channel has widened locally.

The native (darker red) cobbles and gravels deposited on the crossing in Figure A40 show the structure provides free downstream passage for debris and bed material. There is no reason to believe the ford would block fish and other aquatic species at the site going upstream. The forest is satisfied with the ford as a temporary crossing.

Figure A40. Little Brush Creek geocell ford in June 2002.

Figure A41. Looking upstream at erosion of one side of the ford in August 2004, 3 years after construction. Probably tire action and high flows have combined to pluck material out of the cells or undermine them. The ford is still intact and the geocells are covered by native bed material in the active channel.

Alex Gouley and Dan Abeyta of the Ashley National Forest, Utah provided photos and information about the Little Brush Creek geocell installation.

The Humboldt-Toiyabe National Forest used GEOWEB for a ford on the Duck Valley Reservation (Plocher 2001). A 10-foot wide by 30-foot long geocell structure was constructed using 8-inch-wide and 8-inch-deep cells. The site was dewatered, surveyed, and a geotextile filter layer and GEOWEB mat installed, backfilled, and covered with local screened stream channel material. A smooth, firm foundation was established before placement of the geotextile layer and the GEOWEB. The ends of the structure were keyed in by excavating a trench to a depth of 16 inches (two cell heights) along the upstream and downstream edge of the structure and burying the geocells in the trench.

Once the GEOWEB was properly stretched, oriented, and anchored in place with rebar, the cells were backfilled with an angular 1½- to 5-inch screened aggregate. Then the crossing was covered with 3 to 5 inches of screened 3- to 8-inch open-graded gravel free of fines.

The site is reportedly functioning well today, though no specific performance or maintenance information has been provided. The site is being monitored for sediment reduction to determine the effectiveness of the improved ford compared to the natural road crossing as part of the U.S. Environmental Protection Agency Nonpoint Source Pollution Prevention Program.

References

Kostrubala, Thaddeus. 2003. Skull Creek Project 2002 Report, Shoshone-Paiute Tribes-Duck Valley Indian Reservation, Tribal Environmental Protection Program, End-of-Year Report to the U.S. Environmental Protection Agency, Grant C9-9891001-0. January 24, 2003.

Plocher, Krishna. 2001. Skull Creek GEOWEB Crossing-Duck Valley Reservation. Humboldt-Toiyabe National Forest Construction Report, October 10, 2001.

Case Study 8. Agua Fria River Concrete Slab Ford

Location

North Central Arizona. U.S. Department of the Interior Bureau of Land Management Agua Fria National Monument, near Horseshoe Ranch. Approximately 15 miles North of Black Canyon City, AZ, and 3.1 miles south of Cordes Junction, Bloody Basin Road, east of I-17. Forest Road 269.

Crossing Description

This ford was constructed in 1994 on a perennial to intermittent fish-bearing stream. It is a reinforced-concrete slab with concrete approaches. The surface is slightly raised above the streambed surface, but it allows fish passage when the structure is submerged.

Figure A42. Agua Fria River ford.

Setting

Colorado Plateau, Tonto Transition Section (313-C). Short, steep, highly dissected mountain slopes with thin, very rocky soils. Narrow alluvial valleys with schist bedrock not far below the surface. Vegetation is fire-adapted interior chaparral. Willow, sycamore, and juniper grow in drainages.

Appendix A—Case Study 8

Why Was This Structure Selected?

Traffic interruptions are acceptable on this road, road use is moderately low, normal flows are very low (occasionally the channel is dry), and peak flows are very large in this drainage. Thus a low-water crossing is the logical choice of structure. A bridge span would have to be about 150 feet long to avoid constricting the flood channel. The solid concrete slab was chosen to provide enough strength and resistance to movement to survive a major storm event.

Crossing Site History

The previous structure at this location, a ford constructed of concrete planks, jersey barriers, and riprap, was damaged by flooding in 1993. The flood moved many of the planks and riprap boulders downstream from the crossing. Thus the site had to be reconstructed in 1994 and a more durable type of crossing was chosen.

Road Management Objectives

Although located on land managed by the U.S. Department of the Interior Bureau of Land Management, the ford was designed and constructed by the Tonto National Forest as an Emergency Relief for Federally Owned Roads (ERFO) project. The road has an annual average daily traffic count of 75 vehicles, and provides access to popular hunting areas, archeological sites, and to the newly created Agua Fria National Monument. Currently, it receives most use during hunting season but recreational traffic to the monument is expected to increase in future. The road is maintained for passenger vehicles, although road signs at I-17 recommend high-clearance vehicles. Traffic interruptions due to flooding are estimated to occur up to six times each year and last from several days (winter) to a half day (summer) (Gibson, personal communication).

Stream Environment

Hydrology: This is a desert landscape with an annual precipitation in the range of 10 to 25 inches. Most falls as rain during the winter and again during the summer monsoon season (August through September). The drainage basin area above this point on the Agua Fria River is several hundred square miles. The crossing reach is usually perennial but can become intermittent during droughts (Loomis, 2002 personal communication). Floods can be extreme. Flood debris deposited among the trees on the highest natural levee (about 6.5 feet above the low-flow channel) suggests that the 100-year flood in 1993 inundated that surface (figure A45). After the very large flood in January 2005, a tire rim was found embedded in a tree 20 feet above the low-flow channel (Skordinsky, personal communication).

Channel Description: The crossing reach is moderately confined between valley and terrace walls and is controlled by bedrock outcrops in the channel and along one bank a few hundred yards above the ford. Banks are stable and vegetated with trees, shrubs, and grasses. Channel width is about 30 feet, depth about 1 to 2 feet, and slope was estimated at 1 percent (figure A45). Just upstream of the ford, three terraces are distinguishable adjacent to the channel, each one rising about 2 to 4 feet above the previous one, and each bordered by 1- to 2-foot-high vegetated levees. Bed material in transport is primarily sand and gravel, and woody debris trapped on trees shows that debris loads during floods are high. The slightly elevated ford surface has caused the active channel to aggrade somewhat upstream of the crossing.

Aquatic Organisms: Fish biologists have recently identified fish passage as an issue of concern at this type of site (Calamusso, personal communication). As flow decreases, fish need to be able to follow the water to springs, deep pools, or other refuges. At this site, fish were observed moving downstream over the ford in less than an inch of water after a thunderstorm runoff event in May 2003. Later, in August, they were isolated in pools both upstream and downstream from the ford (figure A43). Needs for passage for other aquatic species in this area are unknown.

Figure A43a and A43b. Agua Fria River A43a. Pool several hundred feet upstream of ford in August 2003. A43b. Fish are in isolated pools both upstream and downstream of the dry ford.

Water Quality: Even in this landscape of naturally high erosion rates, sediment delivery from roads is a water quality concern. Protecting water quality and aquatic habitats is an objective of all crossings in the area.

Structure Details

Structure: The ford is an 8-inch thick reinforced concrete slab raised slightly above the bed of the active channel. The driving surface is 15 feet wide and has no curbs. The slab is 65 feet long and flat across the active channel and the lowest flood terrace (figures A44 and A45). Including approaches, the structure extends a total of 170 feet across the channel and flood terraces.

Figure A44. Oblique view of ford and aggraded upstream channel.

Bank stabilization and approaches: Fifty- to 55-foot-long concrete approach slabs slope steeply into the drainage at 15 percent. The road fill obstructs flow on the upper terraces during very high flows, and riprap has been placed along the upstream fillslope to control gully erosion there.

Cost: $95,000, plus 10-percent design cost and 10-percent construction inspection and control. Funding was through U.S. Department of Transportation Federal Highway Administration as EFRO Storm Damage Repair funds.

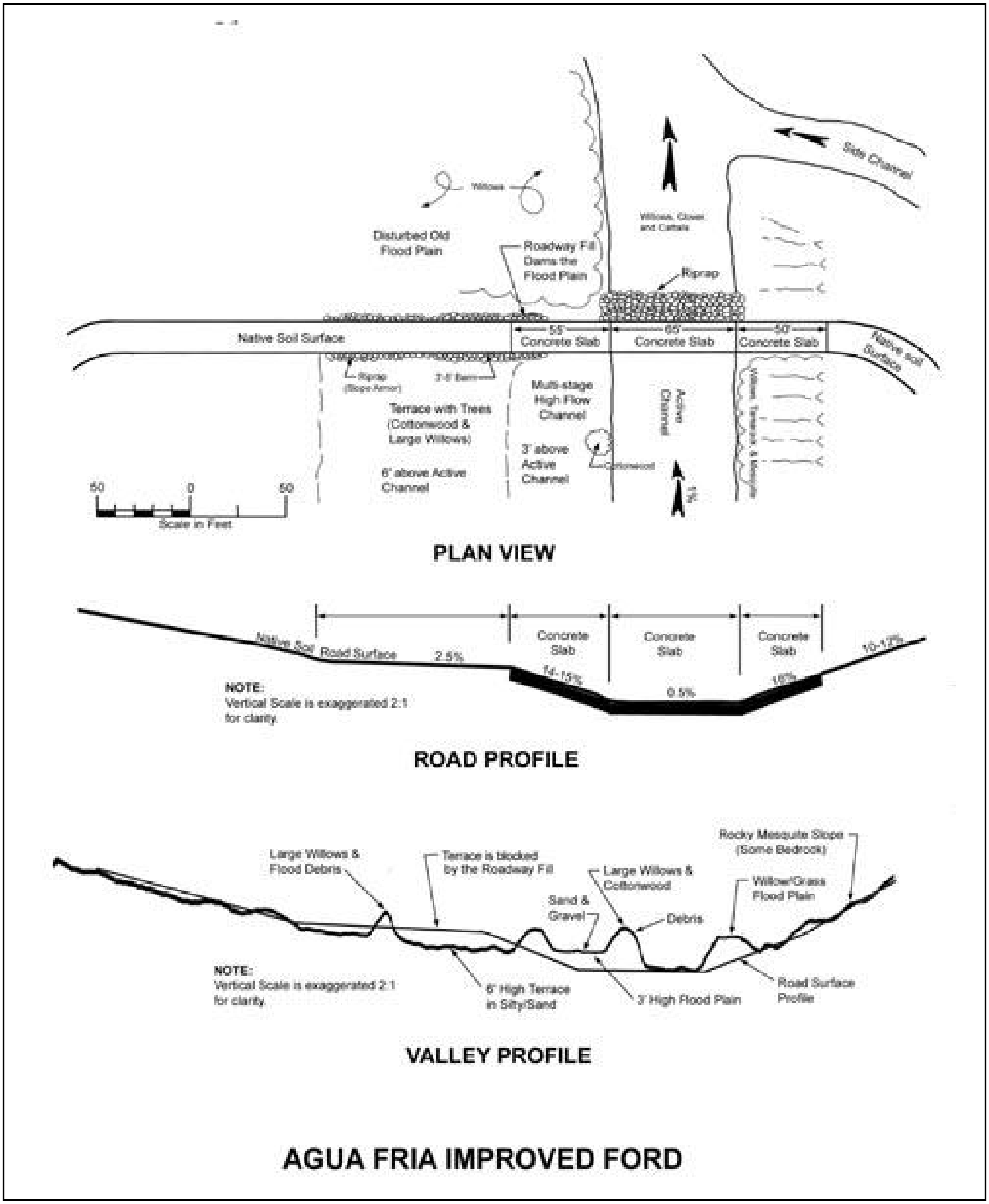


Figure A45. Site plan view and road and valley cross section sketches.

Safety: The crossing is signed before both approaches with “Dip - 5 MPH” and “DO NOT ENTER WHEN FLOODED” signs (figure A46). The road itself is signed as being maintained for high-clearance vehicles only at the junction with the freeway. When water flows over the ford for long times, slippery algae can sometimes be a road hazard.

Figure A46. Warning sign at Agua Fria River ford.

Flood and Maintenance History

Since construction in 1994, this ford required no maintenance until January 2005, when the area received 8 inches of rain in one month. The resulting flood exceeded the structure’s capacity and eroded large volumes of soil from above the armored approach on one side.

Summary and Recommendations

The structure fits the site, with its infrequent floods and moderate road use. It also fits the stream fairly well, except for the fact that it obstructs aquatic organism movement as flow decreases to zero after a runoff event. Since the approach roadfill slightly constricts the flood channel, some gullying and scour are expected along the edge of the road fill.

The downstream edge of the flat slab is about 1-foot above the streambed. Riprap has been placed there to control scour but minor undermining has already occurred in the fine, easily erodible streambed materials. A several-foot deep downstream cutoff wall would be recommended here.

Figure A47. Looking upstream at ford and Agua Fria channel. Fish can move across the ford only when it is submerged.

Gordon Cates, forest engineer (retired); Grant Loomis, forest hydrologist; Bob Calamusso, forest fish biologist; and Marivel Linares, road operations engineer from the Tonto National Forest, and Mary Skordinsky, director of the Agua Fria National Monument provided information for this case study.

Similar Structures in Other Locations

The Ashdale administrative site ford on the Tonto National Forest is another example of an unvented, improved ford with a concrete slab. It is on a very short road (FR24B) that accesses a defunct administrative site, and has primarily light recreational traffic (figure A48). The ford crosses Cave Creek, a moderately entrenched ephemeral to intermittent stream that is closely confined between the valley side walls (figure A49). Channel slope is approximately 3 percent, and much of the bed material is small boulders that are mobile during floods. Annual precipitation in this region is 10 to 25 inches, falling either during the winter or summer monsoon season. Fish or other aquatic organism passage is not a concern on this ephemeral stream.

Figure A48. Ashdale concrete slab ford (downstream is to left).

Figure A49. Cave Creek looking downstream toward the ford.

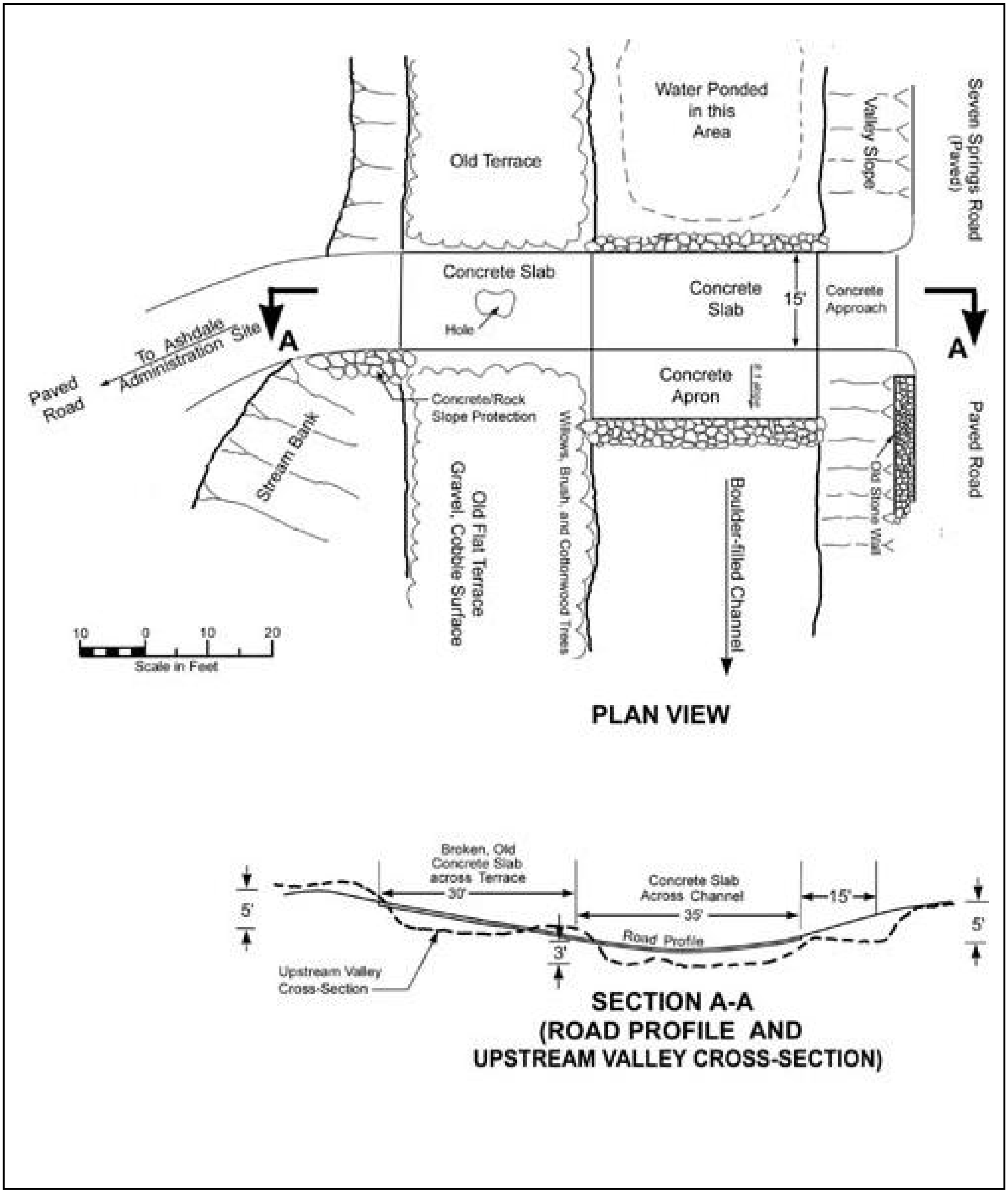


Figure A50. Ashdale ford plan view sketch and valley cross section with road profile.

The ford is 15 feet wide and 35 feet long across the active channel (figure A50), and a total of 80 feet is armored. An 8 to 1 sloping concrete apron transitions to a riprap and boulder cascade reach downstream of the crossing. The structure has a moderate vertical curve with steep, short approaches.

The ford is 50-years old. It has been through many desert floods, including the major 100-year-flood event of 1993. Its concrete surface is battered and has been repaired or extended on both ends. Flows have partially outflanked it at some times in the past, so grouted riprap and pieces of concrete and rock have been placed along the approaches to control scour (figure A51). Downstream scour occurred at some point in its history, leading to the construction of the concrete apron, which currently provides adequate protection against scour. The ford has not received any maintenance since the late 1980s.The structure is appropriate to this high-energy site since it provides for free passage of debris and rock during high flows and there are no aquatic animal issues.

Figure A51. Concrete apron and grouted riprap prevent downstream scour and scour around edges of the ford.

Case Study 9. Mesman Slotted Concrete Slab Ford

Location

South-central Oregon. Fremont National Forest. Thomas Creek crossing on Forest Road 3724. 15 miles Northwest of Lakeview, Oregon.

Crossing Description

This slotted concrete slab ford was constructed in 1996 on a perennial stream with resident redband trout. Previously at this site, there had been a series of structures that either did not pass fish or were not stable. Fish passage is most important during spring high flows for the spawning migration, and the current structure is low enough that trout successfully swim over it during spring flows. To achieve low flow fish passage, there is a 9-inch box slot with a 4-inch opening at the top (similar to the gap in a cattleguard) crossing the middle of the ford.

Since at least the 1980's, objectives for the crossing have included preventing upstream migration of a large headcut moving up through the valley. Today the crossing is part of a restoration project aimed at restoring flood plain and channel connections in the incised reach of stream. The roadway is elevated about 2 feet above stream grade. Class VII riprap faces both the upstream and downstream sides. For specific dimensions, see figure A57.

Figure A52. Looking north at the Mesman ford.

Appendix A—Case Study 9

Setting

Northwestern Basin and Range Section (342-B). This section has near level basins and valleys bordered by long, gently sloping alluvial fans. Pliocene volcanic and shallow intrusive igneous rock occur in the area, and soils are generally aridisols.

Why Was This Structure Selected?

Forest objectives were: to safely pass logging and recreational traffic during the summer; to pass trout during both high and low flows; to avoid flood damage that would harm water quality; and to help restore historical streambed elevations and connections between the stream and its flood plain.

Crossing Site History

The original crossing consisted of a vented ford with three 18-inch culverts, which impeded fish passage. During the fall of 1987, the first channel restoration work was done on the incised section of stream below the crossing. In July 1988, the culvert crossing was replaced with a large (12 foot by 5 foot) bottomless pipe arch with steel footings. During construction, the footings could not be placed at the design depth, and the structure was not properly embedded. One winter in the early 1990's, an ice jam plugged the culvert and the entire structure was carried downstream. The next structure was a ford constructed of rock that apparently was not large enough. The structure eroded to the extent that, by 1995, it was impassable for passenger cars, and this required some action to improve the crossing again. The current structure was completed in October 1996.

Road Management Objectives

This is a gravel surfaced road maintained for passenger cars (maintenance level 3). It is closed by snow during the winter, typically from mid December to June. During the open season, average daily traffic is less than 10 vehicles. Road use is primarily for logging and recreation. Although the road provides access to a heavily used recreation area and is the primary route from State Highway 140 into this part of the forest, traffic volume is low enough that periodic interruptions (less than once per season, on average) from flooding are acceptable. High water results from snowmelt, and by the time the road opens in spring flood flows have usually passed.

Stream Environment

Hydrology: Thomas Creek is a near-perennial stream with peak flows during spring snowmelt runoff, and low summer flows (less than 1 cubic foot per second). Watershed area above the crossing is approximately 20 square miles. Most years, high flows submerge the structure at least 1-foot deep (figure A53).

Figure A53. Spring flow over the Mesman slotted ford.

Channel Description: Above the crossing, Thomas Creek is a Rosgen C or E gravel-bed stream (figure A54a). Gravels in transport are mostly smaller than ½ inch and the streambed is mobile (not armored). Channel slope is 1 to 2 percent in the vicinity of the crossing. Bankfull width varies from about 20 feet to 35 feet, and the banks above the crossing are about 2 feet high. Naturally, floodwaters flow in multiple channels across the flood plain or they may cover it completely.

A large headcut had moved up through the valley to just downstream of the crossing by the mid-1980's (figure A54b). Channel incision was attributed principally to the old grazing system, which had reduced native bank-stabilizing vegetation. The crossing probably contributed to channel instability by blocking the flood plain and concentrating floodwaters through the single crossing structure. In 1988, the forest initiated an effort to restore the incised channel and reconnect it to its flood plain. The channel was reshaped and slope was controlled with rock check dams.

Restoration objectives were to reestablish the natural overbank flow regime, narrow the channel, restore natural vegetation, and improve trout habitat. Shortly thereafter the open-bottom arch culvert that later failed was installed (figure A55).

In October 1996 as the present ford was being constructed, more boulder-weir grade controls were installed and, along with other sediment-retention measures, the weirs have succeeded in raising the streambed. The ford is now functioning as part of a system of structures aimed at channel and flood plain restoration on Thomas Creek. Because of the flood plain issues here, an important objective at this crossing is to interrupt flood plain overflow as little as possible.

Figures A54a and A54b. Thomas Creek in 1988 as seen from the ford (a) looking upstream of the crossing (b) downstream of the crossing.

Figure A55. Looking upstream at the rehabilitated channel during placement of the culvert in 1988.

Aquatic Organisms: Thomas Creek is an important spawning stream for Goose Lake Redband Trout. They need passage during their spring spawning migration, as well as during summer low flows when they may move to find deep pools with cool water or refuge from predators.

Water Quality: Water quality in the drainage is good. The structure was selected, in part, because of its low risk of failing in a way that would create water quality problems.

Structure Details

Structure: The driving surface of the ford is reinforced concrete. Two parallel W-flanges with tops set flush into the concrete run across the ford perpendicular to the roadway. These create an open slot box (9½ inches wide by 10½ inches high), with a 4-inch opening at the top to allow cleaning with hand tools. The slot passes low flows, fish, and possibly other aquatic species. It was designed for a velocity of less than 2 feet per second and a depth of at least 4 inches during normal summer flows to allow passage of both juvenile and adult fish. The ford and the slot slope downstream at 0.5 percent, which is flatter than the stream, and sand and gravel retained in the slot provide at least a partial natural bottom (figure A56).

Figure A56. View of the slot with gravel bottom, August 2006.

Thomas Creek is susceptible to scour, so 24-inch-deep cutoff walls on the upstream and downstream sides were part of the design (figure A57b).

During construction, the interdisciplinary team decided to raise the ford elevation higher than the contract drawings show, to use the structure as part of the system of grade controls being installed to restore the flood plain. As described above, the goal was to induce streambed aggradation and raise flood elevations to historic levels so that the flood plain recovers its historic vegetation, beaver recolonize the stream, and the stream itself narrows to improve trout habitat.

Bank stabilization and approaches: Class VII riprap provides erosion protection on the upstream and downstream sides of the ford and compensates for the slightly elevated grade. Road grades into the structure are 6 percent. An additional benefit of the during-construction ford elevation change was to reduce the vertical curve on the ford, making it easier for lowboys to use.

The designer incorporated several drainage features in the road as it crosses the flood plain approaching the ford (figure A57a). North of the

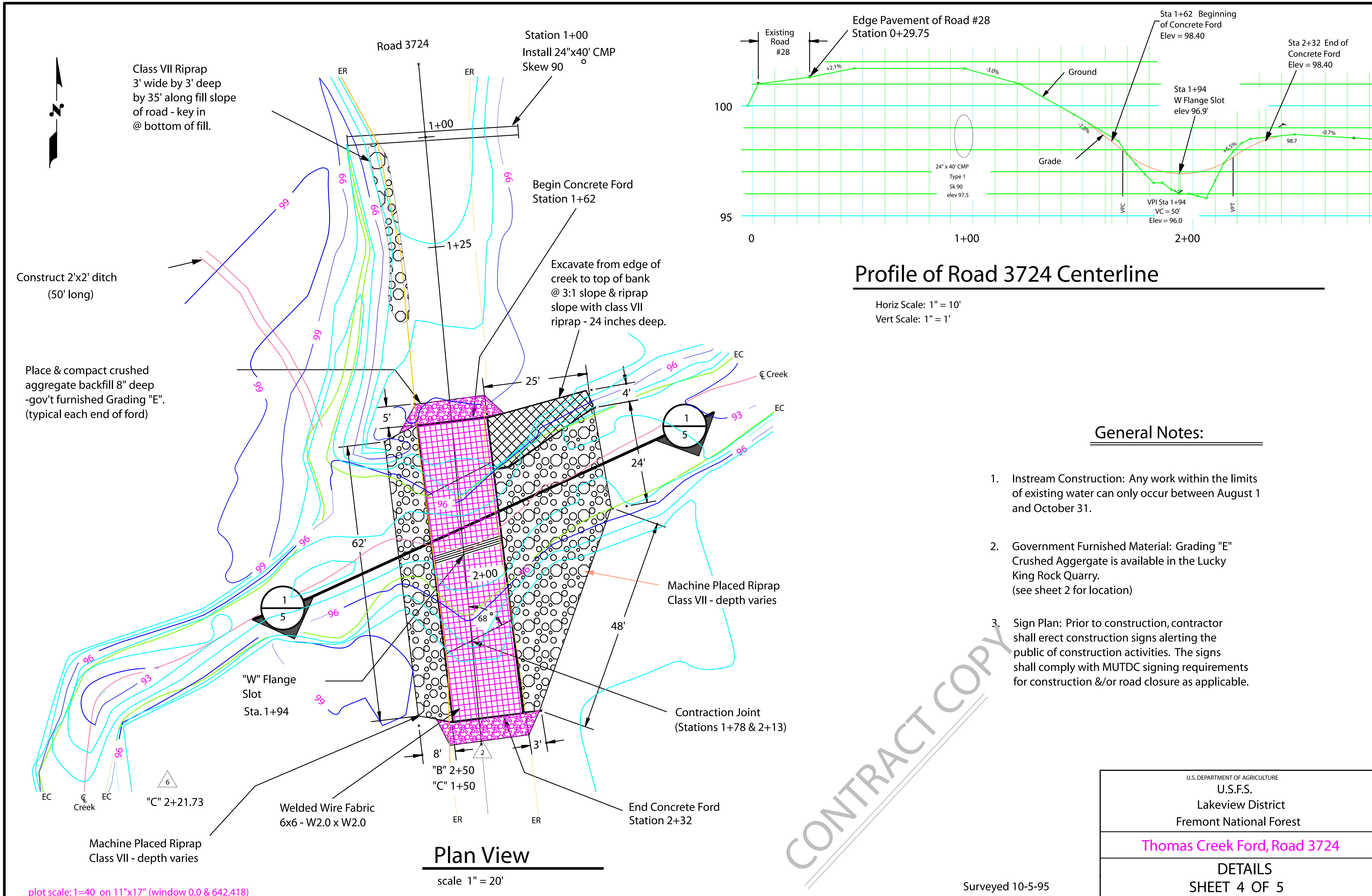
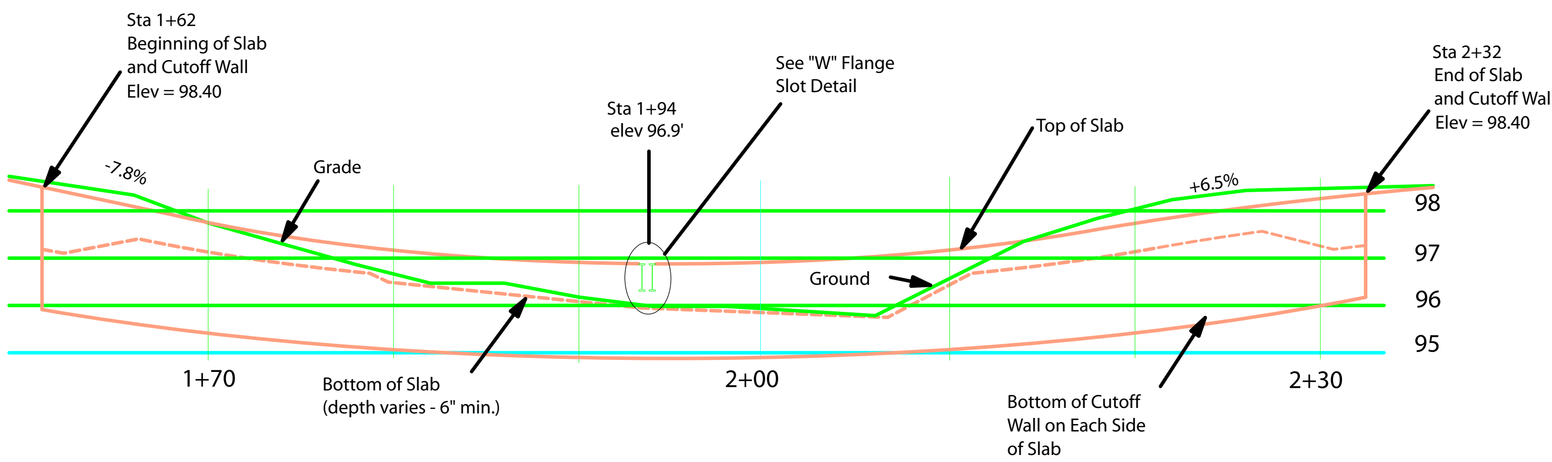
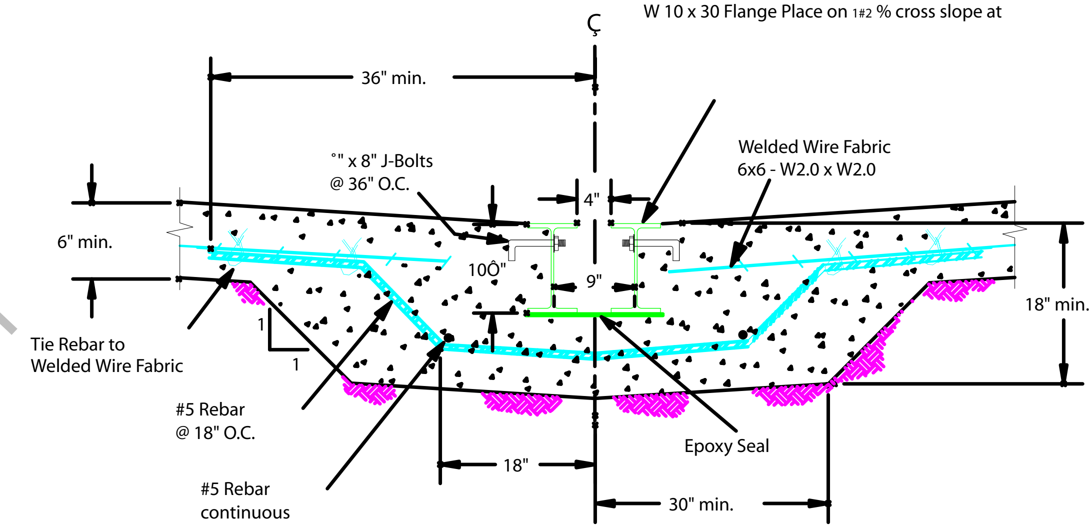


Figure A57a. Thomas Creek ford contract drawings sheet 4: site plan view.



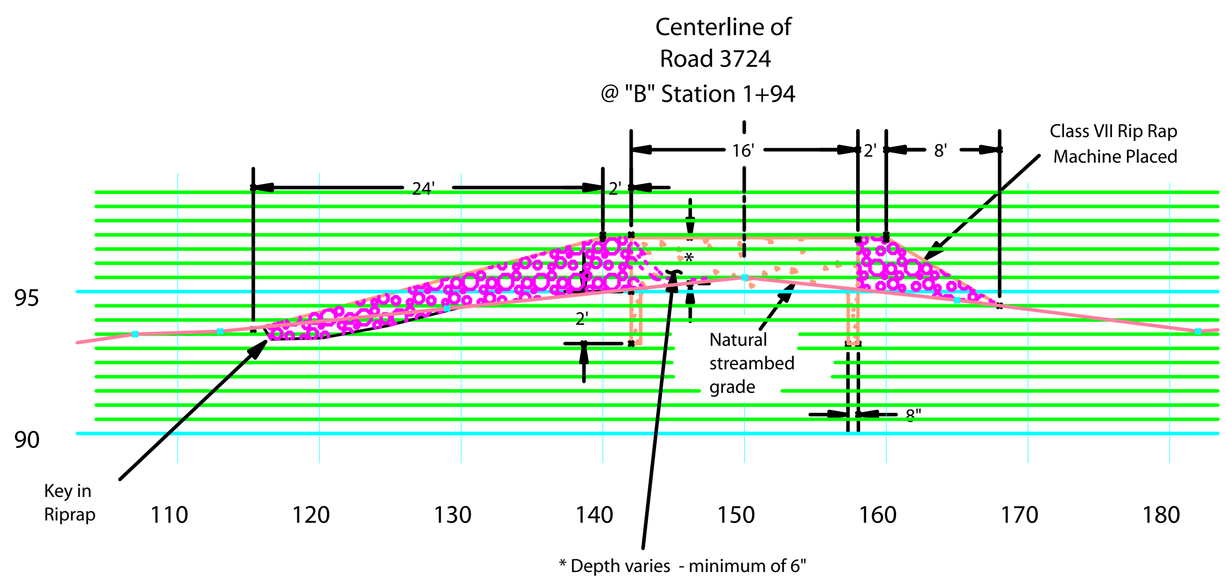
Profile of Road 3724 Centerline

Horiz Scale: 1" = 10'
Vert Scale: 1" = 4'



W Flange Slot Detail

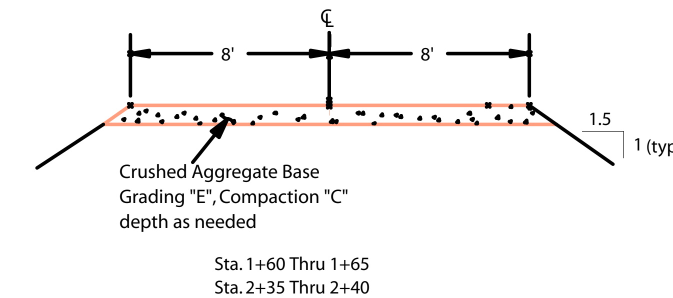
not to scale



X-Section at Creek Centerline

1
5

Horiz Scale: 1" = 10'
Vert Scale: 1" = 5'

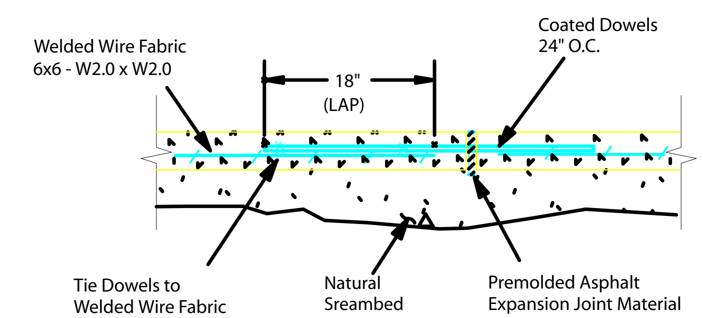


Typical Surfacing Detail

not to scale

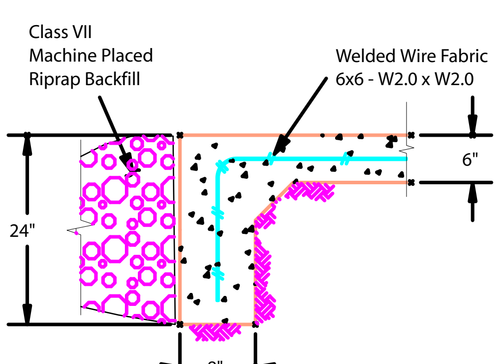
Concrete Notes:

1. All reinforcing steel shall be placed in the middle of the slab with a minimum of 2" below top surface & 2" above bottom of slab.
2. Placement: All reinforcing steel shall be supported by metal, plastic, or precast concrete chairs during placing of concrete.
3. Contraction joints: Shall be constructed at Stations 1+78 and 2+13 and shall be 1/4" wide & 1/4 of the depth of concrete. Joints shall be filled with an approved joint sealant (liquid or preformed elastomeric).
4. Construction joints: Shall be constructed transversely when there is an interuption of more than 30 minutes in the concrete placement operations.
5. Finishing: The concrete shall be struck off with a straightedge and finished to a smooth, uniform texture by troweling and floating. The surface shall then be finished with a deep broom finish. Also all outside edges shall be finished with a 1/4" radius edging tool.



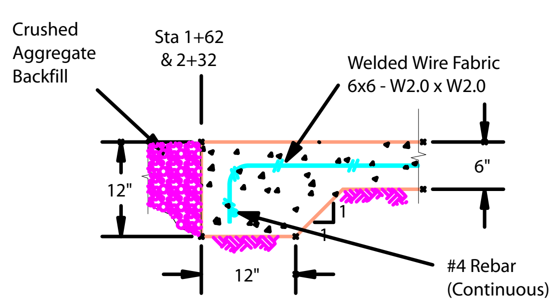
Typical Construction Joint

not to scale



Typical Cutoff Wall

not to scale



Typical Slab End Treatment

not to scale

plot scale: 1=40 on 11"x17" (window 680,0 & 1322,418)

U.S. DEPARTMENT OF AGRICULTURE
U.S.F.S.
Lakeview District
Fremont National Forest

Thomas Creek Ford, Road 3724

DETAILS
SHEET 5 OF 5

Figure A57b. Thomas Creek ford contract drawings sheet 5: road profile, slot detail, cross section along creek.

crossing, a flood plain overflow channel was rerouted toward the ford. There is a flood-plain culvert under the road in that vicinity in case ditch capacity is exceeded. About 150 feet south of the crossing, there is a grade sag in the road surface to permit flood plain flows to overtop the road (figure A58).

Figure A58. Looking south across the submerged ford in January 1999. The road dip beyond the ford is conveying flood plain overflow.

Cost: The original bid for construction in 1996 was $20,900. Final cost was $23,120 due to extra concrete used to raise the center of the structure.

Safety: The crossing is not signed; however safety hazards are minimal. The site is on a relatively straight part of the road with good sight distance. Approach speeds are also low due to the proximity of the crossing to a junction.

Flood and Maintenance History

In 1997, a flood estimated to exceed a 100-year event sent 3,000 cubic feet per second over the ford and submerged the entire flood plain. Other than the loss of a few cubic yards of gravel surfacing from the approaches, no damage occurred (figure A59). In the 10 years the ford has existed, no other maintenance has been required.

Figure A59. Shortly after the 1997 New Year's Day flood. Some gravel washed from the approaches (in foreground) was the only damage from the largest flood on record.

Summary and Recommendations

The forest considers the Thomas Creek slotted ford a very successful application of this type of design. It is working well to achieve channel and flood-plain restoration objectives, and has successfully maintained fish passage by means of the riprap placed up and downstream as well as the low-flow slot. The riprap cascade placed downstream to make up the elevation difference between ford and streambed resembles cascades found a short distance downstream where the meadow ends and slope increases. The cascade is clearly passable to both adult and juvenile trout.

Another reason for the success of this design is that the stream at the crossing site is not entrenched--banks are only 2 feet high--so the approaches are not excessively steep. Also, the stream is wider than normal at the site, due to the previous crossing structures. Spreading the water out wider than the natural channel may partially offset the ford's smoother surface, and help to keep overtopping velocities within the range that spawning trout can negotiate. The road approaches are low and incorporate drainage structures that maintain flood flows across the flood plain, avoiding floodwater concentration at the structure.

A third reason for the ford's success is that although there is an active beaver lodge just upstream of the crossing, the ford does not offer the beaver anything to plug or dam. While the beaver occasionally places twigs in front of the slot opening, they can be cleared out easily. The ford is a much more desirable structure in this kind of stream than a culvert, which most likely would attract the beaver as a dam site.

The only change the forest would make in the design is to extend the concrete further up the approaches to cover the full wetted perimeter of a major flood event.

Photos and information on the Messman ford were provided primarily by Jerry Panter, design engineer. Dave Hogan, fisheries biologist of the Fremont National Forest; Clay Speas, fisheries biologist, Grand Mesa, Uncompahgre, and Gunnison National Forests; Mike Montgomery, district ranger/hydrologist, Malheur National Forest; and Mike Lohrey, regional hydrologist, USDA Forest Service Pacific Northwest Region provided additional historical background.

Case Study 10. Black Canyon Concrete Plank Ford

Location

North central Idaho. Clearwater National Forest. North Fork Clearwater River. Road 250, about 45 miles from Superior, Montana, and 55 miles from Pierce, Idaho.

Crossing Description

This vented ford is one of several built in 1998 on a valley bottom road that crosses the lower end of several steep (greater than70 percent) perennial streams prone to debris and snow slides. This structure consists of concrete planks and riprap, with a 24-inch culvert installed below the planks.

Figure A60. Ford is located on a valley bottom road at the base of an avalanche chute.

Setting

Northern Rockies Section (M333-C). In the Black Canyon area, the North Fork Clearwater River is bordered by very steep, dissected breaklands.

Why Was This Structure Selected?

This type of structure was selected to stormproof the road; that is, to handle large, almost annual snow and debris avalanches without failing. The secondary objective was to reduce maintenance requirements on the road.

Crossing Site History

These structures replaced concrete slab fords that had been constructed in 1983. The slab fords were starting to breakup (inadequate rebar) and were pitched too steeply for easy crossing by recreational traffic such as trailers and campers.

Road Management Objectives

Forest Road 250 is an arterial gravel road (maintenance level 3). It accesses one developed recreational site and numerous dispersed recreational sites. The crossing must accommodate sporadic log and equipment haul as well as summer and fall recreation traffic. The road is closed during winter.

Stream Environment

Hydrology: The North Fork Clearwater River is a steep perennial river. The side drainages experience massive snow slides most years (figure A61). Summer low flows on the side drainages are generally about 1 to 2 feet wide and a few inches deep.

Figure A61. Spring snow slide on top of ford, April 2003.

Channel Description: The ford is located on a steep tributary channel, a Rosgen A1a+ in a bedrock avalanche chute (figure A62). Drainage area is approximately 320 acres, and near the bottom of the slope the channel is approximately 6 feet wide. Banks are not well vegetated or particularly stable.

Aquatic Organisms: There are no known needs for aquatic organism passage. However, the North Fork Clearwater River is a high value fishery and every effort is being made to reduce road-related sediment delivery.

Water Quality: The watershed has high surface soil erosion potential and very high sediment delivery efficiency.

Figure A62. Looking upstream across the ford to the channel. The culvert is to the right out of the frame.

Structure Details

Structure: The concrete planks are 8 inches by 14 inches by 15 feet with steel rebar reinforcement. Planks are separated by 1 to 2 inches. The planks were cabled together and laid over a 1-foot thick foundation of crushed aggregate that was compacted in two 6-inch layers. A 24-inch culvert is located below the planks (figure A63). Riprap was placed at the outlet end of the ford with the top elevation of the riprap conforming to the top elevation of the concrete planks.

Figure A63. Looking downstream toward the North Fork Clearwater River. Note the sediment catch basin in foreground.

Cost: The total Black Canyon project included several fords installed in 1998, with a cost of approximately $300 per plank. The work was accomplished by a national forest (force account) crew.

Safety: Safety is a primary concern. Traffic is allowed only after the road is completely clear of avalanche debris and high flows have subsided. This usually happens in June to early July depending on the amount of snow and debris that has accumulated at each crossing.

Flood and Maintenance History

As expected, snow, sediment, logs, and rocks are deposited on the structure annually. The structures are inspected and cleaned each year before the road opens. Expectations are that the structures will be cheaper to repair than slab fords, since individual planks can be replaced if they are broken by rock or debris during a slide.

Summary and Recommendations

This structure has been in place for 5 years and, like the other plank fords in avalanche chute areas, it has performed well handling annual slides. The 'channels' between the planks, and the culvert under the planks, allow for continued water passage even when the structure is covered with debris. In hindsight, the forest would recommend using a larger culvert (36 or 48 inches), in anticipation of a 100-year runoff event.

Information on the Black Canyon ford was provided by Brian Hensley, watershed restoration technician; Anne Connor, watershed restoration engineer; and Norm Steadman, engineer, of the Clearwater National Forest.

Case Study 11. Babcock Crossing Vented Ford

Location

Northeastern California. Plumas National Forest, Mount Hough Ranger District, at the Indian Creek crossing of Road 26N10, near Road 29N43 (Antelope Lake Road). The site is between Taylorsville, California and Antelope Lake, 14 miles northeast of Taylorsville.

Crossing Description

This ford was constructed in the 1960's on a perennial stream below a reservoir. It was repaired after a major flood in 1982. Fish passage is a key issue. The structure has a 200-foot long, 18-foot wide concrete armored driving surface over four 32- by 44-inch corrugated metal pipe arch culverts. The culverts are set at stream level, with little elevation change between the inlet and outlet. The concrete slab is 6 inches thick and is protected at the inlet and outlet with gabions and grouted riprap.

Figure A64. Babcock crossing roadway has a slight vertical curve.

Setting

Sierra Nevada Section (M261-E). Elevation 4,480 feet. Within a granitic pluton in the northern Sierra Nevada and with dominantly decomposed granitic soils. Mid- to east-side forest area of mixed conifer, pine, and cottonwoods along creeks.

Appendix A—Case Study 11

Why Was This Structure Selected?

This design was chosen because of the large difference between normal flows and flood flows in response to reservoir releases (from Antelope Dam). Several similar vented fords were constructed during the 1970's since it was a popular design in that era.

Crossing Site History

The original crossing at this site was probably an unimproved ford. A 65-foot-long bridge was designed for this site in 1966 but was never built. This gabion, concrete, and culvert structure was designed and built in the late1960's by the forest. Flooding in 1982 undermined the central part of the concrete slab, and significant repairs were required (figure A65). Since that date the structure has required little maintenance.

Figure A65. Downstream scour under the slab after the 1982 flood. The repair was to add a 5-foot-deep vertical concrete cutoff wall.

Road Management Objectives

This is a gravel-surfaced road maintained for passenger vehicles (maintenance level 3). It provides access to the Babcock Peak area and the east side of the forest and is not kept open in the winter. Use is a mix of occasional logging traffic during a timber sale, USDA Forest Service administrative traffic, and the general public. Traffic volume (average daily traffic is 50 vehicles) and type are such that occasional interruptions are acceptable. Also a longer but alternate route is available if necessary to access the area. Traffic interruptions lasting several days can occur up to two times per year after moderately large storm events (figure A66). When the reservoir water level is being lowered, traffic interruption can last several weeks.

Figure A66. Crossing during a flood event. It is clearly not passable at this time. Note the amount of energy and “scour power” where the flow drops several feet over the structure.

Stream Environment

Hydrology: This area has a snow-dominated precipitation regime, with severe runoff events often caused by rain-on-snow. Summer thunderstorms can be intense. The Indian Creek watershed drains approximately 85 square miles on the extreme northeast side of the forest. Indian Creek is a perennial stream controlled by Antelope Reservoir, several miles upstream. It has an estimated 100-year return flow of 4,500 cubic feet per second. Summer low flows are of the order of 5 to 10 cubic feet per second. Flood flows inundate the entire structure 2 to 4 feet deep. Flood-flow velocities were estimated at 7 to 9 feet per second.

Figure A67. Indian Creek looking upstream from the ford.

Channel Description: At this location, Indian Creek is a gravel-bed Rosgen C4 channel with stable banks 2 to 3 feet high. Channel width is approximately 30 feet above the structure and slope is between 1 and 2 percent. Riparian vegetation includes grasses, willow, cottonwood, alder, and pine trees. The channel is wider and shallower below the structure than above because of bank erosion when water overtops the ford.

Aquatic Organisms: This section of stream provides habitat for nonthreatened native fish, including rainbow trout and nongame species. The stream is a popular fishing and recreation area, and providing passage for fish is a key issue. The ford likely impedes fish passage but does not totally block it. At normal flow levels a beaver dam backwaters the pipes, and fish have been observed swimming through them. Movement for other aquatic organisms is at least partially blocked by the culverts.

Water Quality: Sediment delivery and movement in this watershed is a high concern, and this east side watershed produces a moderate amount of sediment in decomposed granite terrain. However the reservoir traps a high percentage of sediment so that water released below the reservoir is relatively high quality.

Structure Details

Structure: This structure is a 6-inch thick concrete slab roadway over four 32- by 44-inch corrugated metal pipes. It was originally constructed 130 feet long, but after the 1982 flood, an additional 70 feet of concrete surface was added (part on both ends) to protect the entire wetted perimeter of the crossing. Five-foot deep downstream cutoff walls were also added in 1982. This structure has a low vent area ratio, as can be seen in the sketch below (figure A68). Currently the structure is outlet controlled due to a downstream beaver dam.

Bank stabilization and approaches: After the 1982 event, one set of gabion baskets was placed below the outlet of the culvert pipes for scour protection and energy dissipation. Additional scour protection includes the 5-foot deep concrete cutoff walls along both sides of the ford (as shown on the site sketch) that are tied into the concrete slab roadway. Grouted riprap was placed outside of the cutoff walls along the upstream and downstream edges of the structure. The ford slopes gently into the drainage at 3 to 5 percent on both approaches.

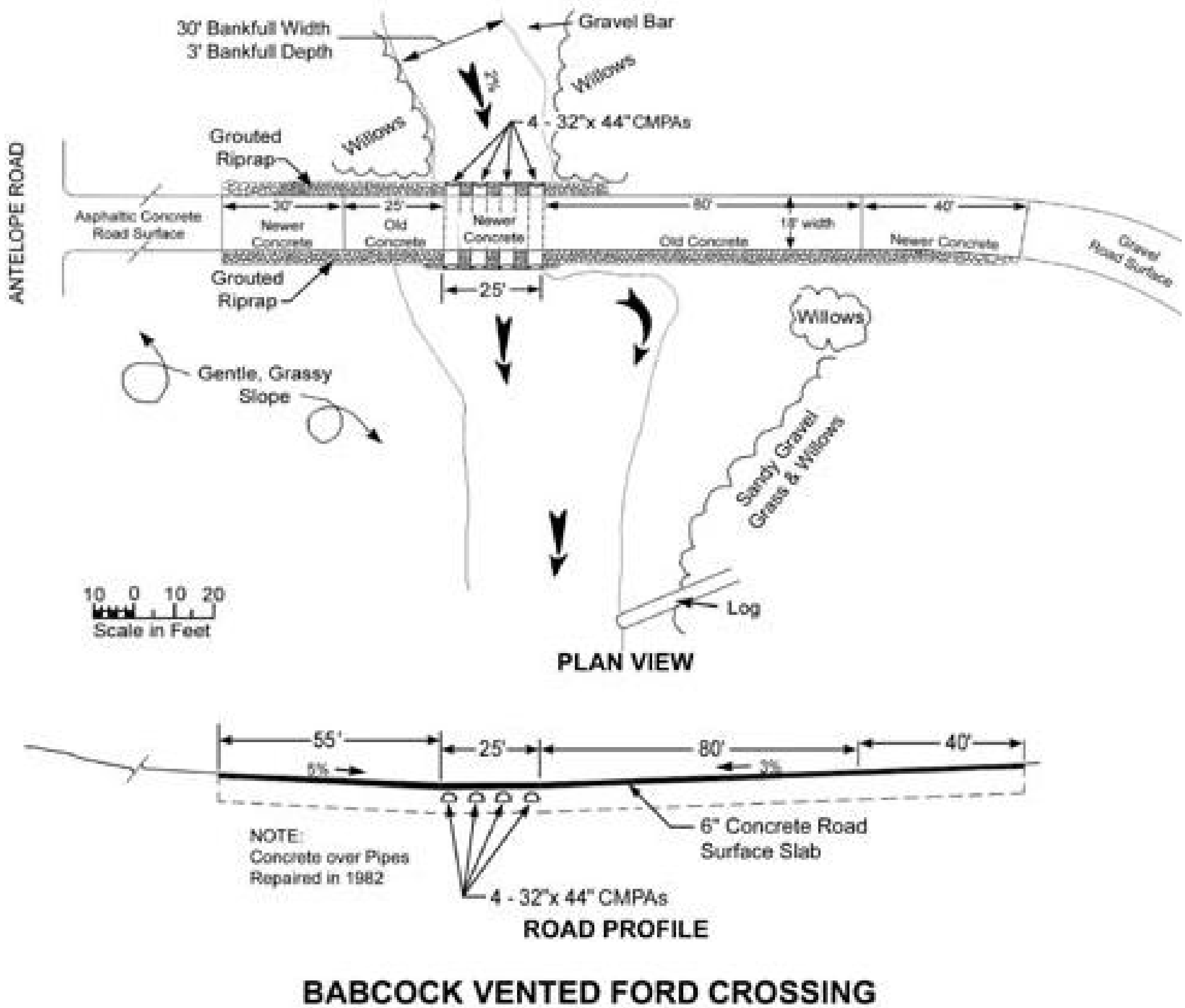


Figure A68. Site plan view and road cross-section sketch. Note the 5-foot deep concrete cutoff wall (dotted lines).

Cost: Initial construction cost is unknown. Repair costs in 1983 were $48,700. This cost likely equaled or exceeded the initial cost of the structure.

Safety: The crossing is unsigned. However, the entire structure has a low profile, only 3 to 4 feet above the channel bottom, and there are gently sloping (1.5h:1v) grouted riprap shoulders along the edge of the roadway. The site is very open and on a nearly straight section of the road with good sight distance. Thus, safety issues are minimal. At one time road managers considered adding a guardrail, but decided against it because it would trap debris. Object markers and depth stakes could be added for additional safety.

Flood and Maintenance History

A vented ford has existed at this site for about 30 years. The initial structure was a concrete slab roadway over the four 32- by 44-inch arch corrugated metal pipes. In 1982 the original ford was damaged and underwent significant repairs. Portions of the original upstream and downstream gabion slope protection were scoured away and the mid portion of the concrete slab over the culverts along the downstream edge was undermined, causing part of the slab to crack and settle (figure A65). Much of the roadway cross-section over the pipes was refilled, a new concrete slab was poured, cutoff walls were added, and rock riprap was replaced and grouted along the upstream and downstream edges of the roadway. Repairs in 1982 required a total of 103 cubic yards of concrete and nearly 200 cubic yards of grouted Class IV riprap.

Since that time the structure has endured two major storm events (in 1986 and 1997) with only minor downstream scour damage. Maintenance includes removing debris from the top of the structure and from the culverts. Slope protection with concrete and gabions along the margins of the roadway has been successful.

Summary and Recommendations

This structure has survived for over 30 years. Although an event in 1982 severely affected the structure and required significant repairs, there have been no significant problems since this event. Bank scouring during floods has caused local channel widening below the structure, but its extent is very limited. Increasing structure sag, and using larger culverts would likely decrease downstream erosion problems. Larger culverts would also decrease the potential for small-size debris to obstruct flow, as in figure A69. The 1982 repairs could have been avoided by constructing upstream and downstream concrete cutoff walls, several feet deep, for scour protection along the edges of the structure.

Figure A69. Small debris partially plugs the pipes.

Gordon Keller, geotechnical engineer on the Plumas National Forest, provided information and photos for this case study.

Similar Structures in Other Locations

The Ouachita National Forest in west central Arkansas has traditionally made frequent use of concrete vented fords with round concrete culverts on second- and third-order streams. The crossing on lower Harris Creek on the Ogden Ranger District is a good example (figure A70).

Figure A70. Lower Harris Creek concrete vented ford.

Appendix A—Case Study 11

Harris Creek is a moderately entrenched gravel- to cobble-bed stream with a drainage area of about 3 square miles. It is perennial, but flow can go very low in summer. It is habitat for the endangered leopard darter, among other weak-swimming fish. These fish need free passage to find deep pools with cool water during the summer heat, and to recolonize areas where local extirpations have occurred due to extreme low flows (Gagen and Rajput 2002). The Harris Creek vented ford is thought to be a complete passage barrier.

Figures A71a and A71b. Figure A71a. Harris Creek upstream of ford. Figure A71b. Downstream of ford.

Note the bank erosion and widened channel downstream of the structure (figure A71b). As figure A70 shows, the ford is nearly flat across the stream, and when it overtops flow can go around the ends of the structure, eroding the banks. The same type of turbulence shown in figure A66 at the Babcock crossing undoubtedly happens here during overflow, with similar results. Scour protection at this ford consists of a concrete splash apron (figure A72) and riprap. The riprap is placed in a trench just downstream of the apron.

The forest plans to replace this structure with a high vent-area ratio concrete box culvert that provides darter passage during low flows, like the crossings in case study 14.

Richard Standage, Jim Getchell, and Herb Mansbridge of the Ouachita National Forest provided the information for this example.

Figure A72. Concrete pipes outlet on splash apron with riprap downstream. Fillslope is also protected by concrete. Note erosion to side of fillslope concrete armor.

Case Study 12. Grubbs Concrete Slab Vented Ford

Location

North central California. Plumas National Forest. Mount Hough Ranger District. Grizzly Creek. 3 miles west of Bucks Lake, CA. Forest Road 23N92Y, just off the Oroville-Quincy Highway (FH119).

Crossing Description

This partially vented ford is a massive concrete slab that was constructed in 1986 on a 55-foot-wide high-energy perennial stream. The channel is not steep at this site (approximately 2 percent), but it is immediately downstream of steeper, unstable terrain, and it moves boulders up to about 1½ feet in diameter during floods. The ford consists of a 65-foot long reinforced concrete slab about 1-foot above channel grade with one opening for fish passage: an embedded 3-foot-wide concrete-walled box covered with a cattleguard grating (figure A73). The opening frequently plugs with debris and boulders, and upstream fish passage is questionable most of the time. The downstream edge of the structure is protected against scour with gabions. The structure withstood the major 1996 flood with no damage.

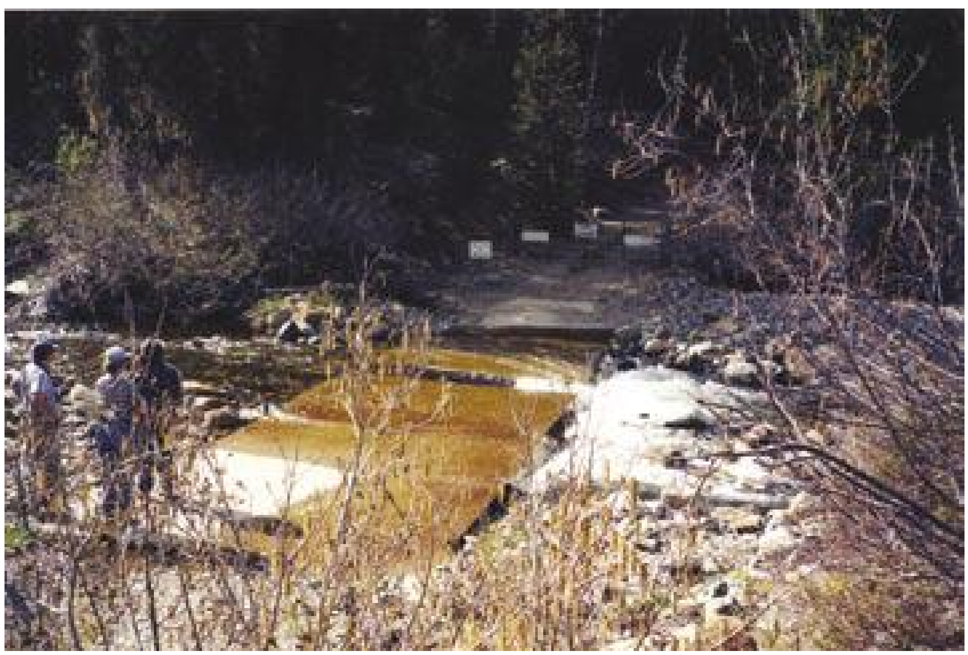


Figure A73. Grubbs crossing on Grizzly Creek, May 2002.

Setting

Sierra Nevada Section (M261-E). Northern end of the Sierra Nevada in granitic and strongly metamorphosed volcanic and sedimentary rocks. Elevation 4,950 feet. Vegetation is Douglas fir-mixed conifer, with willow, cottonwood, and alder along the creek.

Appendix A—Case Study 12

Why Was This Structure Selected?

A slab ford with vent was selected at this site for three main reasons: stream power and bedload movement are high during storm events, and the previous structure was not strong enough; fish passage is a concern; and the crossing receives little use. The site's broad, shallow profile makes it a good location for a ford.

Crossing Site History

The previous crossing structure was a vented ford constructed in 1984 to provide access across the stream during a timber sale. It was a gabion-type structure fabricated from surplus pieces of welded wire from a retaining wall, and had two corrugated metal pipes as vents. It was too weak for the dynamic forces of the stream at this site, and was destroyed in 1986 (figure A74).

Figures A74a and b. The original gabion vented ford. (a) as built and (b) after the 1986 storm.

Road Management Objectives

This road accesses a block of private land and a small piece of USDA Forest Service land, and is closed with a gate on the far side of the crossing. Use is a mix of occasional logging traffic during a timber sale, USDA Forest Service administrative traffic, and some private use. The road is native surfaced and is maintained for commercial vehicles (maintenance level 2).The typical annual average daily traffic count is 0, although during a timber sale, average daily traffic can be 20 to 50.

The structure is inundated for several weeks during annual spring peak flows. During the season of use (summer to fall), traffic interruptions are expected one or two times per year, for approximately 12 to 48 hours.

Stream Environment

Hydrology: Grizzly Creek is a perennial tributary of the North Fork of the Feather River that drains about 5 square miles. Average annual precipitation is 75 to 80 inches. Winter snow is generally heavy in this area and spring runoff peaks early and moves large (up to 18-inch) boulders. Grizzly Creek is spring-fed in its alpine headwaters and has a strong base flow. Summer low flows are on the order of 30 cubic feet per second. The design storm flow (Q100) is estimated at 1,900 cubic feet per second. Flood debris deposited on the crossing slab showed that the most recent 100-year flood (1997) totally inundated the entire channel several feet deep (figure A78). Peak flow velocities were estimated at 8 to 10 feet per second.

Channel Description: At the site, channel slope is 2 to 2½ percent, and the substrate is a well-graded mixture of gravels, cobbles, and boulders to a maximum size of about 18 inches. The bankfull channel is about 55 feet wide, and is slightly entrenched (figure A75). Streambanks are fairly stable, and riparian vegetation includes willow, alder, fir and cottonwood.

Figure A75. Grizzly Creek downstream of the ford, May 2002.

Aquatic Organisms: This section of stream provides habitat for nonthreatened rainbow trout, as well as nongame fish. Fish passage is a key issue at this location, but little is known about how successfully fish move across the structure. Accelerated water velocities across the smooth concrete probably inhibit fish moving upstream and the vent is normally plugged. Young fish have been seen moving downstream across the slab.

Water Quality: Water quality in the stream is naturally excellent and maintaining it is an important objective. This massive concrete structure is a good structure type for water quality protection, because it does not chronically contribute sediment to the stream, and it can sustain the largest floods without failing.

Structure Details

Structure: This structure was designed and rebuilt by the Plumas National Forest under a public works contract as part of the 1986 storm damage repair program. Two concrete "boxes" were poured, each 30 feet long by 14 feet wide, with a 4-foot-deep cutoff wall extending across the entire channel, tying the two boxes together. The core was backfilled with gravel and an 8-inch-thick concrete slab was poured to form the driving surface on both sides.

Between the two concrete boxes, a 3-foot-wide embedded box culvert was constructed for fish passage (figure A76). A steel Irvine Type "HV" bridge decking with welded metal grating bridges the box to connect the driving surfaces.

Figure A76. A 3-foot wide gap left between the two sides of the ford forms a narrow concrete-floored vent.

The project took approximately 3 months to construct and required a total of 42 cubic yards of reinforced concrete and 35 cubic yards of gabions.

Bank and bed stabilization and approaches: The ford slopes into the channel at 7 to 9 percent (figure A77). Four-foot-deep concrete cutoff walls were constructed along both edges of the roadway for scour prevention. The downstream edge was also armored with two rows of gabions. The upper row sits on a concrete sill attached to the wall of the structure, and the lower row sits directly on the streambed.

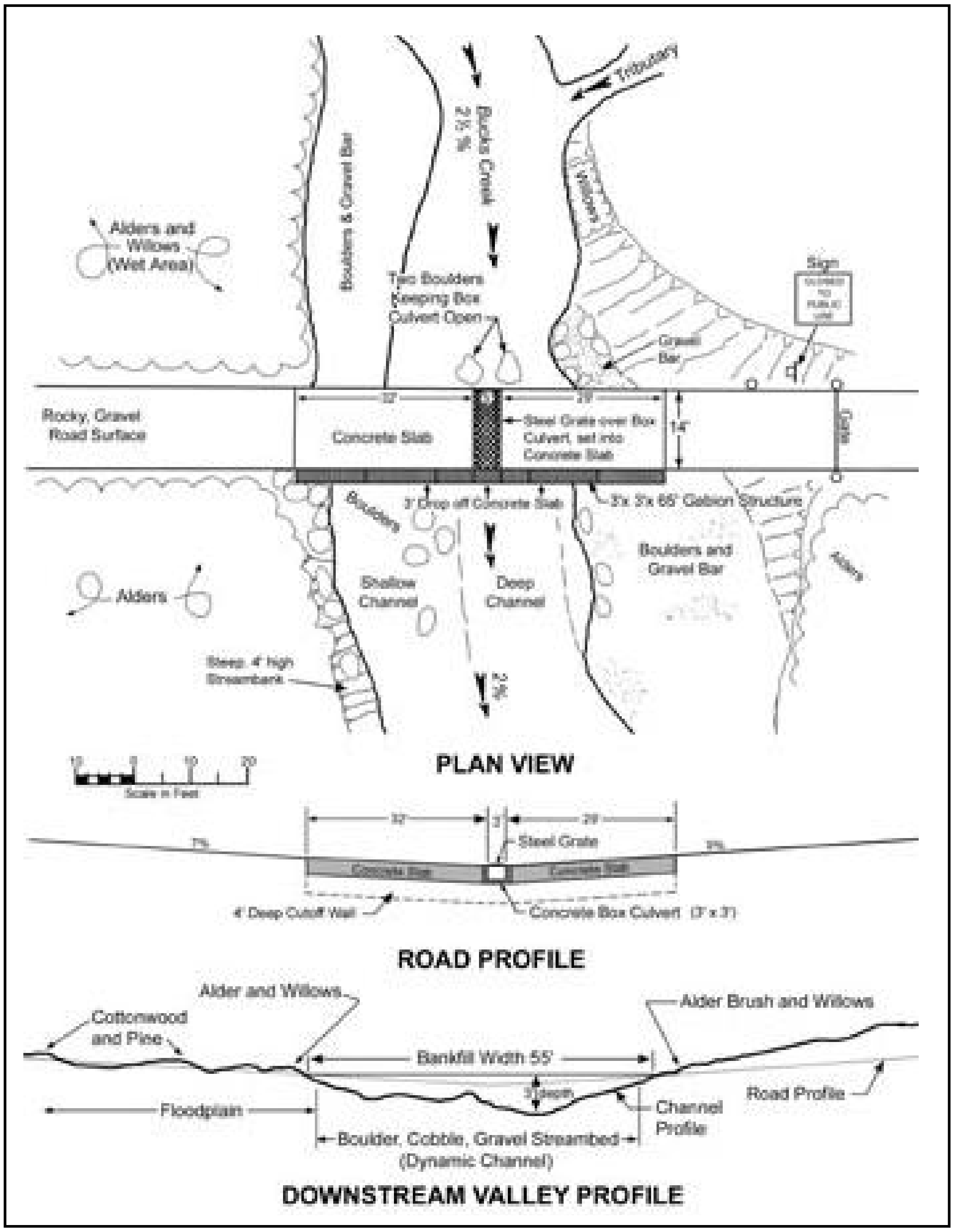


Figure A77. Site plan view and cross-section sketch.

Cost: Total new construction cost in 1987 was $44,500.

Safety: The structure has no safety measures other than object markers at each end of the ford. The ford sees limited use most of the time, and because the driving surface is close to the streambed, safety concerns are minimal. The ford is on a straight section of the road and the water depth is relatively easy to see.

Flood and Maintenance History

This massive reinforced concrete structure survived the major 1997 flood event with no damage (figure A78). Minor maintenance is frequently required to remove rocks and boulders off the slab and from the concrete box. Boulders moving in the channel during high flows are not much smaller than the box width, and in conjunction with small debris they tend to keep the box plugged most of the time. Some of the downstream gabions will need replacement soon due damage and abrasion of the wire.

Figure A78. After a major storm, medium and large boulders and large root wads cover the ford, but the structure is undamaged.

Summary and Recommendations

The Grubbs low-water crossing is a relatively massive concrete structure capable of withstanding major storm flows and major bedload movement (figure A79). This type of structure is necessary for a ford in a very dynamic stream environment. There has been little downstream scour, probably due to coarse streambed material. However the embedded box intended for fish passage is too narrow given the size of the bed load moving in the channel; it plugs frequently, and requires maintenance to clean the vent. After 20 years, the gabions are worn and need repair.

Figure A79. Grubbs ford immediately after construction in 1986. The vent appears to be a velocity barrier when it is not plugged.

This high stream power, high-value fishery site is a very difficult location for a low-water crossing. Any structure here will have to sustain high floods transporting large boulders, and it should pass fish and other aquatic organisms most of the year. Both objectives could be accomplished using a high VAR vented ford with embedded concrete boxes approximating the bankfull channel width.

Gordon Keller, geotechnical engineer on the Plumas National Forest, provided information and photos for this case study.

Case Study 13. North Fork Consumnes River Tributaries Box Culvert Vented Fords

Location

Central California. Eldorado National Forest, Placerville Ranger District. About 18 miles ESE of Placerville. North Fork Consumnes River basin. Meiss Cabin Road, Forest Road 52 upstream of Capps Crossing.

Crossing Description

These structures are concrete boxes with removable grate tops, designed to permit removal of bedload and woody debris that could jam the opening. The example here has slab approaches, upstream and downstream cutoff walls, and a sloping concrete floor intended to concentrate low flows along one wall for fish passage (figure A80). The box is set at natural stream grade and slope. At that slope, flow across the smooth concrete floor is too fast to allow fish to swim up. Riprap protects all four cutoff walls. There are several of these structures along Forest Road 52 near the Capps crossing (case study 21).

Figure A80. One of several grating-top box culvert fords on tributaries of the North Fork Consumnes River.

Setting

Sierra Nevada section (M261-E). Rocks are mixed granitic, volcanic, and meta-sedimentary. Ponderosa pine-mixed conifer forest. Summers are dry. Rain on snow is a common cause of floods.

Appendix A—Case Study 13

Why Was This Structure Selected?

The Meiss Cabin road runs along the edge of the North Fork Consumnes River valley bottom, where several steep tributaries exit steep, confined valleys and abruptly deposit their bedload. The grate-top box structures are designed to survive plugging without failing. A secondary goal at some sites was to permit fish passage up-and downstream.

Crossing Site History

Previous structures at these sites were culverts, which had plugged and been replaced by progressively larger culverts over a period of years. All of the tributary crossings failed in the January 1997 storm event (figure A81). At one crossing, a Hilfiker welded wire headwall was so battered by boulders that it had to be removed. Refer to case study 21 for a review of watershed history and condition that explains why these tributaries are transporting so much rock and sediment.

Figure A81. Typical flood damage at edge of North Fork Consumnes River valley after 1997 rain-on-snow flood.

Road Management Objectives

Forest Route 52 is a gravel-surfaced, main collector road (maintenance level 3) used for recreation, timber haul, administrative access, and access to private land. Occasional closures due to severe weather are acceptable, but dependable summer access is required.

Stream Environment

Hydrology: These tributaries drain watersheds that are only a few square miles in area. Some streams are perennial; others intermittent. Large floods often occur during midwinter rain-on-snow events, but spring snowmelt normally causes the annual peak flow.

Channel Description: In gold rush days, roads ran right up the channels to get to mining or timber harvest areas. Coarse sediment is in ample supply in the streambeds (figure A82). These tributaries may naturally be B3 channels, but they are so disturbed in the vicinity of the crossings that they are difficult to classify. Channel slopes are at least 3 percent. Valleys are narrow and the streams are moderately entrenched.

Figure A82. Aggraded boulder-bed intermittent tributary of the North Fork Consumnes River, July 2002.

Aquatic Organisms: Little is known about fish use of these tributaries, but the assumption is that fish use the perennial streams, and may even access the intermittent ones during high flows. Downstream fish passage is required during falling flows to avoid isolating fish in upstream pools. The boxes were designed with a tilted floor and small trench to concentrate water to pass fish and other aquatic species during low flows (figure A83). These may indeed provide downstream passage. However, because the concrete floor is much smoother than the streambed, and the structure is at stream slope, water velocities are likely too fast for upstream movement during low flow. Three-inch fish downstream of one culvert in July 2002 were unable to swim past the backwatered section (figure A83). There may be flows where some fish can move upstream. The structures are no more than 12 feet long, so larger fish may be able to negotiate them at higher flows.

Figure A83. Vented ford showing low-flow trench at left and partial backwatering. Fish were attempting to move upstream in July 2002, but flow in the trench was too shallow and too fast.

Water Quality: These structures are unlikely to adversely affect water quality. By comparison with the previous structures at these sites--culverts and fills that failed during floods--they will protect water quality by not adding road derived sediment to the already high sediment loads in this watershed.

Structure Details

Structure: The structure is a small box culvert with an open top and cattleguard driving surface that can be removed for cleaning (figure A84). Concrete approaches dip into the ford, which has a total length of 75 feet (figure A85). The concrete box is 8 feet wide and 4 feet deep. The box floor slopes slightly perpendicular to the direction of flow to force low flow to concentrate in the trench at one side of the box. An upstream cutoff wall 9 inches deep runs the full length of the ford and is heavily riprapped.

Bank stabilization and approaches: Class VII riprap is used to armor the streambanks up and downstream of the concrete approaches where the structure would overtop.

Figure A84. Close up of grated-top vented ford.

Cost: No information available.

Safety: There are no ford signs, but object markers with posts are at each corner of the concrete slab. Sight distance is good, so the structures can be seen from a long distance away.

Summary and Recommendations

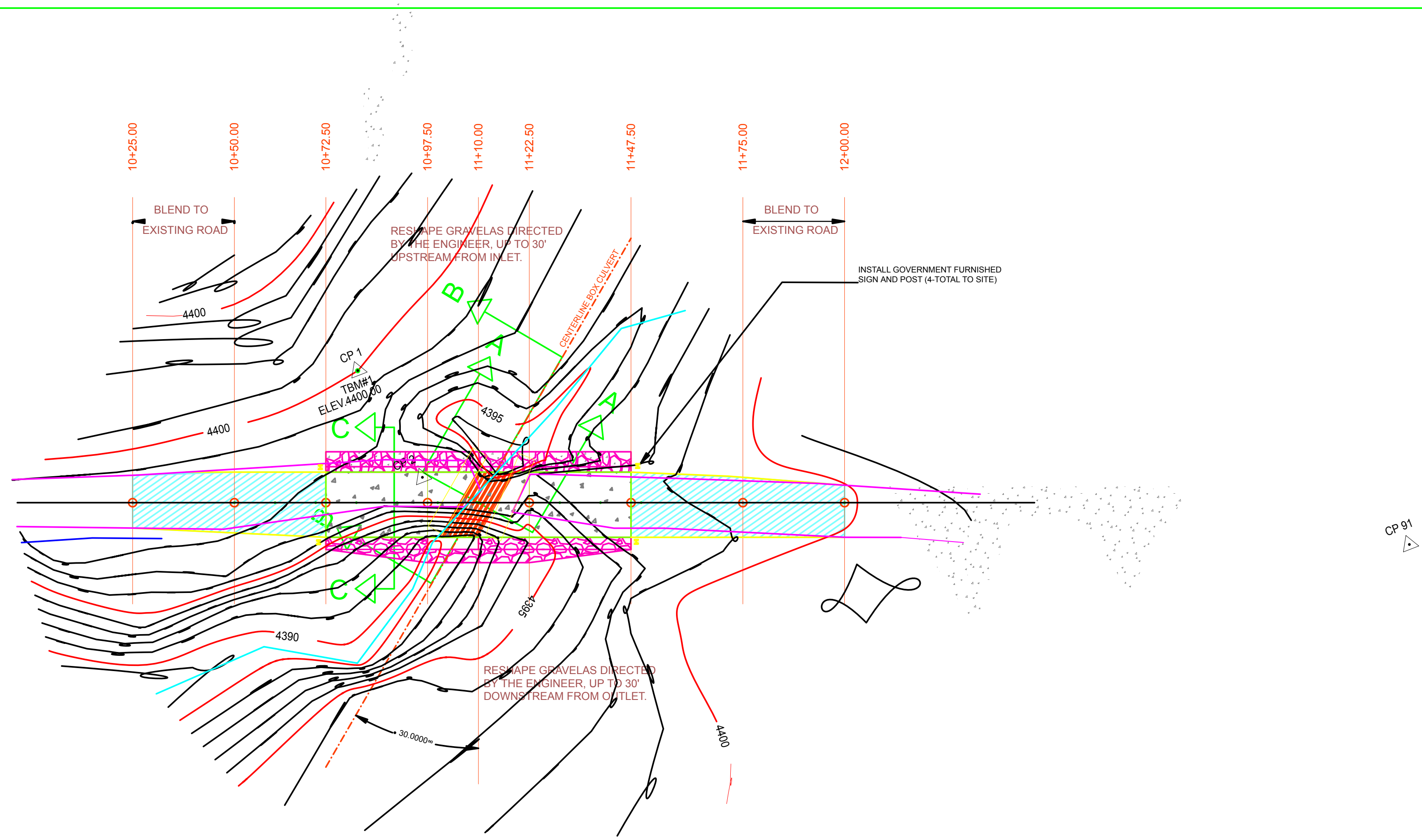
All the vented fords functioned well during the large flood in January 2006, an estimated 85-year flow. They were overtopped, but not blocked or damaged, and flow was not diverted away from the stream channels. For durability and ease of maintenance, these structures appear to be very appropriate in these difficult depositional settings.

Fish passage is not required at all these tributaries, but where required, a similar grated structure with an open bottom would better fit the need.

Ken Pence, engineering technician (retired); Cheryl Mulder, zone hydrologist; and Dave Jones, design engineer, from the Eldorado National Forest provided the background information and photos for this case study.

PROJECT	SHEET NO.
McKINNEY ERFO	3 OF 10

SITE #74 PLAN & ELEVATION



PLAN

SCALE: 1"= 40'

GENERAL NOTES:

SPECIFICATIONS: CONSTRUCTION - U.S.FOREST SERVICE GENERAL PROVISIONS & STANDARD SPECIFICATIONS FOR CONSTRUCTION OF ROADS & BRIDGES, 1985 EDITION WITH ACCOMPANYING SPECIAL PROJECT SPECIFICATIONS.
DESIGN LOAD : HS 20-44.

CONCRETE: CLASS "A" CONCRETE WITH A 28 DAY MINIMUM COMPRESSIVE STRENGTH OF 3500 P.S.I. AND SHALL BE VIBRATED. EXPOSED CORNERS SHALL BE CHAMFERED 3/4". ALL VERTICAL SURFACES SHALL BE FORMED. ADDITIVES CONTAINING CALCIUM CHLORIDE SHALL NOT BE USED. AIR ENTRAINMENT SHALL BE 4% TO 7%.

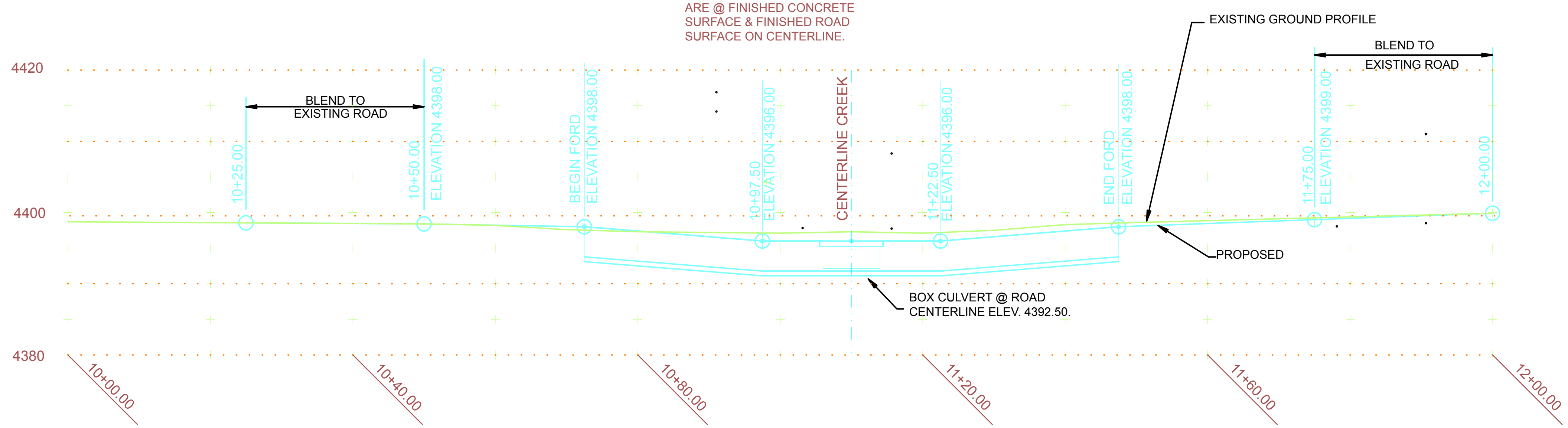
REINFORCING STEEL: REINFORCING STEEL SHALL CONFORM TO AASHTO M31 (ASTM A-615), GRADE 60. MINIMUM COVERING TO FACE OF DIMENSIONS SHOWN RELATING TO SPACINGS OF REINFORCING STEEL ARE TO CENTER OF BARS UNLESS OTHERWISE SHOWN. MINIMUM COVERING TO THE FACE OF ANY REINFORCING BAR IS 2" UNLESS OTHERWISE SHOWN. WHERE CONCRETE IS PLACED AGAINST EXISTING SOIL THE MINIMUM COVERING SHALL BE 3".

STRUCTURAL STEEL: ALL STRUCTURAL STEEL EXCEPT THE FORMED RAIL SECTIONS SHALL CONFORM TO ASTM DESIGNATION A-36. FORMED RAIL SECTIONS SHALL CONFORM TO ASTM DESIGNATION A-441. ANCHOR BOLTS AND NUTS SHALL CONFORM TO AASHTO M 314-90. ANCHOR BOLTS & NUTS SHALL BE ZINC COATED BY HOT DIP OF MECHANICAL DEPOSITION. ALL WELDING SHALL BE DONE IN CONFORMANCE WITH THE LATEST EDITION OF THE AMERICAN WELDING SOCIETY SPECIFICATIONS FOR WELDED HIGHWAY & RAILROAD BRIDGES. ALL STRUCTURAL STEEL EXCEPT ANCHOR BOLTS SHALL BE PREPPED & PAINTED WITH ONE COAT OF RUST INHIBITIVE METAL PRIMER AND ONE COAT OF FOLIAGE GREEN BRIDGE PAINT. GUARD ANGLES SHALL BE PAINTED AFTER CONCRETE IS PLACED.

HYDROLOGY: DRAINAGE AREA = 1.00 SQ.MI.
Q 100 = 312 C.F.S.

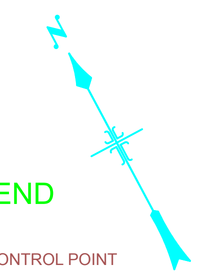
NOTE:

VALUES GIVEN AS ELEVATIONS ARE @ FINISHED CONCRETE SURFACE & FINISHED ROAD SURFACE ON CENTERLINE.



ELEVATION

HORIZ: 1"= 20'-0"
VERT: 1" = 20'-0"



LEGEND

- CONTROL POINT
- TBM AND TREE
- EDGE OF EXIST. ROAD
- CENTERLINE OF WET DRAINAGE
- CENTERLINE OF DITCH
- BOSS CONTOUR
- MINOR CONTOUR
- EXIST. 48" CMPA
- REALIGNMENT OF ROAD, 4" OF AGG. BASE
- CONCRETE LOW WATER CROSSING
- RIPRAP

Figure A85. Site plan for McKinney Creek crossing, similar to Meiss Cabin Road box culverts but without the tilted floor.

Case Study 14. Rocky Creek Vented Box Culvert Ford

Location

West Central Arkansas. Ouachita National Forest; Oden Ranger District. Rocky Creek crossing on Forest Road 887 (Muddy Gibbs Road).

Crossing Description

This is a concrete vented ford on a perennial stream that provides habitat for several fish and mussel species. The structure consists of three 6- by 3-foot concrete box culverts, with a splash apron extending downstream of the roadway (figure A86). Six-inch curbs focus water into the center culvert for low-flow passage for weak-swimming fish and boulders embedded in the concrete provide resting areas for them .

Figure A86. Looking upstream at the concrete vented ford and splash apron.

Setting

Ouachita Mountain Section (M231-A), elevation 740 feet. Parallel ridges and valleys on sandstone and shale are drained by a trellis-patterned drainage network (McDougal et al 2001). Drainage density is high and there are frequent bedrock controls. Predominant vegetation includes shortleaf pine, red and white oak, hickory, dogwood and willow.

Appendix A—Case Study 14

Why Was This Structure Selected?

This structure design was chosen to achieve the following objectives.

- Provide safe and reliable vehicle access during most flows without the expense of a bridge.
- Avoid plugging by woody debris during floods. (Previous structures were a constant maintenance headache because of plugging. Just before the crossing was reconstructed, the area had experienced a major ice storm, and trees falling into streams were plugging culverts and causing them to fail.)
- Provide passage for several endemic aquatic species. (The site is part of a research project into what kind of structures local fish can pass.)

Crossing Site History

In 1964, an unvented ford was installed at this site with 39-inch gabions supporting the downstream edge of a gravel roadbed. The gabion structure was frequently damaged when high flows outflanked the approaches. By 1979, two 24-inch pipes had been placed under the roadbed, and the road was surfaced with concrete (figure A87). The pipes plugged frequently, and many repairs were needed. In 2000, when the existing structure was built, there were several generations of concrete to be removed along with the gabions and pipes.

Figure A87. The previous crossing on road 887 at Rocky Creek was a gabion-culvert structure that was frequently damaged during high flows.

Road Management Objectives

The Muddy Gibbs road is a school bus route maintained by the county, and is designed for passenger vehicle use. Average daily traffic is 20 to 30 vehicles.

Stream Environment

Hydrology: Rocky Creek is a perennial stream draining about 1,700 acres of timbered land above the ford. Although rain occurs throughout the year, the two main rainy seasons are winter and spring. Average precipitation is 48 to 56 inches per year. Floods occur during sustained intense rainfall on already saturated soils or during summer thunderstorms. High flows generally do not last more than several hours.

Channel Description: Rocky Creek at the site is moderately entrenched between terraces about 5 to 6 feet above the streambed. Stream substrate is small boulders and large cobbles, with some larger boulders and bedrock outcrops. Channel slope is approximately 2.5 percent, bankfull width is about 15 to 20 feet, and depth at bankfull is 2 feet. The flood plain is narrow, about 2 feet wide. Banks are rocky and well-vegetated upstream of the structure (figure A88). Downstream, banks are scoured and the stream is wider, but the effects of the crossing on channel stability appear to be restricted to the immediate vicinity of the crossing.

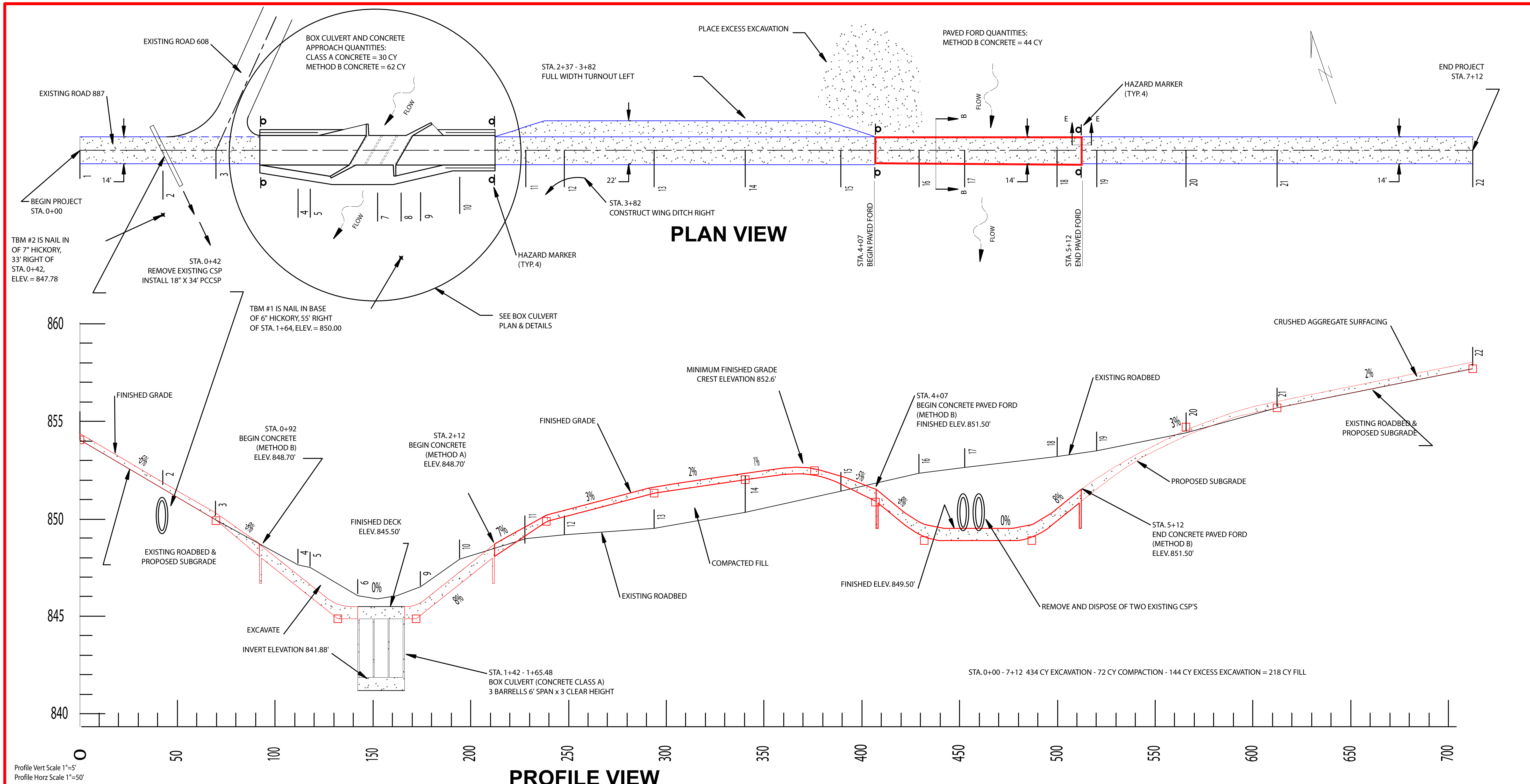
Figure A88. Looking downstream at the crossing on Rocky Creek.

Aquatic Organisms: Two State endemic fish species are found in this watershed: the orangebelly darter and the Caddo madtom. A threatened mussel that occurs downstream depends on several of the native species—including darters—to disperse. Several species of turtles and crayfish; Ouachita dusky; spotted, tiger, and marbled salamanders; as well as frogs and toads also use the stream. A study done for the Ouachita National Forest showed that traditional concrete pipe vented fords (see case study 11) are associated with significant reductions in the number of fish species and individual fishes upstream as compared to downstream of the fords (Gagen and Rajput 2002). Passage is required not only for spawning but also for thermal refuge, as fish seek out deep pools with cooler water in the heat of the summer. Aquatic species must also be able to recolonize areas after local extinctions due to droughts. The need for fish passage was one of the primary drivers for this replacement structure.

Structure Details

Structure: The structure consists of three 6- by 3-foot concrete box culverts set at streambed elevation (figure A89). A 10-foot long splash apron protects the structure against scour during overtopping flows, and a 6-inch curb at the apron's downstream edge is intended to prevent formation of a plunge there by creating a reverse eddy. Curbs under the roadway backwater flows in the side culverts and concentrate water toward the center box (figure A90) for low flow fish passage. The curbs help to retain some bed material in the floor of the culverts, which is also expected to help aquatic species passage through the culvert. Four- to 6-inch boulders embedded in the concrete floor further assist fish passage by providing resting areas.

Figure A90. Looking upstream at the splash apron and backwater curbs.



NOTES:
1. IF SUBSTANTIAL BEDROCK IS ENCOUNTERED AND IT BECOMES NECESSARY TO BE REMOVED FROM CHANNEL FOR CONSTRUCTION OF THE BASE OF BOX CULVERT, WITH APPROVAL OF THE ENGINEER, THE BOX CULVERT AND VPIs AT STA. 1+32 AND 1+72 MAY BE RAISED A MAXIMUM OF 6" (0.5') WITH NO ADJUSTMENT TO ANY QUANTITIES OR COST. ELEVATIONS AT STA. 0+92 & 2+12 SHALL REMAIN THE SAME. ELEVATION OF APRON AT OUTLET OPENING SHALL REMAIN AS SHOWN ON SHEET 5.
2. STA. 1+11.5 -1+74 EXISTING CONCRETE LOW WATER STRUCTURE SHALL BE EXCAVATED AND ALL CONCRETE AND RUBBLE REMOVED FROM GOVERNMENT LAND.
3. STA. 0+42 (ONE LINE) AND 5+52 (TWO LINES) REMOVE EXISTING CSP AND DISPOSE OF OFF GOVERNMENT PROPERTY.
4. ALL DISTURBED GROUND, INCLUDING EXCESS EXCAVATION, SHALL BE SEEDED AND MULCHED.
5. TAPER AGGREGATE THICKNESS FROM 8" THICK AT EACH END OF CONCRETE TO 4" THICK 25' AWAY FROM CONCRETE.

VPI STA.	1+32	1+72	3+76	4+32	4+87	5+66
LVC	12'	12'	32'	20'	20'	30'
SUBGRADE ELEV.	844.88'	844.88'	852.25'	848.88'	844.88'	854.20'

PLAN AND PROFILE VIEW

OUACHITA	National Forest	
Road No.	Sheet No.	Total Sheets
887	4	13

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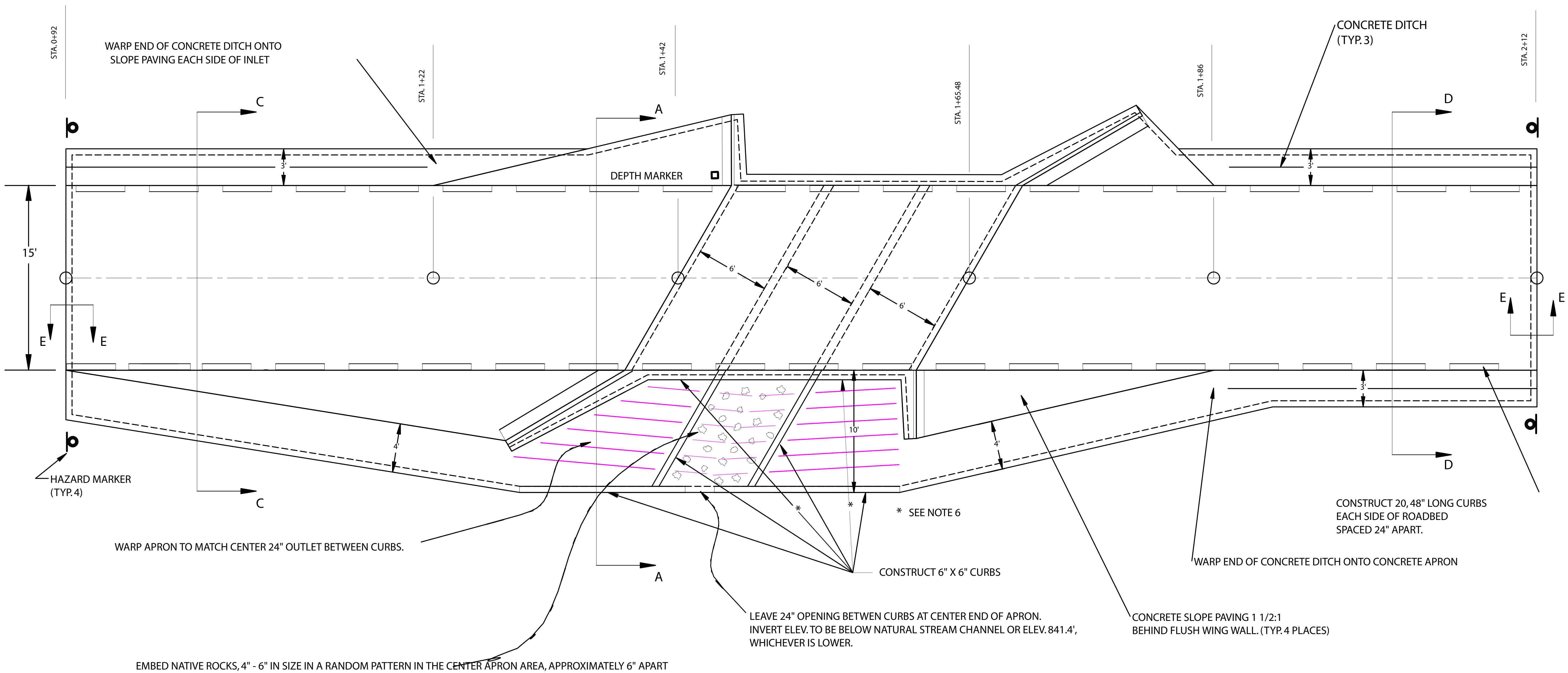
Figure A89a. Plan and profile drawings of the concrete box culvert vented ford at Rocky Creek.



BOX CULVERT PLAN VIEW

CLASS A CONCRETE = 30 CY

METHOD B CONCRETE = 62 CY

NOTES:

1. CONSTRUCT 40 CONCRETE CURBS (20 EACH SIDE OF ROADBED) 48" LONG, 24" APART, APPROXIMATELY WHERE SHOWN. SEE CURB DETAIL ON OTHER SHEET.
2. AT ENDS OF CONCRETE STRUCTURE, TAPER AND BLEND EARTHEN DITCH TO MATCH CONCRETE DITCH (3 PLACES).
3. CONCRETE BOX CULVERT, INCLUDING WING WALLS SHALL BE CONNECTED TO THE ADJACENT CONCRETE STRUCTURE, INCLUDING ROADBED, SLOPE PAVING AND APRONS, WITH 24" LONG #4 REBAR SPACED 24" ON CENTERS AND EMBEDDED 12" IN EACH STRUCTURE.
4. CONSTRUCT CONTRACTION JOINTS AT APPROXIMATELY STA. 1+12, 1+32, 1+72 AND 1+92. CONTRACTOR SHALL ADJUST EXACT LOCATION OF CONTRACTION JOINTS AND/OR CURB SPACING TO PREVENT LOCATING CONTRACTION JOINTS THROUGH CURBS.
5. ALL CURBS SHALL BE AN INTEGRAL PART OF THE ROADBED OR APRONS AND SHALL HAVE STEEL DESIGN THE SAME AS THE SHOULDER CURBS ON ROADBED.
6. NOT SHOWN ABOVE. A CONTINUOUS CURB (6" X 6") SHALL BE CONSTRUCTED ACROSS THE OUTLET OPENINGS OF EACH OF THE OUTER BARRELS OF BOX CULVERT.
7. WING WALLS ON THE ARKANSAS STATE HIGHWAY COMMISSION DRAWINGS HAVE BEEN MODIFIED TO BE FLUSH WITH THE TOP OF THE ADJACENT SLOPE PAVING.
8. DO NOT DISTURB STREAM CHANNEL BEYOND 30' EACH SIDE OF ROAD CENTERLINE.

OUACHITA National Forest

Road No.	Sheet No.	Total Sheets
887	5	13

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Figure A89b. Plan drawing of the concrete box culvert vented ford at Rocky Creek.

This structure was designed to fit the landform. It comes close to matching channel width and the boxes slightly exceed bankfull depth. Although the forest has not monitored flows, they believe the structure overtops several times per year for no longer than several hours at a time.

Bank Stabilization and approaches: The driving surface and approaches are concrete. The structure is protected during overflow by concrete armored wings with ditches both above and below the crossing (figure A90). The approaches slope at 8 percent into the ford and the ditches on the downstream side empty onto the concrete apron below the structure, protecting the streambed from scour by high velocity ditch flows.

There is an overflow channel about 300 feet from the main channel that receives flow during most floods and takes some of the stress off the main structure. Before the replacement, water from the overflow channel would run down the road to the ford. Figure A89 (profile view) shows how the road alignment was modified to prevent diversion and protect both the road and water quality. The two pipes in the overflow channel were replaced by a concrete slab ford at stream grade that cannot plug and that greatly increases the volume of flow the overflow channel can accommodate.


Figure A91. Looking downstream from ford. Note local channel widening.

Figure A91 looks downstream of the main crossing showing the locally widened channel. Although the channel is rocky and quite stable, flows that overtopped and spread out over and around the previous structure likely caused the bank erosion there. The road's skew relative to the channel may have intensified the potential for that damage.

Cost: Constructed in 2000 for approximately $70,000.

Safety: Like most of the low-water crossings on roads maintained by the county, this crossing is not signed. Interrupted curbs on the roadway edges provide vehicle protection during overflow conditions, figure A92).

Flood and Maintenance History

The box culvert vented ford has sustained numerous overtopping floods without requiring any maintenance.

Summary and Recommendations

The splash apron, curbs, concrete fillslope armoring, and ditches are working well to keep this structure and the roadway stable. There is no channel bed scour, and the bank scour visible in figure A91 appears to be very limited. The boxes are high enough to prevent plugging so far (5 years after construction).Traffic interruptions are brief enough to be tolerable even on this school bus route.

Fish are often observed in the crossing when it is wet. This particular crossing has been the subject of two fish passage studies but the stream is susceptible to drying and is quite remote so that fish passage detection has been difficult. Nonetheless, 4 of the 8 to 13 species found above and below the crossing have been documented as passing the structure: grass pickerel, central stoneroller, orangebelly darter, and green sunfish. There is a thin veneer of fines on the floor of the box and many embedded boulders (figure A92), but the bed lacks areas with different water velocities and depths, and may not provide passage for the non-fish species present in the stream.

Figure A92. The floor of the central box has a thin veneer of sediment at low flow.

Recognizing that a natural streambed is preferable where aquatic species passage is a goal, the forest is moving to embed more recent box culverts below streambed elevation (see Long Creek vented ford, below). Current practice is to embed the floor below the best estimate of final channel grade, keep the deck as low as possible so that overflows are not much wider than in the natural channel, and provide openings equivalent to the full channel width.

Richard Standage, forest fisheries biologist, and Jim Getchell, engineer, both of the Ouachita National Forest, provided information and photos about the Rocky Creek and Long Creek vented fords.

Similar Structures at Other Locations

Long Creek Embedded Box Culverts, Ouachita National Forest

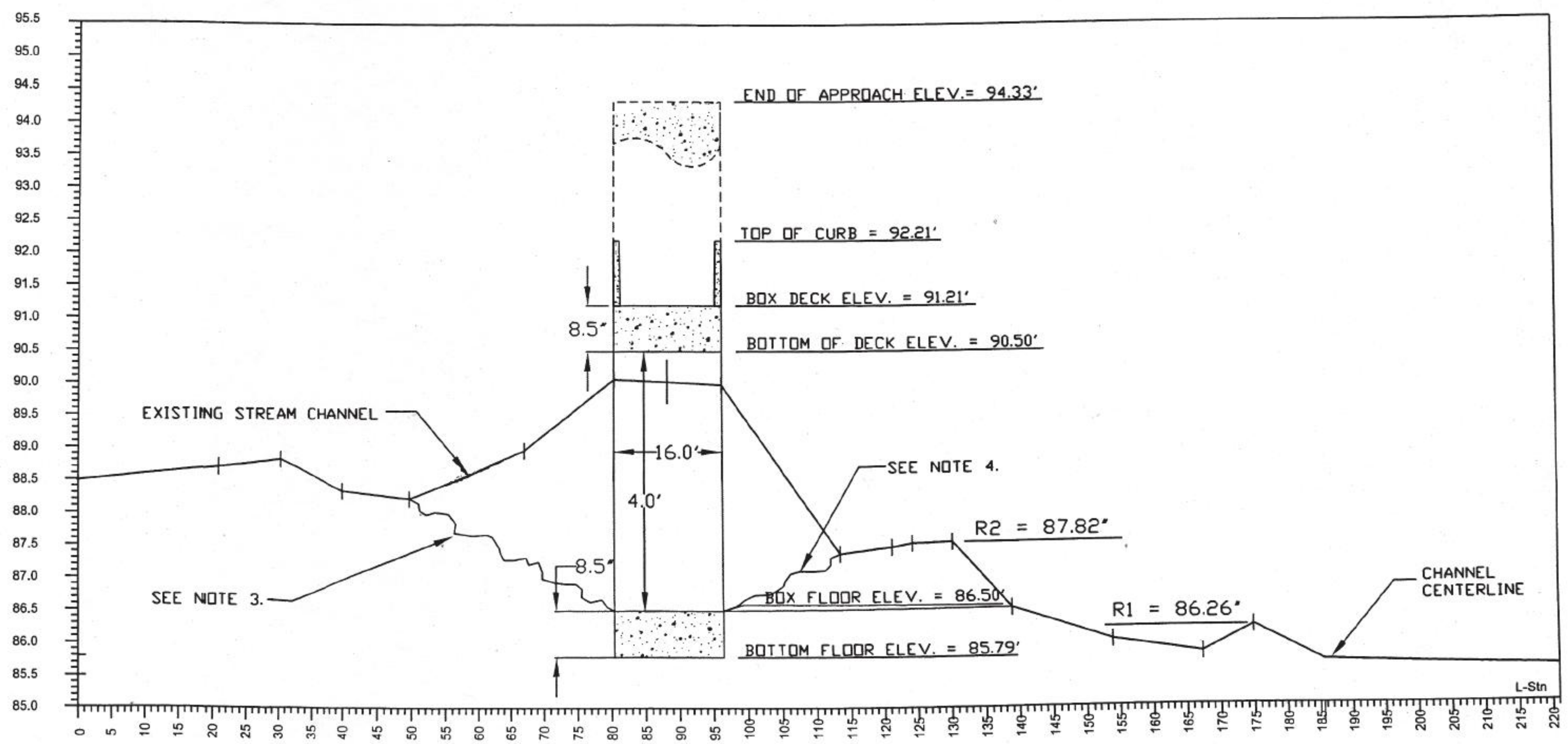
Forest Road 512 crosses Long Creek about 30 miles southwest of the Rocky Creek crossing described above. The stream types and road issues and constraints are similar. Figure A93 shows a ford similar to the old unvented ford at the Long Creek crossing. The new 2004 replacement has five 4-foot-high box culverts that were allowed to self-embed to a planned depth of 1 to 2 feet (figures A94 and A95). The crossing's total open width is now just under bankfull width.

Figure A93. Unvented ford similar to the one replaced at FR 512 crossing on Long Creek, Ouachita National Forest.

Figure A94. Looking upstream at the embedded box culverts that replaced the unvented ford in 2004.

BLASTING AND BEDROCK NOTES

1. It is anticipated that BEDROCK WILL BE ENCOUNTERED and blasting will be necessary to achieve the required elevations, grades and templates. After bedrock is encountered, the elevation of the box culvert may be raised a maximum of 12" with the approval of the Engineer after consultation with the Forest Service Fisheries Biologist. APPROVAL IS NOT GUARANTEED! The elevation of the floor of the box culvert is critical to fish passage and approval to raise the elevation will be based on the recommendation of the Fisheries Biologist. A request for approval will not be considered until after the existing structure has been removed and bedrock has been exposed at the box culvert site. Approval will require a field visit by the Fisheries Biologist and may take up to 3 days to schedule inspection. Contractor is urged to keep the engineer informed of his excavation schedule to facilitate the presence of the Fisheries Biologist. Contractor is also urged to consider the impacts of bedrock removal before submitting his bid!
2. Where bedrock is encountered, the full depth of all footings may be decreased, with the approval of the engineer if 12" long, #4 rebar pins are placed 6" into bedrock, every 12" along footing length to anchor footings to the bedrock. Under no conditions will the thickness of the box floor be reduced.
3. Upstream of the box culvert, the entire width of the channel, shall be graded from the inlet end of the box culvert, 30' upstream on a uniform slope. If bedrock is encountered blasting may be necessary to ensure that there are no abrupt drops in grade between inlet and 30' upstream. If bedrock is encountered, the slope will not be smooth, but left in a roughened condition over the 30' distance upstream.
4. Downstream of the box culvert there shall be as little disturbance of the channel as possible. If bedrock is encountered, this may include an abrupt change in elevation that may very well block drainage of the box culvert. This is acceptable and preferable! Contractor shall not disturb more than 20' downstream of outlet of box culvert and less if possible. Point labeled R2, on cross section above, is over 30' downstream, it is exposed bedrock, it is planned to be higher than the floor of the box culvert, and it shall not be disturbed.
5. If approval is granted to raise the elevation of the box culvert, the clear height of 4'in the box shall not be shortened. The elevations of the VPI at Stations 2+18 and 3+00 shall also be raised the same amount. However, the elevation of the ends of the concrete approaches at Stations 1+78 and 3+32 shall remain the same.

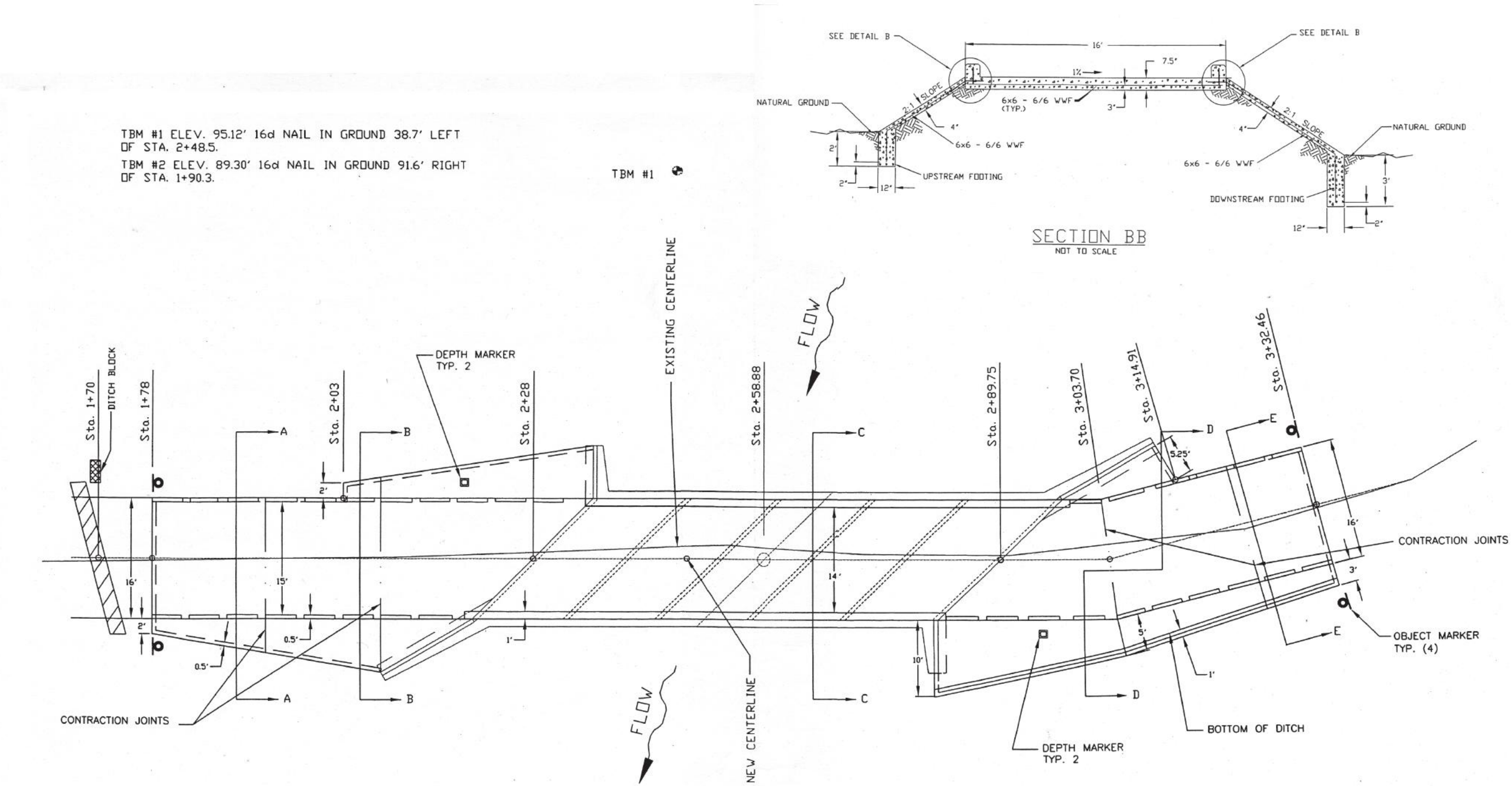


CROSS SECTION OF BOX CULVERT

AT CENTER STA. 2+58.88

OUACHITA National Forest		
Road No.	Sheet No.	Total Sheet
512	9	19

Figure A95a. FR 512 contract drawing: cross section of box culvert (along the stream). Points R1 and R2 are bedrock outcrops that are not continuous across the channel.



NOTES:

1. CONSTRUCT CONTRACTION JOINTS ACROSS ROADBED AND SLOPE PAVING AT APPROXIMATELY STA. 1+92, 2+08, 3+03.70, 3+22 OR AS STAKED BY THE ENGINEER. THE CONTRACTOR AND ENGINEER SHALL ADJUST EXACT LOCATION OF CONTRACTION JOINTS AND/OR CURB SPACING TO PREVENT LOCATING A CONTRACTION JOINT THROUGH A CURB.

PLAN VIEW DETAIL

NOT TO SCALE

OUACHITA National Forest

Road No.	Sheet No.	Total Sheets
512	7	19

Figure A96. Plan view contract drawing and cross section detail of structure near the channel centerline.

Figure A95a is a contract drawing showing the longitudinal profile of the stream. The plan was to allow the embedded boxes to fill in with streambed material naturally over time. However, a large storm during construction overtopped the structure and completely plugged the boxes with construction-generated material and natural bedload. The structure was partially cleaned out, leaving substrate at grade and the streambed has maintained itself. In gravel-bed streams, not filling the embedded culverts during construction could produce a headcut. However, in this case there was no headcutting risk because bedrock is intermittently exposed along and across the channel above and below the crossing.

Given the near-surface bedrock, open-bottom arches might appear to be feasible in these streams; however, they are rarely used, not only because bedrock locations are unpredictable with available technology, but also because the intent is to keep the deck as low as possible to give woody debris the best chance of going over the structure rather than plugging it. Also, even with the occasional need to blast to embed the boxes (as was done here), boxes are generally cheaper. They are strong, reliable structures that survive the worst of storms.

The cost of the replacement in 2004 was $110,000. Note that the curbs on this ford are continuous. Since the ford is the low spot on the road, it retains water on its surface and the curbs do not allow it to drain. In future, the forest plans to add polyvinyl chloride-formed drainholes in the road surface.

Case Study 15. Moonlight Crossing Concrete Box Vented Ford

Location

Northeastern California. Plumas National Forest. On Lights Creek, 8 miles north of Taylorsville, CA., Forest Road 29N46 near the intersection with Plumas County Road PC213.

Crossing Description

This large concrete box vented ford, reconstructed in 2000, is located on Lights Creek, a perennial fisheries stream. Its design is a trapezoidal shape over four reinforced-concrete box culverts, one containing a fish ladder (figure A97). The roadway surface across the ford, including the steel cattleguard and the 6-inch-thick reinforced concrete approach slab, is 15 feet wide and 109 feet long. The driving surface over the boxes (across the active channel) is 32 feet long.

Figure A97. Moonlight crossing with fish ladder 2001.

Due to flow acceleration over the smooth concrete surface on the downstream part of the apron, the water drops into a large plunge pool, approximately 50 feet across, which is lined with large stone riprap. It was determined to keep the structure in the same location for two reasons: there is a great deal of private land above and below the site; and because decades of upstream aggradation and downstream degradation had created an 8-foot differential elevation at this site, and some form of grade control was deemed necessary.

Appendix A—Case Study 15

Setting

Eastern Sierra Nevada, Section (M261-E). Elevation 3,700 feet, within a metamorphic unit of the northeastern Sierra Nevada. Mid-forest area of mixed conifer and oak hardwoods.

Why Was This Structure Selected?

After a preliminary evaluation of costs and alternatives by the U.S. Army Corps of Engineers, a ford structure was selected and designed by the Plumas National Forest. The structure was constructed under a Public Works Contract. This design was selected for four main reasons: 1) Fish passage is a key concern, so a fish ladder was incorporated into the design; 2) The structure needed to be massive and strong enough to withstand the power of the stream. A previous structure had been repaired and failed twice; 3) A bridge was considered, but the cost was prohibitive (twice as much); and 4) It was determined that there was a need for a grade control structure to maintain the 8 foot difference in elevation between the upstream and downstream stream channel levels.

Crossing Site History

The previous, possibly original structure was a lightly constructed concrete slab over seven 24-inch culverts. The culverts exited onto a grouted rock apron that sloped down to the much lower streambed. During the major 1986 storm event part of the downstream apron was undermined and new large boulders and concrete grout (figure A98) were placed at that time. Also a small fish ladder was built on the east side of the structure below one culvert pipe. This structure again washed out in 1997, undermining the concrete slab (figure A99). Most likely the downstream depth of riprap was inadequate and the toe of the apron was undermined by scour, leading to progressive failure of the entire apron (figure A100). Also during the low-flow years the pipes tended to plug up because of their small size and the high sediment load in Lights Creek.

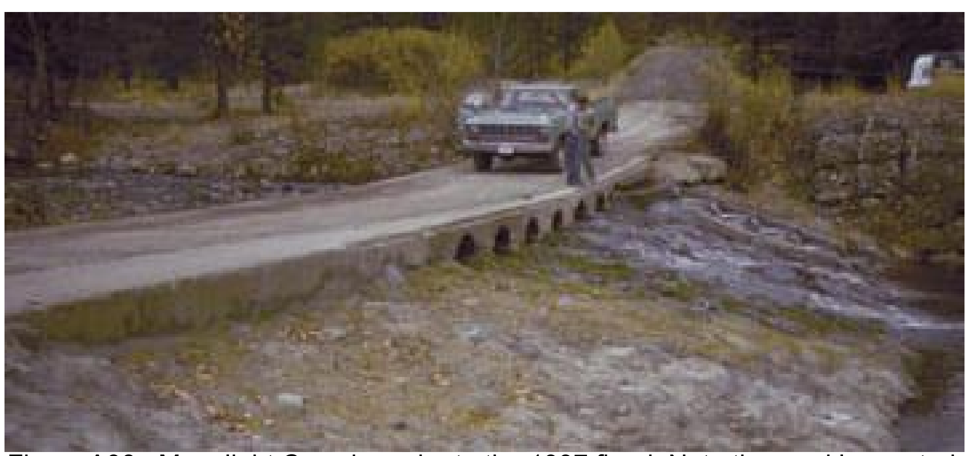


Figure A98. Moonlight Crossing prior to the 1997 flood. Note the weakly grouted small riprap armoring the downstream apron. There is no cutoff wall.

Figure A99. Damage to the Moonlight low-water crossing after the 1997 flood. The downstream rock armoring was undermined and washed away, partially undermining the concrete slab driving surface.

Figure A100. Moonlight crossing in 1999 prior to construction of new structure.

Road Management Objectives: This is a maintenance level 3 road, gravel surfaced, and maintained for passenger vehicles. Road use is a mix of occasional logging traffic during a timber sale, USDA Forest Service administrative traffic, and general recreational traffic. One residence uses this crossing as access. This road has an annual average daily traffic count of 100 vehicles, and provides access from Indian Valley to the Westwood area on the Lassen National Forest. The through route is closed during the winter, though the section of road at the ford is rarely closed. Traffic volume and type is such that occasional interruptions are acceptable. Traffic interruption is considered likely to occur every few years and last several days each time.

Stream Environment

Hydrology: Lights Creek is a perennial stream draining about 47 square miles and is tributary to Indian Creek and thence to the North Fork of the Feather River. Average annual precipitation is approximately 40 inches. The upper reaches of the watershed are snow dominated, and rain-on-snow events produce large flows. Summer low flows are of the order of a few cubic feet per second. Flood debris deposited among the trees on the streambank suggests that the most recent 100-year flood in 1997 inundated the entire channel and was several feet deep above the streambanks. Bankfull flow is estimated at 380 cubic feet per second. The 100-year peak flood flow (Q100) is estimated at 5,750 cubic feet per second.

Channel Description: Lights Creek underwent severe downcutting prior to the installation of this grade control structure, and some aggradation has occurred upstream. The upstream banks are about 2 feet high and stable, with riparian vegetation including willow, cottonwood, alder, and pine trees as well as some shrubs (figure A101a). The channel is narrow with easy access to a wide flood plain on the right-hand bank. Downstream, the banks are over 8 feet high, nearly vertical, and subject to scour and raveling. The channel is 40 to 50 feet wide and widening, forming mid-channel bars, without flood-plain access (figure A101b). Channel slope was measured to be about 1 percent. The streambed is made of a well-graded mixture of sands, gravels, and cobbles. Occasional boulders exist to a maximum size of 8 inches.

Figures A101a and A101b. Lights Creek a) upstream and b) downstream of the ford.

Aquatic Organisms: Providing passage for fish is a key issue at this location. This section of stream provides habitat for nonthreatened native brown and rainbow trout, as well as nongame species. How effective the fish ladder is in providing passage for all fish and lifestages in the stream is unknown. The large pool downstream of the structure aids fish passage through the structure by providing a resting area and take off point for the jump into the ladder (figures A102 and A103).

Figure A102. Detail of the fish ladder built into the Moonlight Crossing.

Figure A103. Roadway across the Moonlight ford.

Water Quality: Sediment delivery and movement in this watershed is an important concern. The structure is being used as a grade-control structure to prevent the movement of massive amounts of fine and coarse sediments presently stored in the channel upstream of the ford. Water quality in the stream is relatively good.

Structure Details

Structure: The structure consists of four, 3.1-foot deep by 6.5-foot wide concrete boxes covered with a removable metal cattleguard-like grating (figure A104a). Massive concrete was used because of previous failures of grouted riprap. The roadway surface has a well defined dip to insure that flows stay over the structure and do not go around the structure. The vents have a capacity of about 500 cubic feet per second. A fish ladder with six step-pools is built into the eastern-most concrete box. This fish ladder design was developed in consultation with personnel from the California Department of Fish and Game.

The project took approximately 5 months to construct and required a total of 150 cubic yards of concrete. Because of the complexity of the site there was a 1-foot error in the elevations at the bottom of the structure, such that the downstream lip of the apron is 1-foot higher than designed. This causes a 6-inch drop to the downstream pool level. If this pool level drops, it may be a problem for access to the fish ladder and may require additional downstream work.

Bank and bed stabilization, and approaches: The immediate approaches are concrete and slope steeply into the drainage at 14 percent (figure A104a). Considerable Class VIII and Class XII riprap (4-foot-plus-diameter boulders) was placed along the approaches, along the downstream 6-foot-deep cutoff wall at the downstream edge of the concrete spillway, and at the downstream edge of the plunge pool to form a grade control structure (figure A104c).

Also a vortex weir structure made with 3-foot-diameter boulders was placed across the channel 130 feet upstream of the structure to direct the flow towards the vents.

Cost: The structure was totally reconstructed in 2000 for a cost of $240,000. Local materials were used as much as possible. The rock source for this project was a local on-forest quarry.

Safety: The structure has a low (8 inches high) steel curb along both sides of the road, with a low enough profile to prevent major accumulation of debris. The crossing is marked with object markers at each approach, and it is located on a tangent section of road, so safety appears adequate for its use. There are no safety warning signs or depth markers. The metal grating is reported to be “slippery when wet.”

Appendix A—Case Study 15

Flood and Maintenance History

The structure suffered no damage from moderate flood flows in January 2006. However, because of the large amount of large woody debris moving through this channel and the relatively small size of the vents, the vents have plugged up with debris several times. They require annual cleaning, making the structure a maintenance headache.

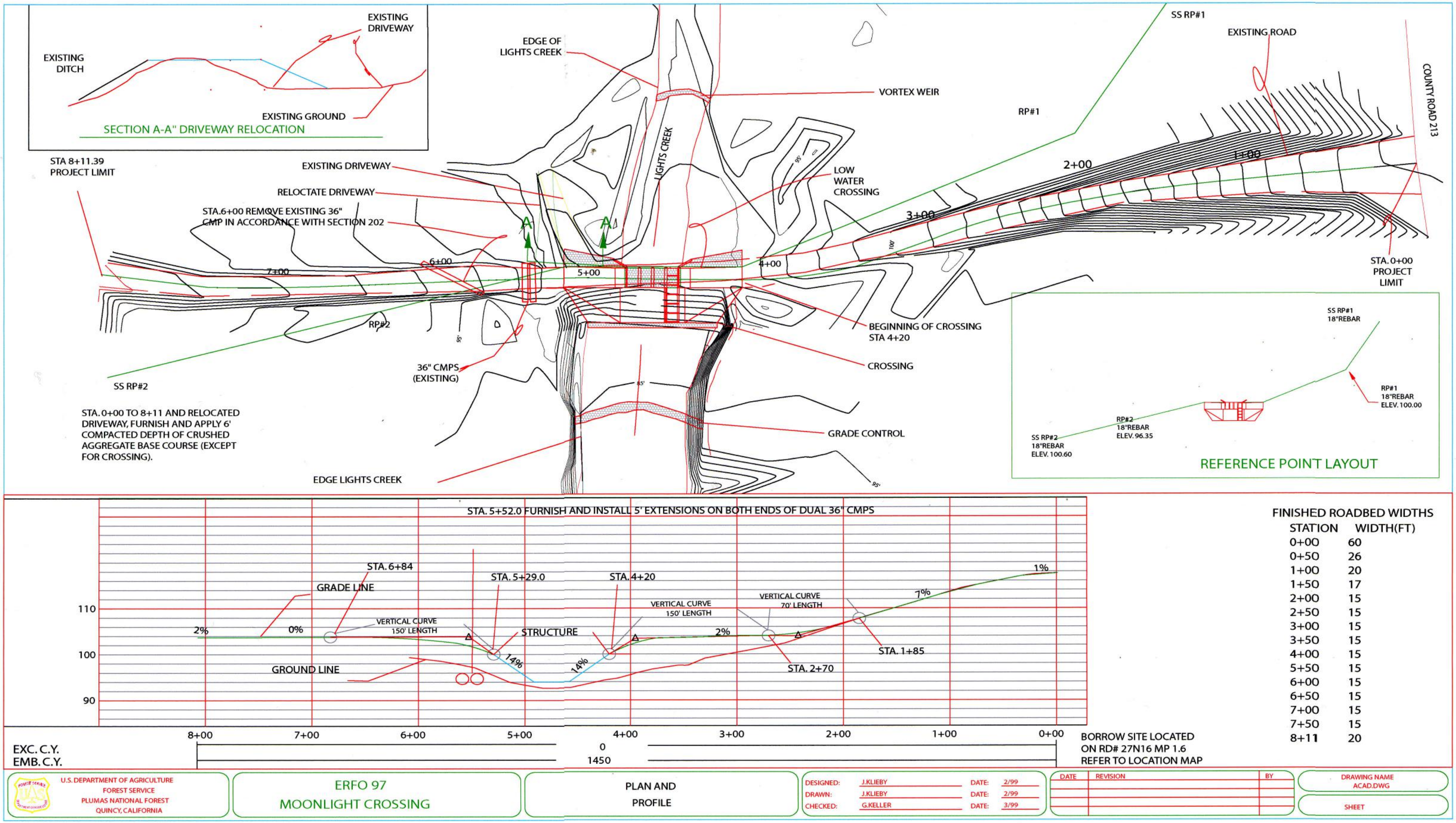
Summary and Recommendations

Moonlight Crossing on Lights Creek is a relatively massive integral concrete box structure with a cattleguard driving surface designed to withstand major storm flows, major sediment movement, and to resist significant scour potential. The cost and effort were large but necessary to prevent the structure from failing, to keep the road open most of the time, and to prevent both the upstream migration of a headcut and the downstream movement of the large volume of sediment accumulated above the crossing. Repairs may someday be needed downstream of the structure to hold or raise the elevation of the downstream plunge pool, prevent a waterfall, and keep the fish ladder functioning.

Had the amount of debris moving through the drainage been better understood, several alternative designs would have been considered, such as: larger vents, tapering concrete wings in front of the boxes to help the debris float up over the structure, or a short span, low-water bridge. The structure is functioning well, but does cause excessive annual maintenance work cleaning the concrete vents.

More communication and a more careful review of the design during construction might have prevented the 1-foot elevation error. Approaches leading to the structure should be paved as the gravel roadway surface constantly ravels onto the concrete approach slabs.

Gordon Keller, geotechnical engineer for the Plumas National Forest, provided information and photos for this case study.



Figures A104a. Contract drawings; (a) site plan and profile.

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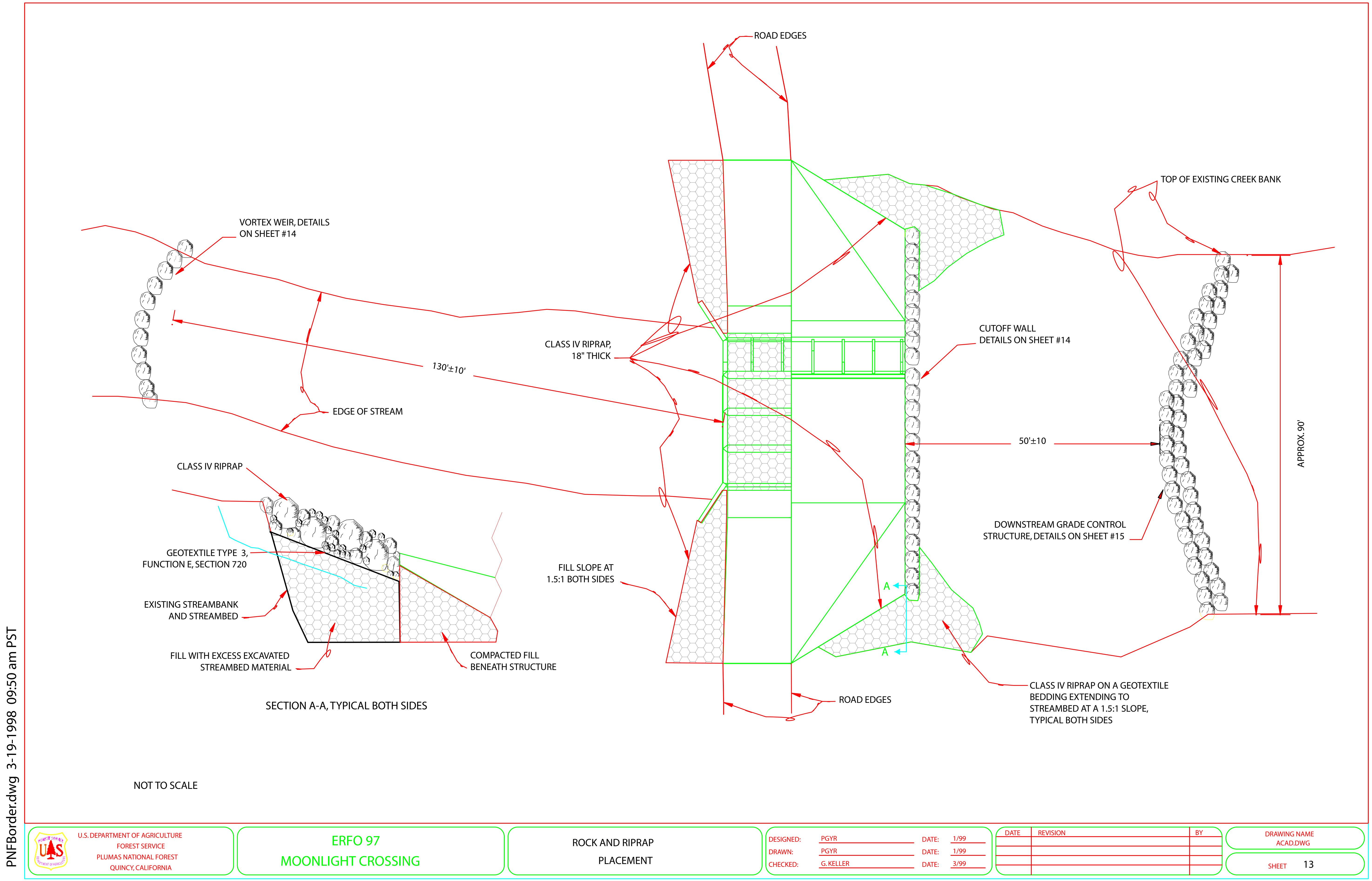


Figure A104c. Contract drawings; (c) rock placement.

Case Study 16. Sibley Creek Vented Ford

Location

Washington. Mt Baker-Snoqualmie National Forest. Mt Baker Ranger District. Cascade River Road (County Road No. 15, Milepost 10.2).

Crossing Description

This massive vented ford was constructed in 1997, after rain-on-snow floods washed out the crossing. The stream is very steep and prone to debris torrents, and previous drainage structures have failed repeatedly over the years. The road is closed in winter, but is a major access route to North Cascades National Park, and long-term traffic interruptions (which occur when this crossing washes out) are not desirable. The structure is a large concrete edifice with three box culverts with removable concrete tops (figure A105). The design allows it to pass large rocks and debris over the top, and to withstand the high stream power at this location.

Figure A105. Sibley Creek vented ford.

Setting

Western Cascades Section (M242-B). Steep, highly dissected, volcanic terrain. Alpine glaciation. Silver fir and Douglas fir forest.

Appendix A—Case Study 16

Why Was This Structure Selected?

A large, strong structure was needed to withstand debris flows and to pass as much debris and rock as possible. The structure must sustain battering by boulders and large wood during floods.

Crossing Site History

Previous structures at this site have included multiple culverts, which have been washed out at least 6 times since 1960 (1962, 1976, 1988, 1989, 1990, and 1995) (figure A106). Those events had resulted in significant sediment deposition of roadfill material in coho salmon spawning areas in lower Sibley Creek, as well as temporary loss of public recreation access.

Figure A106. Two-culvert crossing on Sibley Creek blew out in November 1995.

Road Management Objectives

The Cascade River road is a major public recreation access route to Cascade Pass in the North Cascades National Park and the Glacier Peak Wilderness area. It is a two-lane paved road to MP 5 and gravel-surfaced beyond.

Stream Environment

Hydrology: The stream is perennial and the annual peak generally occurs during snowmelt in late spring and early summer. Landslides and debris torrents caused by rain-on-snow events are common in November and December. Flows estimated using regional equations for this 4.7 square mile watershed were 144, 172, and 198 cubic feet per second for the 25, 50 and 100-year flows respectively (Peter Wagner, design file).

Channel Description: Sibley Creek is a steep (approximately 25 percent), incised, Aa+ channel with a boulder-cobble substrate, low sinuosity and no flood-plain development. The site is located near the break-in-slope between the very steep debris torrent-prone glacial valley walls and the milder mid-slope zone.

Aquatic Organisms: Sibley Creek is considered to be too steep to support fish at this location. Coho salmon spawning habitat is not far downstream. In this wet environment, amphibians travel overland and should not need passage through the crossing. The road is not considered a barrier to aquatic species.

Water Quality: This crossing has affected water quality and fish habitat in the past when roadfill material was washed downstream during floods. This massive, well-armored structure has so far prevented downstream sedimentation.

Structure Details

Structure: This is a cast-in-place reinforced concrete ford with three 7-foot-wide by 5-foot-high box culverts. Together the boxes convey the 100-year flood (water only). The ford itself has a 6-percent grade on the approach slabs and is designed to convey 1½ times the 100-year event over the concrete top, in case debris plugs the inlet (figure A107). The I-beam trash rack slopes at 6:1 to allow large debris to pass over the top in case of a debris torrent (figure A108). The tops of the boxes are covered by level precast concrete slabs that can be lifted to remove smaller debris. The bottoms of the boxes are set at such a steep grade (20 percent) that high velocity water removes cement and fine aggregates until the coarse aggregates are exposed. As they are exposed, the 3-inch aggregates used in the concrete produce roughness and protect the concrete against further degradation.

Bank stabilization and approaches: The graveled road approaches slope at between 3 and 6 percent into the ford. Riprap was used above the inlet to stabilize the streambanks, which may erode somewhat because the structure is not aligned perfectly perpendicular to the stream (figure A109). In this location where deposition is expected during major storms, the riprap is a temporary solution until the next major event. Downstream, large rock was placed at the toe of the concrete apron to avoid undermining.

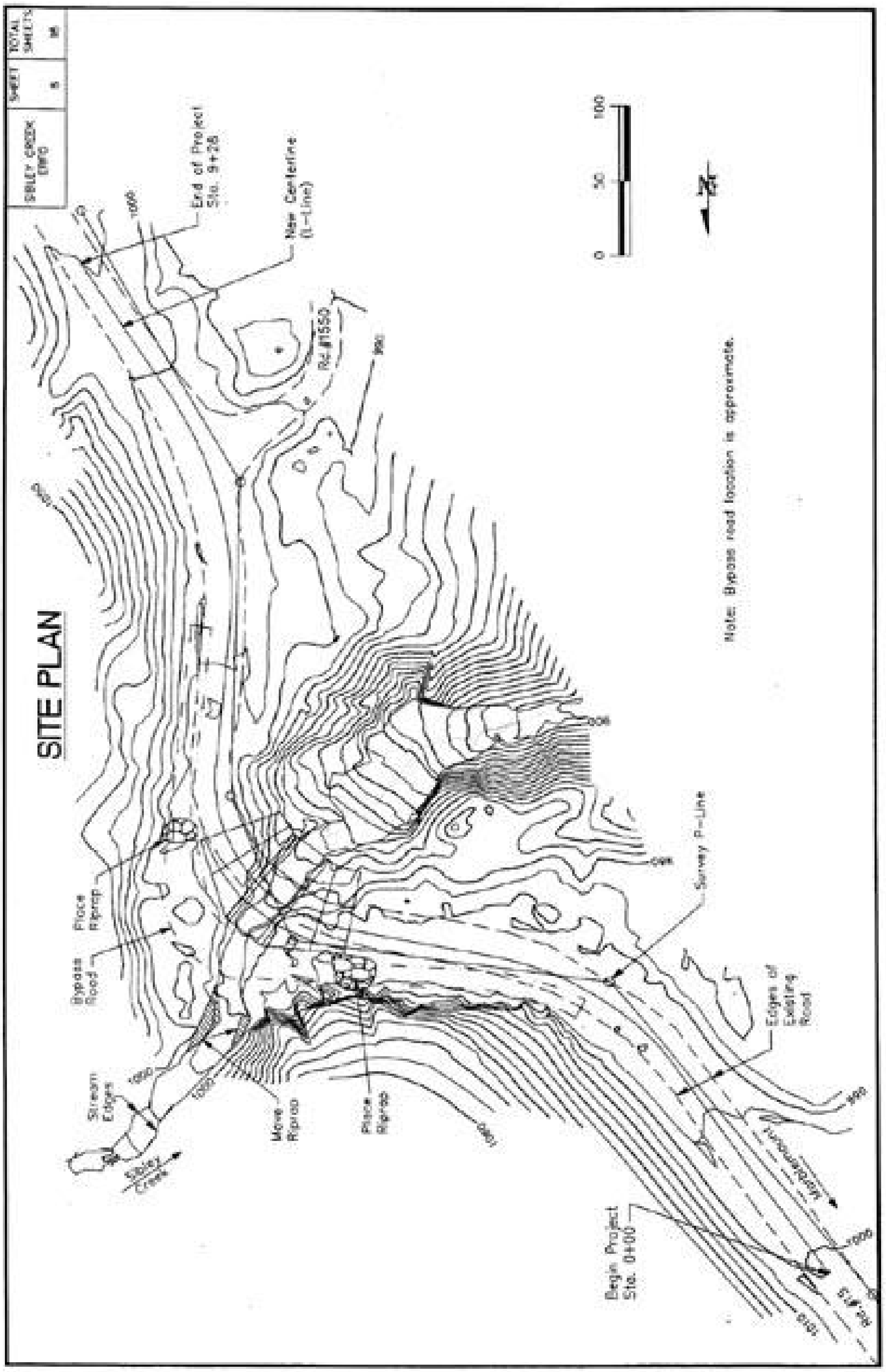


Figure A107a. Site plan map.

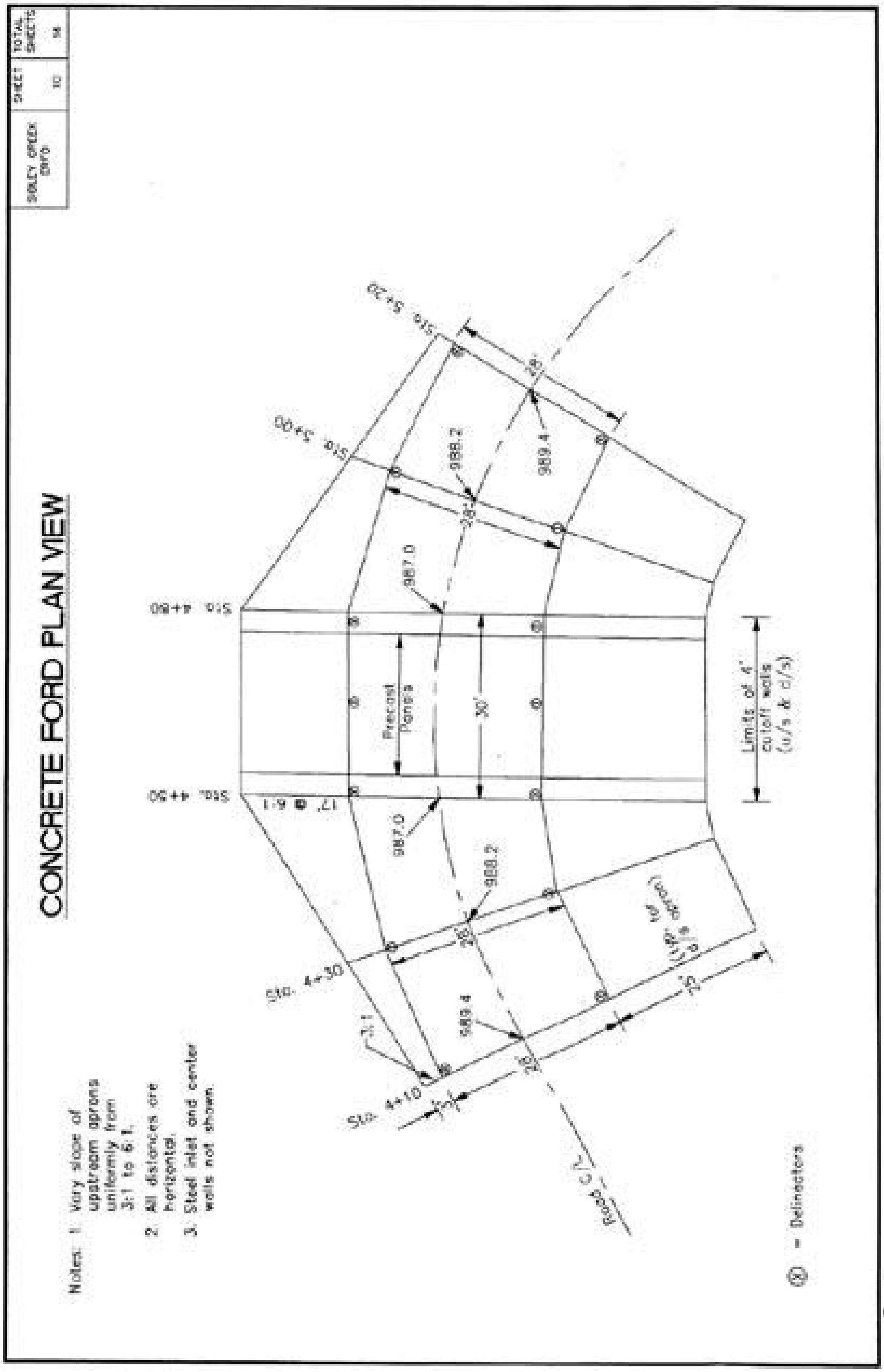


Figure A107b. Ford plan view.

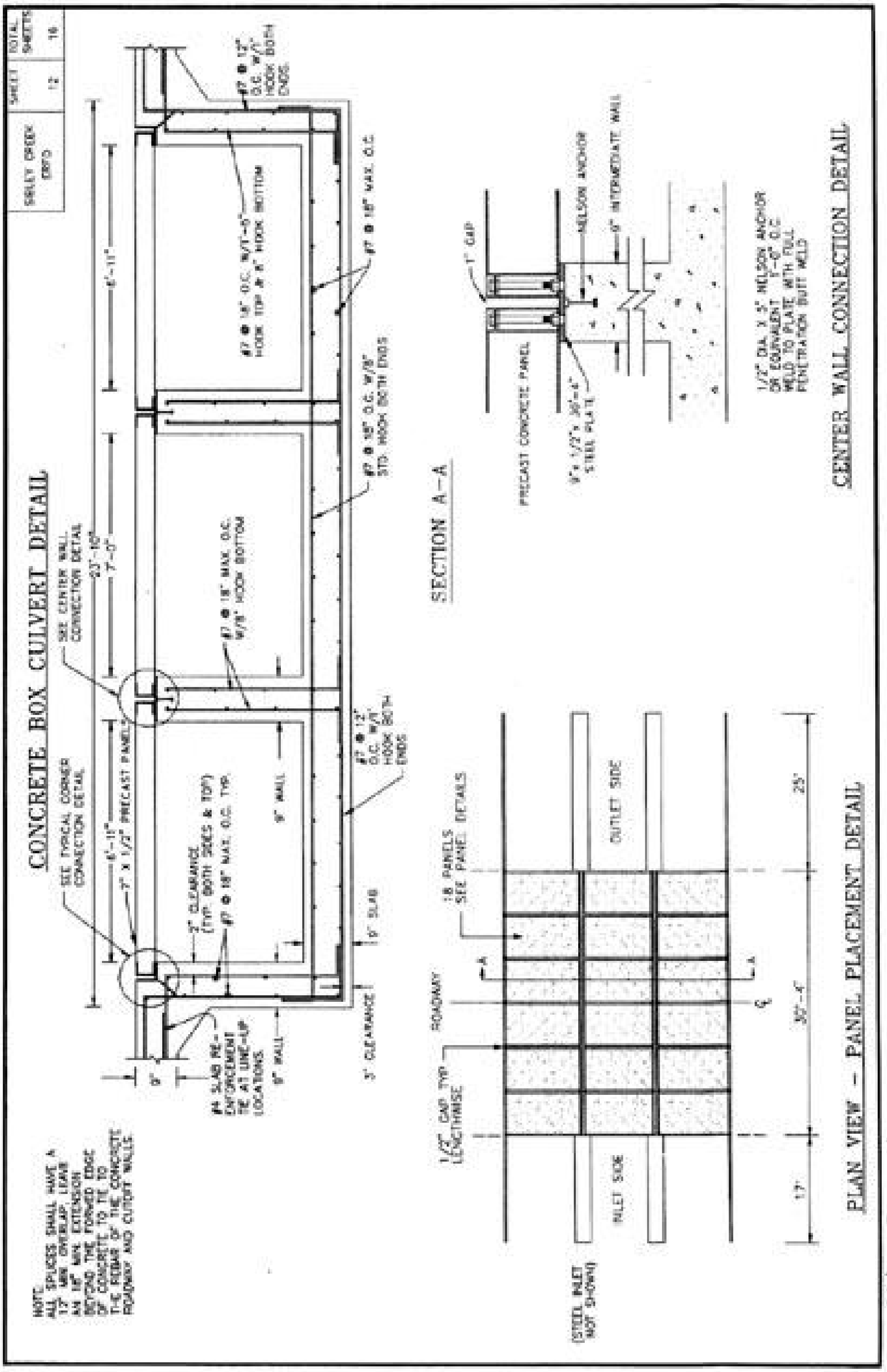


Figure A107c. Box culvert profile.

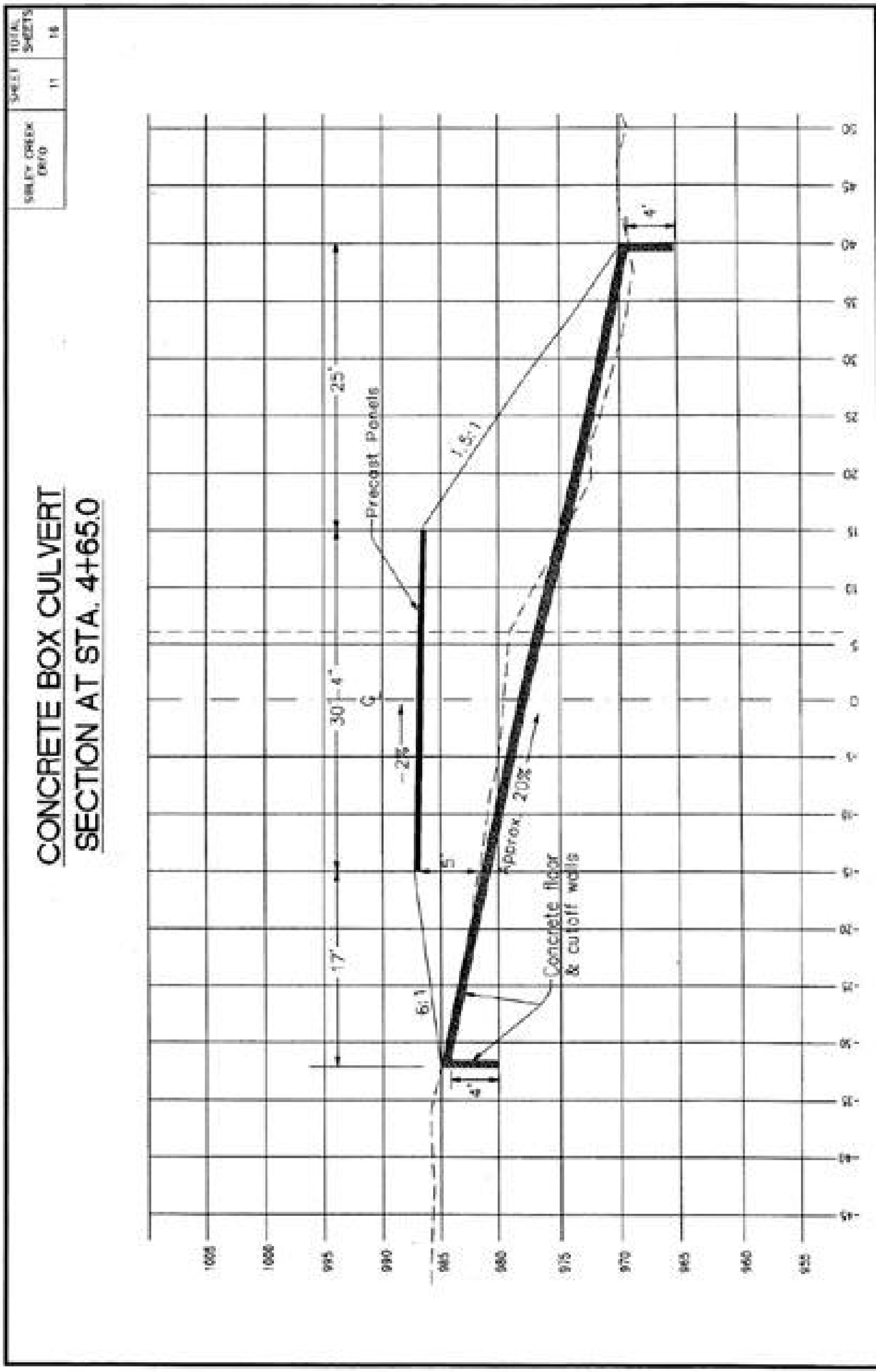


Figure A107d. Detail drawings.

Figure A108. Looking downstream at the ford.

Figure A109. Sibley Creek currently approaches the inlet at a slight angle.

Cost: $ 185,000 in 1997.

Safety: Delineator posts define the road edges and type III object markers are at both ends and both sides of the ford to focus traffic toward the road center (figure A110).

Figure A110. Safety markers on ford and approaches.

Flood and Maintenance History

The only major flood event since the structure was built—in October 2003—did not cause any problem at the Sibley Creek crossing. The only maintenance that has been necessary is to clean rocks and wood off the inlet trash rack periodically. There have not been any other maintenance needs or any problems with the structure.

Summary and Recommendations

It is an extreme challenge to maintain a crossing structure on a stream this steep and prone to debris torrents. After many attempts with other structure types, this massive concrete ford appears to fit the site and its geomorphic processes well. It makes every provision for debris, rock, and water passage in spite of expected blockages. Similar concrete structures are in use elsewhere on nonfishbearing streams on the Mt Baker-Snoqualmie, Gifford Pinchot, and Olympic National Forests.

Wayne Hamilton, assistant forest engineer; Peter Wagner, bridge engineer; Jim Doyle, fisheries biologist (retired) and Roger Nichols, geologist provided the information for this case study.

Similar Structures In Other Locations

Robert Askin (Askin 1992) describes a rockfill ford on a similar channel in the Catherine Creek watershed on Vancouver Island, British Colombia. The ford was designed for a new (1992) logging road to cross a channel that had a 27-percent slope and a serious risk of debris torrents. Objectives were to keep costs low, pass water and debris, and avoid diverting flood flows down the road. After over-excavating the channel bed below the predicted depth of scour, large riprap was interlocked to construct a foundation, and the structure was built up to grade using coarse fill materials (figure A111). The crossing surface is about 8 feet above the natural channel bed, and it is outsloped at 9 percent to permit debris to move over the surface. Low flows move either through or over the permeable ford.

As of April 2002, the ford had not been subjected to a debris flow. It was functioning well, but the original vertical curve had been compromised by road grading over the years so that a large flow might now be diverted down the road (Askin, personal communication).

Askin's 1992 paper discusses how he estimated the volume of debris that could come down in a debris torrent and be trapped behind or on the structure, and it provides details on costs and materials volumes. It is another excellent example of designing for geomorphic processes at a site.

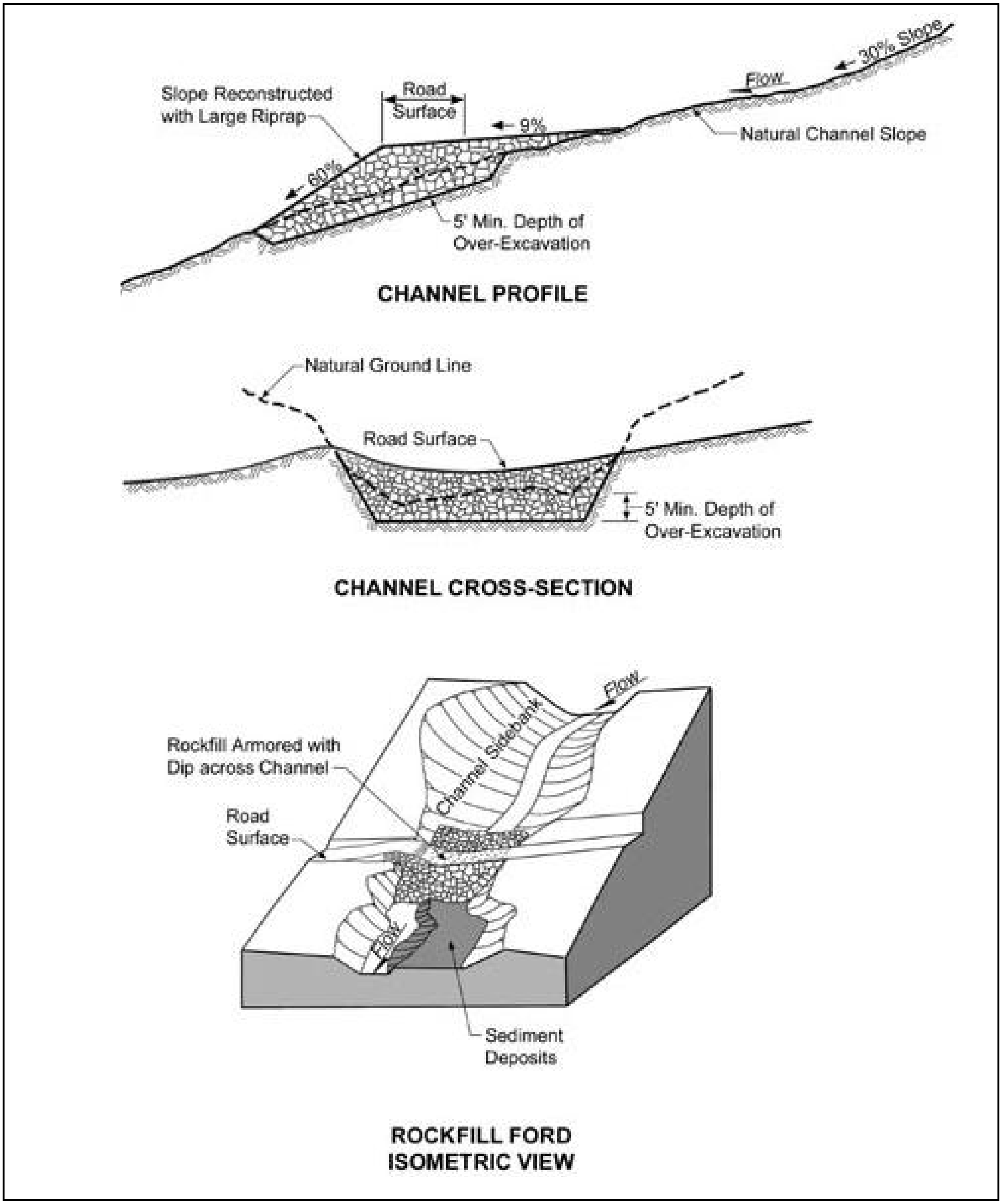


Figure A111. Stream and ford longitudinal profile, Catherine Creek, Vancouver, B.C. Redrawn from Askin 1992.

Case Study 17. Stony River Treated Timber Box Culverts

Location

Northern Minnesota. Superior National Forest, Isabella Ranger District. Stony River, south of Boundary Waters Wilderness Area. 8 miles west of Isabella, adjacent to State highway 1, approximately ½ mile from McDougal Lakes. Forest Road 933.

Crossing Description

This structure was constructed in 1984 on a perennial fish-bearing stream (figure A112). It is a series of treated timber box culverts embedded into a cobble-boulder streambed. The opening is about 85 to 90 percent of bankfull width on a relatively straight pool-riffle channel. Low-flows pass through the structure at similar velocities and depths as in the channel itself, and the structure appears to be passable to fish most or all of the year. The ford was designed to pass the 25-year flow under the bridge deck, and to resist common ice jams. Water has barely overtopped the deck twice, and the structure has required only occasional debris removal and some reinforcement of the joints and connectors.

Figure A112. Stony River box culvert ford.

Setting

Northern Superior Uplands Section (212-L), Laurentian Highlands subsection. Level to rolling glaciated uplands on ground moraine, end moraine, and outwash. Surface materials are well-drained loamy till and gravelly to sandy outwash, with small interspersed areas of peat and swamp. There are many lakes, and except in frozen conditions runoff is moderated by high infiltration and percolation rates. Dominant vegetation in this subsection is mixed pine with aspen-birch, fir, spruce, tamarack, and cedar (Superior National Forest, 1998).

Why Was This Structure Selected?

The vented ford structure was selected to accomplish the following objectives.

- Permit fish passage.
- Allow overflow in the event of ice plugging.
- Sustain ice jamming.
- Protect water quality.
- Protect scenic quality. (The structure can be seen from the adjacent State highway and a low profile structure of native materials was desired for aesthetic purposes.)
- Minimize cost. (The forest's estimated cost of construction ($45,000) was lower than the anticipated cost for a timber bridge long and high enough for the site ($60,000).)

Crossing Site History

This is the first structure at this site.

Road Management Objectives

Forest Road 933 is a spur originally constructed as a timber haul road and designed for a 55-foot loaded log truck and 12-yard gravel truck. It is a gravel road currently maintained for high-clearance vehicles (maintenance level 2). Current use is for occasional recreation.

Stream Environment

Hydrology: Average precipitation in this area is 26 to 31 inches per year. Flow variability is moderate: flow is snowmelt-dominated and rain-on-snow is uncommon. The crossing's location less than ½-mile downstream of McDougal Lakes, where storage capacity is enhanced by a low dam, also helps to moderate flow variability. For the 71-square-mile drainage area, the estimated annual flood is 234 cubic feet per second and the 100-year flood is 608 cubic feet per second, less than three times the annual flood (R. Pekuri, design notes, 1984). In situations like this where flow variability is low or moderate, low-water crossings are often not considered. However, in this area ice is a significant consideration for all road-stream crossings. Ice cover commonly forms while flow is still relatively high in early winter, occasionally even freezing to the streambed. Spring snowmelt often runs on top of the ice, so that water elevations are higher than would be anticipated for water only. During spring snowmelt ice blocks break free and drift downstream, which can cause ice-jamming at crossings. Little woody debris moves in the stream.

Channel Description: Stony River is low sinuosity pool-riffle channel (a B2c or C2 stream type) about 50 feet wide. Boulder riffles provide streambed structure, and pools are quite shallow. Slope near the site is approximately 1.25 percent. Boulders vary from large to small, with a predominance of small to medium sizes. The adjacent riparian area has some tree cover, with dense shrub and sedge vegetation, and the potential for large woody debris recruitment to the channel is low to moderate. Boulders, wood, and vegetation provide good bank stability. The channel is moderately entrenched to unentrenched at the site, with a 5-foot terrace on one bank, and a narrow flood plain on the other (figure A113).

Figure A113. Stony River looking upstream from the ford.

Aquatic Organisms: Fish passage is required at this site. Stony River is within the range of the Creek Heelsplitter (Lasmigona compressa), a regional forester's (Eastern Region [R9]) sensitive mussel whose numbers have declined relative to its historical abundance. Host fish are required for the mussel to propagate, but on the Superior National Forest it is not known precisely which species are hosts. On the Chippewa National Forest, host species are listed as the spotfin shiner, slimy sculpin, crappie, and perch (Kitchell, 1999)

Water Quality: Water quality at this site is good, and management objectives are to maintain it. Because the graveled approaches slope directly to the crossing and some gravel washes into the river, forest personnel recommend paving the approaches.

Design and Construction Details

Structure: The project consists of three double-barrel nail-laminated creosote wood culvert boxes 7½ feet wide and 5 feet tall, embedded in channel substrate. The center box is 8 inches lower than the outer sides of the end boxes to concentrate flow in the center of the channel. The boxes are 5 feet high and were filled to a depth of 1½ feet with streambed material, to provide weight and stability to the structure, as well as to facilitate fish passage. The structure was designed to accommodate the 25-year flow 6 inches under the bridge deck. On both the up- and downstream sides of the structure, timber cutoff walls extend from the bottom of the boxes 3 feet down into the streambed to prevent scour and increase resistance. The upstream faces of the boxes and deck are protected by metal facings against rock, ice, and debris battering. The structure has a solid timber deck and 8-inch timber curbs.

Bank stabilization and approaches: Wingwalls are deadmanned into the road template with buried logs to prevent dislocation by frost heave, which can be extreme in this boreal environment. Approaches are graveled on a slope of 4 percent.

Cost: Actual contract cost was $63,000 in 1984.

Safety: Curbs are provided on both edges of the low-water bridge. Stony River is lightly used by kayakers, and it has been suggested that warning signs be provided upstream, along with take-out and put-in areas to facilitate kayaks being portaged around the bridge.

Flood and Maintenance History

The flood history of this site is unknown, but there have been very heavy storms in the general vicinity within the structure’s lifetime. Since construction, flow has twice been observed to just overtop the structure. Some shifting has occurred and the box connectors have required reinforcement. Debris removal from the upstream face of the structure has been the only other maintenance need.

Summary and Recommendations

This high vent-area-ratio ford continues to function well after 20+ years. Boulder streambed material covers 100 percent of the structure bottom, so that streambed continuity and flow velocities similar to the natural channel are maintained through structure. The designer would opt for using concrete if he were building a similar box structure today, because of structural strength and durability. Other recommendations from forest personnel are to pave approaches to protect water quality, and to provide an upstream take-out and portage for kayaks.

Roger Pekuri, forest engineer (and designer of the ford) and Barbara Leuelling, soil scientist, both of the Superior National Forest, provided information for this case study.

References

Superior National Forest. 1998. Characteristics of the Superior National Forest landtype associations. Duluth, MN: Superior NF.

Case Study 18. French Creek Embedded Concrete Box Vented Ford

Location

North central California, Plumas National Forest, on French Creek. Three miles northwest of Brush Creek and 15 miles northeast of Oroville, CA. Forest Road 22N34.

Crossing Description

This structure, constructed in 1981, is located on a perennial stream where fish passage and woody debris jams are issues of high concern. The structure has a long, low profile. It is a 15-foot-wide, 240-foot-long concrete structure with five concrete boxes across about 50 feet of active stream channel (figure A114). The boxes are set just below the streambed elevation and native streambed material covers most of the floor. The top of the ford, about 5 feet above the channel, has a metal grating driving surface. The structure required minor repairs and lengthening of part of the armored driving surface after some large storm events when large amounts of debris accumulated behind and on top of the structure. Due to flow acceleration over the smooth concrete surface through the boxes, a large plunge pool has formed downstream of the ford. To prevent the ford from being undermined, a long gabion “mattress” has been placed across the channel at the downstream edge of the structure .

Figure A114. Looking upstream at the French Creek vented ford.

Setting

Sierra Nevada Section (M261-E). Elevation 2,100 feet, within a granite batholith on the west side of the Sierras.. The site is located in a “west-side” forest area with mixed conifers and moderate hardwoods, particularly tan oak and madrone.

Appendix A—Case Study 18

Why Was This Structure Selected?

The large box culvert with grated top design was selected to fit the geomorphic and hydrologic characteristics of the site, and to avoid the expense of alternative structures. This is a wide stream (over 50 feet) and a very broad flood plain with large peak flows that carry substantial amounts of both bedload and debris. Normal culverts would likely clog or have insufficient capacity, and a bridge would need to have a high profile and span several hundred feet to cover the large flood plain and avoid constricting it. These factors led to a choice of a vented ford that could withstand overtopping and could be easily cleaned out

Crossing Site History

This box culvert ford replaced an old railroad-flatcar bridge with log abutments, which severely constricted the channel and had washed out on several occasions. The crossing site is actually a poor location, on a river bend with a point bar and a broad flood plain. The crossing could not be relocated because of its location at an intersection, as well as existing road alignment and private property constraints.

Road Management Objectives

This is a maintenance level 2 road, alternately native or gravel surfaced, and maintained for passenger vehicles. It has an annual average daily traffic count of 50 vehicles, and provides access between two Sierra Nevada foothill areas, Brush Creek and Chino Ridge. This route is often closed during the winter due to other problems along the road. Traffic is a mix of occasional logging traffic during a timber sale, USDA Forest Service administrative traffic, and general recreational traffic. Traffic volume and type are such that occasional interruptions are acceptable. Traffic interruption due to flooding occurs only once every several years, lasting approximately a few days.

Stream Environment

Hydrology: French Creek is a perennial tributary to the North Fork of the Feather River, with a drainage area of about 29 square miles. Average annual precipitation is 50 to 55 inches, falling as a mix of rain and snow. Summer low flows are 20 to 50 cubic feet per second. The bankfull flow (Q_2) is 960 cubic feet per second, and the design flow (Q_{100}) is approximately 7,100 cubic feet per second. During major storm events (Q_{20+}) heavy debris deposited in the trees along the stream suggests that the entire ford is inundated several feet deep. Peak flow velocities of 7 to 9 feet per second are expected. The structure is designed to pass 800 cubic feet per second under the deck, so the structure is overtopped every 1 to 2 years.

Channel Description: French Creek is an unentrenched C4 channel; bankfull width and depth are about 55 feet and 2 feet respectively (figure A115). The substrate is a well-graded mixture of sands, gravels, and cobbles, and there is considerable bed movement during storms. Channel slope is less than 1 percent. The crossing is located on a broad bend, and the ford crosses French Creek from a low terrace on the east side across a point bar-flood plain sequence on the west side. Heavy riparian vegetation, including willow, alder, and blackberry vines stabilizes the 8-foot high terraced banks. The five boxes match the stream bed width so that low flows pass the structure freely. However, to keep vehicles out of the water during normal high flows and maintain a level driving surface across the point bar, the slab is raised 2 to 3 feet above the point bar. This induces some scour immediately downstream of the structure as water pours over the raised slab.

Figure A115. Looking upstream from the ford at French Creek.

Aquatic Organisms: This section of stream provides habitat for rainbow trout and a variety of nongame fish and providing fish passage is a key issue. Stream-channel material that has filled in the bottom of most of the boxes shows that water velocity in the boxes is similar to the natural channel at moderate flows. This makes it likely most, if not all, swimming species can pass the structure.

Water Quality: Sediment delivery in this watershed is a moderate concern. Water quality in the stream is relatively good and should not be degraded.

Structure Details

Structure: The structure was designed by the Plumas National Forest and constructed under a Public Works Contract. The project took 100 days to construct and required a total of 140 cubic yards of concrete, 190 cubic yards of gabions, and 77 cubic yards of Class VII riprap. The structure is made with five box culverts, with each concrete stem wall 1-foot thick. Each concrete box is 9 feet wide by 4 feet high, and they are embedded 6 to 12 inches below the natural stream channel bottom elevation to maintain streambed continuity through the structure (figure A116).

Four-foot deep concrete cutoff walls are located along the upstream and downstream edges of the structure (figure A116). Gabion mattresses protect both edges from scour. The raised concrete driving surface over the boxes and across the flood plain extends for a total of 240 feet.

The driving surface is 1 to 2 feet above the flood plain elevation so as to pass bankfull flows and small debris. Across the active channel this capacity was good, but the raised concrete slab roadway across the flood plain has caused a "damming" effect which has led to upstream debris deposits and downstream scour.

During construction water was bypassed around the west side of the structure while the concrete boxes were poured and backfilled. Then the removable metal deck grating was added, the flow returned to its natural channel location (through the boxes), and the ford approaches were constructed.

Bank stabilization and approaches: The ford slopes gently into the drainage at 5 percent on the west side and is nearly flat to the east across a broad flood plain. The approaches are not surfaced. Bank stabilization includes riprap of large boulders and willows (figure A118a). Both gabions and concrete blocks were placed along the downstream edge of the elevated driving surface across the flood plain areas (figure A118b).

Cost: Construction cost of this vented ford in 1981 was about $155,500.

Safety: The structure has a 6-inch-high steel curb along both sides of the road as a traffic safety measure. The crossing is on a tangent section of road, near an intersection, so there is excellent sight distance and visibility. The structure is not signed, but road use is unlikely on this remote road during storms when the structure is overtopped.

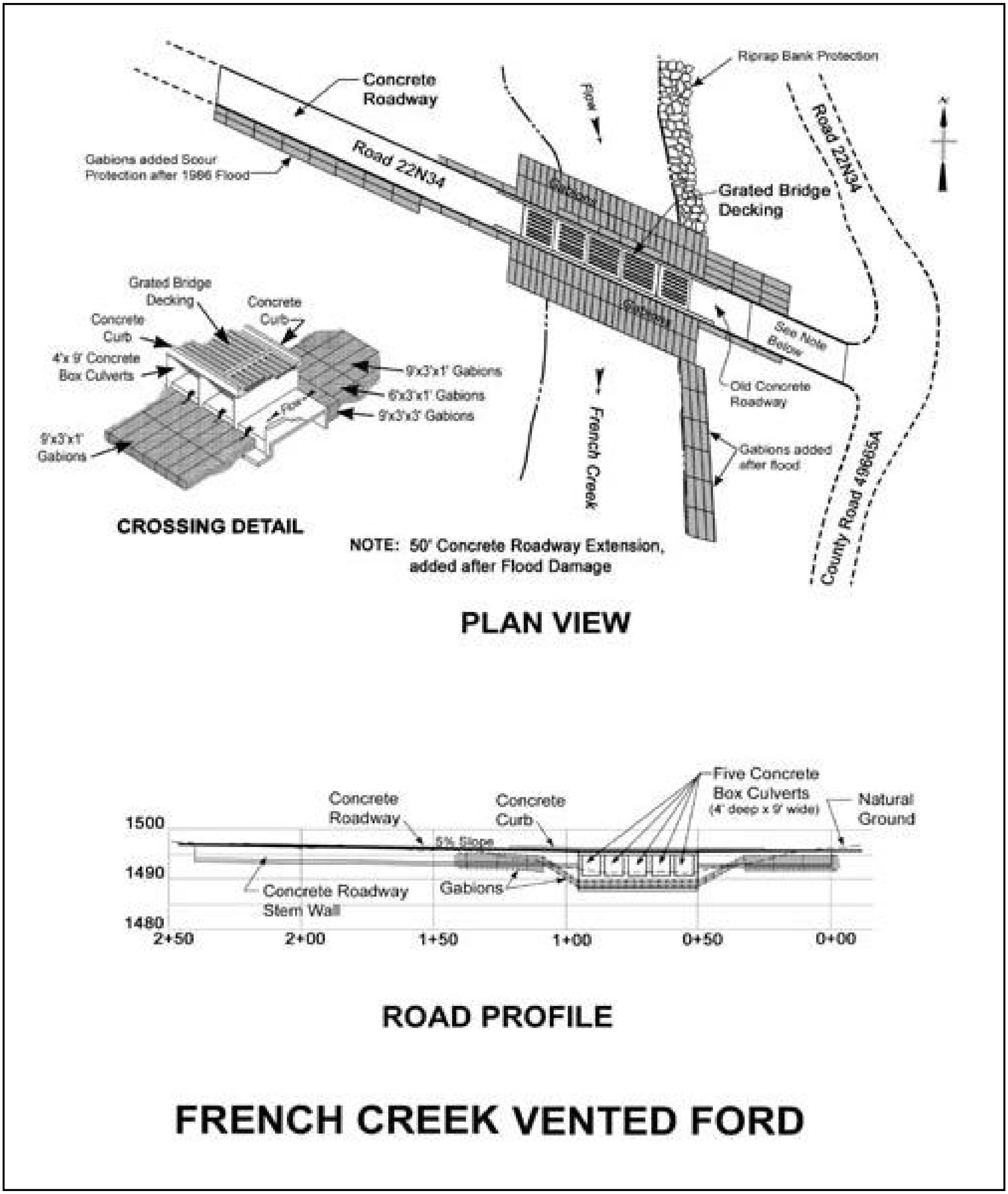


Figure A116. Site plan view with valley and road profile sketches.

Flood and Maintenance History

The vented ford was slightly damaged by scour in 1982, the year after it was constructed, and again during a flood in 1986. In 1986, the structure was overtopped and a scour hole formed in the roadway where the original concrete armoring ended (figure A117). The concrete roadway surface with 3-foot deep cutoff walls was extended 50 feet on the east side, covering the area of scour. Also some energy dissipation measures were added along the downstream edge of the structure where the water flows over the concrete slab roadway. Large articulated concrete blocks were used, as well as some additional large riprap (figure A118b).

Figure A117. Scour around the east end of the structure after the 1986 flood. The concrete driving surface was then extended 50 feet.

In the 100-year event of 1997 the entire structure was plugged with debris, as seen in figure A119, causing the channel to move to the west side of the structure, in the flood plain area. The original channel was cleared and flow returned to the main channel. The structure itself was not damaged.

Figures A118a and A118b. Scour protection measures a) using riprap with vegetation along the channel (left) and b)concrete blocks and gabions along the elevated roadway (right).

Figure A119. Debris dammed the structure during the 1997 flood event. The main thread of flow shifted to the west and is spilling over the elevated roadway. The white sand deposited everywhere except the higher forested ground in the upper left and lower right of the photo shows that almost the entire area was flooded in 1997. The area that was scoured east of the ford in 1986 is also delineated.

Summary and Recommendations

The French Creek crossing is a relatively massive integral concrete box structure with a steel grating driving surface (figure A120). It is designed to withstand major storm flows and major sediment movement, and to resist significant scour. The site is poor because it has a broad flood plain where channel depositional processes can be disrupted by a blockage such as the raised slab. In addition, the stream can shift its location during floods when the structure plugs with debris. A narrower, more entrenched channel location would have been a better site for a crossing. A few hundred feet above the crossing site is a straight and more confined reach of French Creek. Both banks at that location are 8-foot high, and there is no flood plain. A bridge at this site would have had less site problems, but would have been a much more expensive structure. Also other site constraints prevented relocating the road.

A ford is an appropriate structure compared to culverts which would plug and overtop more frequently, or a much more expensive bridge at a location unlikely to be used during major storm events anyway. The heavy debris load in the watershed requires maintenance of the structure after each major flow. The original structure should have been made longer to protect the entire wetted perimeter, and the boxes should have been set slightly deeper to ensure full coverage of the box floors with natural streambed material. However, the floors are already approximately 90-percent covered and subsequent repairs have added the necessary downstream scour protection. Also the roadway elevation should have been set a couple feet lower across the flood plain to prevent the water drop over the roadway and subsequent scour in this area.

Figure A120. Looking downstream at the vented ford with point bar on right.

Gordon Keller, geotechnical engineer on the Plumas National Forest, provided information and photos for this case study.

Case Study 19. Mill Creek Embedded Box Culvert Vented Ford

Location

Southeast Missouri. Mark Twain National Forest; Houston-Rolla Ranger District. Southeast of Rolla, south of Interstate 44, off of State Road P: Forest Road 1576. Mill Creek, tributary of Little Piney Cr, Gasconade River basin.

Crossing Description

The current structure was built in 1994 in a State-designated wild trout management area. Traffic access is required year-round for private residences and recreation; fish passage is also required. The structure is a set of three box culverts that overtops at least once per year on average. The boxes are embedded about 1 foot so that the natural streambed is continuous through the structure (figure A121). The supports slope up toward the deck to facilitate large debris riding over the structure rather than damming it during overtopping flows.

Figure A121. Looking upstream at Mill Creek box culvert vented ford, 2002.

Setting

Ozark Highlands Section (222-A). Gasconade River Hills. Soils are rocky and thin over carbonate and sandstone bedrock and large springs are characteristic of the karst geology (Draft Descriptions of Missouri Ecological Subsections, USDA Forest Service Mark Twain National Forest, 1999). Elevation is 748 feet. Mill Creek flows through a long, gently sloping valley generally around ¼-mile wide. Vegetation is mostly grass and riparian hardwood forest. The valley is bordered by rounded, forested ridges about 150 feet high.

Appendix A—Case Study 19

Why Was This Structure Selected?

This structure was selected because it:

- Allows passage of fish, other aquatic organisms, and large woody debris.
- Is less likely than the previous structure to be damaged by large woody debris and therefore has reduced maintenance costs.
- Was less expensive to build than a bridge.
- Provides greater public safety and fewer traffic interruptions than previous structures, due to fewer overtopped days.

Crossing Site History

Most road crossings in this area are vented or unvented concrete slab fords, which are inexpensive and easy to replace. The original crossing structure at the Mill Creek site, a slab, was replaced in 1976 with a low-water bridge, probably in response to fisheries concerns. However, the bridge was very low and its piers were closely spaced. It trapped woody debris, and not only was debris removal required after every large storm, but the piers scoured and erosion occurred around the ends.

Road Management Objectives

This road accesses recreation facilities, grazing allotments, and private residences. It is gravel-surfaced road managed for passenger cars (maintenance level 3). During hunting season--the peak season--traffic is approximately 100 vehicles per day. Traffic interruptions are undesirable; an alternative access route exists, but it is less convenient and may be impassable during high water flood events.

Stream Environment

Hydrology: Low flow in Mill Creek is sustained by Wilkins Springs, a 59F spring that supports Mill Creek's important cool water fishery. High flows are quite flashy in this area of thin soils and historically channelized streams (figure A122). Most of the 45 to 50 inches of precipitation in the area falls in the spring, and peak runoff usually occurs from drenching rains between March and May. Summer thunderstorms also produce flashy peaks. Drainage area above the site is approximately 37 square miles.

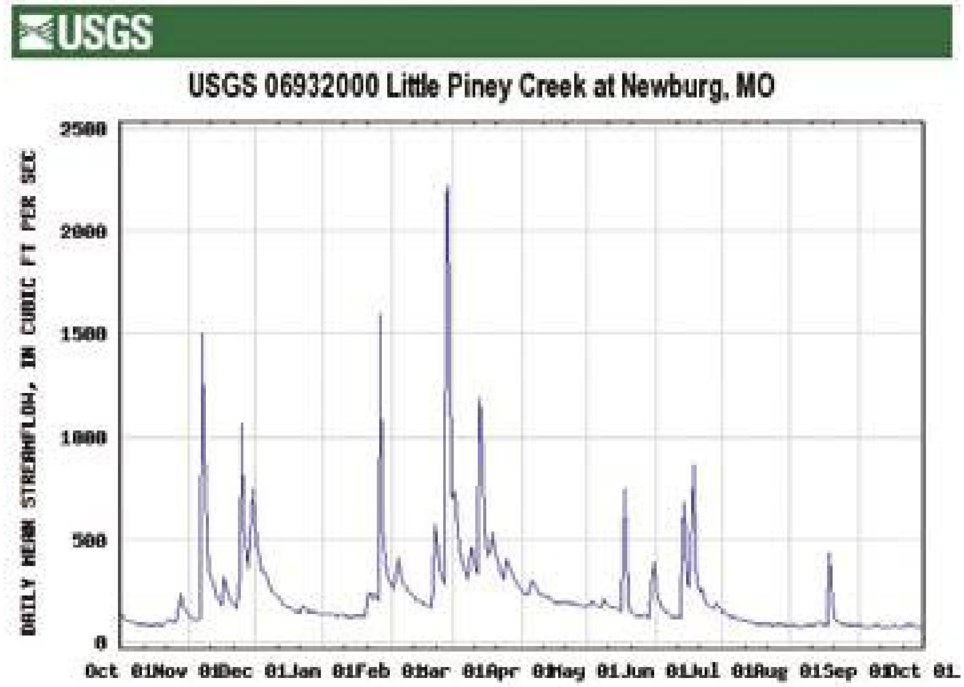


Figure A122. Little Piney Creek at Newburg. The hydrograph for water year 1997 illustrates how flashy high flows are in this area. From USGS National Water Information System Web site: http://nwis.waterdata.usgs.gov/nwis/sw. Newburg is about 3 miles north of the Mill Creek crossing site. Watershed area for the Little Piney Creek gauge is 200 square miles.

Figure A123. Looking downstream on Mill Creek from the box culvert ford.

Channel Description: This reach of Mill Creek is a pool/riffle, gravel bed stream with an estimated gradient of 2 percent. It is about 40 feet wide away from the widened section at the crossing, and banks are 2 to 3 feet high (figure A123). The well-vegetated flood plain is about 3 feet below the wooded terrace that forms the broader valley floor. The channel appears to be vertically stable, but has at least moderate potential to migrate laterally. The crossing is on a slight bend, and crosses a gravel bar on the right bank (bar is on left side of figure A121). Historical land use in this area of the Ozarks, especially riparian grazing and stream channelization, affected streams by removing riparian vegetation and inducing bank erosion. This mobilized large volumes of gravel, and streams responded by widening and shallowing (Jacobson and Primm, 1997). Bank erosion is prevalent on some reaches of Mill Creek.

Aquatic Organisms: Rainbow trout were introduced between 1880 and 1890. Mill Creek is now one of only five creeks in Missouri with a self-sustaining population, and the State of Missouri has classified Mill Creek as a wild trout management area. Passage for trout is considered important; no other aquatic organism passage needs have been identified. Fish can be seen using the structure for cover.

Water Quality: This structure protects water quality by keeping traffic out of flowing water. Also, since it passes most debris and only slightly constricts the bankfull channel, it is unlikely to cause bed or bank erosion.

Structure Details

Structure: This current structure has three boxes, with sloping wings designed to sweep debris up and over the deck. Open area under the deck approaches bankfull cross section area, but is being reduced by gravel accumulation on the right bank (looking downstream, figure A124). The interior openings of the boxes are 14 feet wide and 5 feet high, and they are embedded 1 foot into the streambed so that the natural streambed is continuous throughout. The design is a standard Missouri Department of Transportation design that is available on the Internet. See Concrete Triple Box Structure drawing 703.81F for sample plans (http://www.modot.org/business/standards_and_specs/currentsec700.htm).

Bank stabilization and approaches: Concrete approaches slope slightly down into the center of the structure, and have solid wing walls resting on 2-foot-wide by 1-foot-high footings. The approaches obstruct flood-plain flow, but there is very little evidence of downstream scour, perhaps because gravel loading is so high in the stream. Some riprap is used to stabilize the banks immediately adjacent to the structure (figure A125).

Figures A124a and A124b. Downstream side of the box culvert crossing. Between 2003 and 2006, gravel bar enlarged to block one box.

Cost: $95,300 in 1994.

Safety: This crossing has curbs. It does not currently have safety signing, and the road is not closed during storm runoff.

Flood and Maintenance History

The structure overtops annually, sometimes more than once per year, but generally no maintenance is required. In May 2002, the region received 18 inches of rain in 18 days, the largest flood over the structure to date. Woody debris and sediment were deposited on the deck and approach slabs and had to be removed but, except for the tension cracks described below, there was no damage to either the structure or the channel. USDA Forest Service personnel generally remove large woody debris 1 or 2 times each year. Prior to the current structure, such activity occurred monthly.

The bridge inspection in 2003 found what appeared to be tension cracks in the top of the deck between the piers. For similar structures, designers should check to ensure there is enough steel reinforcement in the tension zones.

Summary and Recommendations

The structure's length approximates bankfull channel width in straight, undisturbed reaches, but the walls, curbs, and approach slabs are enough of an obstruction to flood flows that sediment deposition is altering the site somewhat. Gravel is accumulating both on the bar and on the riffle upstream. Flow constriction and the resulting accelerated water velocity have caused some bed scour in the box furthest from the gravel bar. These changes do not appear to have reduced the structure's effectiveness for aquatic organism passage, but they may impede traffic by causing more frequent overtopping. The approaches do obstruct flood-plain flows, but no scouring is apparent on the banks or the well-vegetated flood plain. In general, the structure appears to be working well in a challenging environment of flashy flows and high sediment loads.

Larry Furniss, forest fisheries biologist; Amy Sullivan, forest hydrologist; and Lori Wilson, transportation planner, on the Mark Twain National Forest provided information and photos for this case study. Scott Groenier, engineer at the USDA Forest Service Technology and Development Center in Missoula, MT supplied information about the 2003 bridge inspections, which he conducted.

Similar Structures In Other Locations

Forests in the middle part of the United States and in the southeast are increasingly using low-profile embedded box culverts as crossing structures on roads where brief traffic interruptions are tolerable. Unlike the Mill Creek structure, many are designed to overtop several times every year. The Long Creek structure (described at the end of case study 14) is an example on the Ouachita National Forest. The Kinkaid Lake low-water crossing on the Shawnee National Forest is another example.

Forest Road 772 on the Shawnee National Forest is an unimproved native surface road that accesses about 1,000 acres of hilly National Forest System land and some private land used for fall hunting. The embedded box culvert crossing is located where the road crosses Little Kinkaid Creek, a perennial tributary of Kinkaid Lake.

The previous crossing structure was a concrete slab ford (figure A125). Silty sediment and woody debris routinely accumulated on it during high water, frequently making it impassable. The slab collapsed when the stream undercut it on one side. The soil at the site has difficult engineering properties. It is a poorly-drained silt loam characterized by a seasonally high water table, frequent winter flooding and stream bank erosion. Severe erosion of the 4-foot to 5-foot high banks around the ford is apparent in figure A125.

Figure A125. Looking upstream at failed Kinkaid Creek crossing, 2000. Stream slope is 0.3 percent.

Sustained concentrated rainfalls of several inches per day cause peak flows in this area, and peaks on Little Kinkaid Creek are very flashy. Since traffic use is low and would be interrupted only a few hours during any one runoff event, a low-water crossing was a desirable and cost-effective solution here. However, the design had to account for the unstable, erodible banks and tendency for debris and bedload plugging. The designer selected a very low-profile structure to encourage woody debris to go over the top and to avoid large changes in flow width that would put pressure on the banks at bankfull and higher flows. The structure is a set of four 5-foot wide concrete boxes with metal-grate decking that can be removed to clear the boxes. The box walls slant out and down, as at Mill Creek, to help debris slide over the top (figures A126 and A127).

Figures A126a and A126b. Kinkaid crossing just after construction in 2001. A126a. Close up of embedded boxes; A126b. View along vented ford showing riprap.

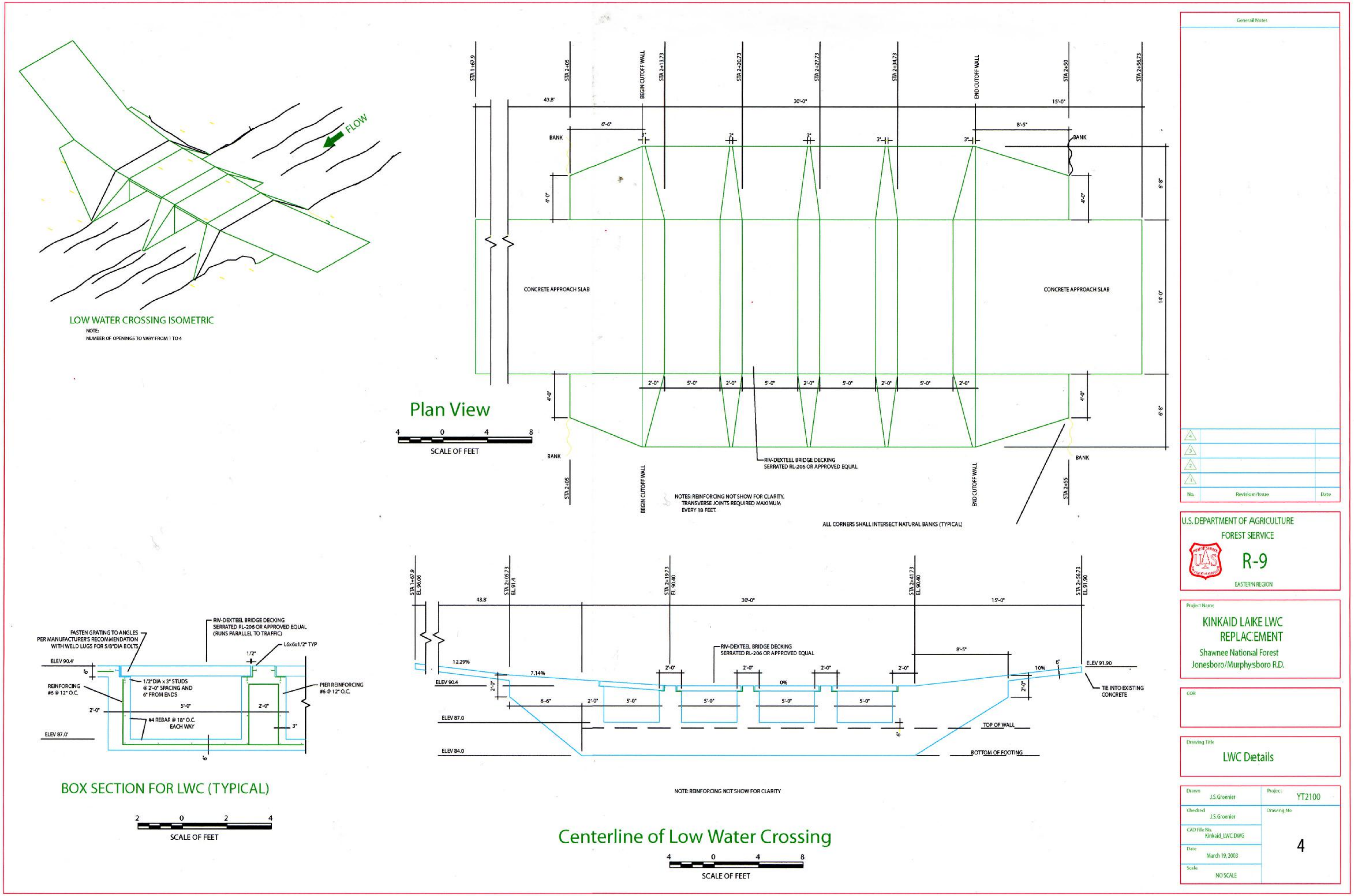


Figure A127. Plans for Kinkaid low water crossing replacement, 2001.

The 3-foot high boxes are embedded about 1 foot into the streambed for fish passage (figure A126a). The boxes were allowed to fill naturally with streambed material, and in this case the streambed was mobile enough (medium to coarse gravel) and the sediment supply high enough that no headcut resulted. The streambed in the boxes has maintained itself successfully through two approximately normal rainfall years.

The new structure was designed to pass the mean annual flow underneath the deck at a depth of 6 to 8 inches, and it is submerged at frequent high flows (3 to 4 times per year). Approach slopes are steep at 10 to 12 percent but at a site where the natural banks are nearly vertical, the structure had to be somewhat wider than the channel. Riprap provides erosion protection upstream and downstream of the cutoff walls (figure A126b). The structure cost $23,000 to install in 2003.

Two years after installation, the structure is functioning well. Traffic is not interrupted by sediment and wood deposition as with the old slab structure. The new one does require removal of woody debris after high flows, but no other maintenance has been needed. Fish successfully pass the structure and the adjacent streambanks are stabilizing.

Scott Groenier, east zone structural engineer, (Northeast Region (R9)Technical Skills Team, now at Missoula Technology and Development Center), and Anthony Kirby, Mike Welker, and Steve Widowski of the Shawnee National Forest provided information and photos on the Kinkaid crossing.

Case Study 20. Deep Creek Low Water Bridge

Location

North Central Florida. Osceola National Forest. Road 237-1 at Deep Creek, 1/4 mile north of Forest Road 262-2 and about 11 miles NE of Lake City, Florida.

Crossing Description

This low-water bridge was constructed in 1991 (figure A128). It is built of preformed concrete T-sections set parallel to the direction of streamflow. The T-sections are supported by two concrete mud sills placed on the sand and clay streambed. The channel and surrounding area are quite flat and the flood plain is several hundred feet wide. The bridge approximates the channel dimensions, and it does not alter flow velocities and sediment transport enough to cause significant channel changes. When water overtops the bridge, there is virtually no plunging flow (the site is backwatered) and velocities remain moderate. Periods of submergence typically last for 1 to 2 weeks.

Figure A128. Looking downstream at the low-water bridge, November 2003.

Setting

Coastal Plains and Flatwoods Section (232-B). The landform is a flat alluvial plain with poor natural drainage and an abundance of wetlands. Elevation of the channel bottom at the crossing is 97 feet above mean sea level. Riparian cover is a dense, multilayered mixture of hardwoods, gum, and palmetto.

Why Was This Structure Selected?

The principal reasons for choosing a low-water bridge here were water quality protection and cost. The district wanted a bridge to keep vehicles out of the water and to protect the streambed and banks. Deep Creek is a perennial, fish-bearing stream that has extended periods of very low flow. Because of the wide flood plain, a bridge with normal clearance would have been several times as long to span the frequently flooded area and would have cost over three times as much. Fish passage was another objective, and the low-water bridge provides it.

Crossing Site History

The previous structure at this location, a wooden bridge, was destroyed by fire in the late 1960's. All-terrain vehicles continued to ford the stream at the site. Water quality and channel damage concerns led to a cooperative effort between the forest and the Florida Department of Environmental Protection to construct a permanent crossing (Webb 1994).

Road Management Objectives

Road 237-1 is maintained for passenger vehicles, and is used for both timber management and recreation. Road density in the area is high and there is alternative access to the area beyond the crossing. The long duration traffic interruptions (overflow occurs 1 to 2 times each year for several weeks at a time) are acceptable because of the availability of alternative routes.

Stream Environment

Hydrology: Annual rainfall in the Flatwoods is about 55 to 60 inches, well-distributed throughout the year. The area is a mosaic of swamps and drylands with only a few feet of relief distinguishing them. It is difficult to define drainage-basin boundaries in this area of extremely low relief, but the contributing watershed at the site is probably on the order of 10 to 20 square miles. As in the rest of the Flatwoods, flow in Deep Creek fluctuates widely. During most of the year, the stream flows only a few feet wide in the center of the channel and may be subsurface in some locations. Generally, overbank flows are expected once or twice a year. Streamflow rises very rapidly as the shallow groundwater storage fills during rainfall events, and overbank flow is typically sustained for two or more weeks.

Channel Description: Deep Creek is a Rosgen E5 channel type. Channel slope estimated from the topographic map is on the order of 0.1 percent and the frequently inundated flood plain is several hundred feet wide. A traditional bridge would have required approach fills, effectively damming part of the flood plain, but this low water bridge allows floodwaters to utilize the entire width of the flood plain and to flow freely down the valley. The stream is about 10 feet wide where it flows through undisturbed forest, with nearly vertical 2-foot-high banks stabilized by an intertwined mass of roots. At the crossing site, the stream is about 40 feet wide, and the bridge matches this width. Soils in the area, including the streambed and banks, are mixed sand and clay. Because of long periods of very low surface flows, vegetation overgrows much of the streambed and tends to stabilize sediment deposits. During overbank flow in March 2003, water velocity in the thread of fastest flow was estimated at between 1 and 2 feet per second (figure A129).

Figures A129a and A129b. A129a. March 13, 2003. Bridge is under approximately 6 feet of water. Note depth markers in center. A129b. Looking opposite direction along bridge, November 2003.

Aquatic Organisms: There are no riverine threatened or endangered species in the Flatwoods. Warmouth (a perch), pikerel, catfish, and grinnel (a mudfish) along with several aquatic snakes and spotted frogs, leopard frogs, and bullfrogs are present in area streams. Frog numbers are limited by predatory fish. The fish survive extended low or subsurface flow periods in holes that are deep enough to remain wet throughout the year. Fish passage is desired and this structure provides it. Fish (perch) have been observed (and caught) passing over the bridge during high flows. It is not clear whether the riprap blanket under the structure may constitute a barrier for aquatic species crawling along or through the streambed.

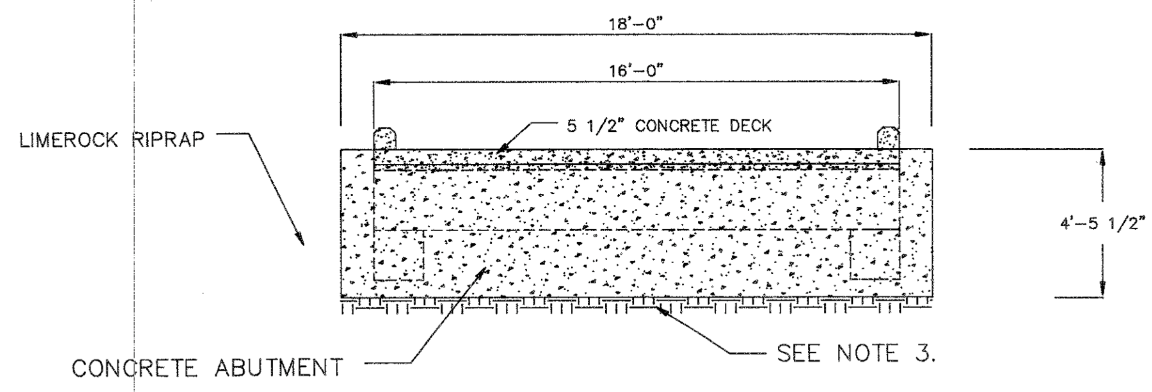
Water Quality: Streamflow in the Flatwoods is brown in color due to its organic content. pH can be below 5. Hydrocarbons and other vehicle-derived toxic chemicals are a concern contributing to the use of bridges rather than rocked fords on perennial streams like Deep Creek. The structure and its hardened approaches protect water quality by keeping vehicles out of the water and by protecting the stream's bed and banks from rutting.

Structure Details

Structure: Two 18- by 18- by 40-inch prestressed concrete beams were set across the channel with the top of the beam at channel bed elevation (figure A130a). Eight-foot wide by 2-foot high by 18-foot long double-T sections, precast to HS 20-44 bridge specifications, were placed parallel to streamflow on the concrete beams. Normally in this kind of construction, the foundations are placed on the stream banks supporting the T-sections which span the channel. Here, the supports cross the channel and the T-sections are parallel to the direction of flow. Three-foot deep by 4½-foot high abutments on each end hold the structure in place. A concrete deck 5 ½-foot thick, and curbs create a safe running surface on the T-sections.

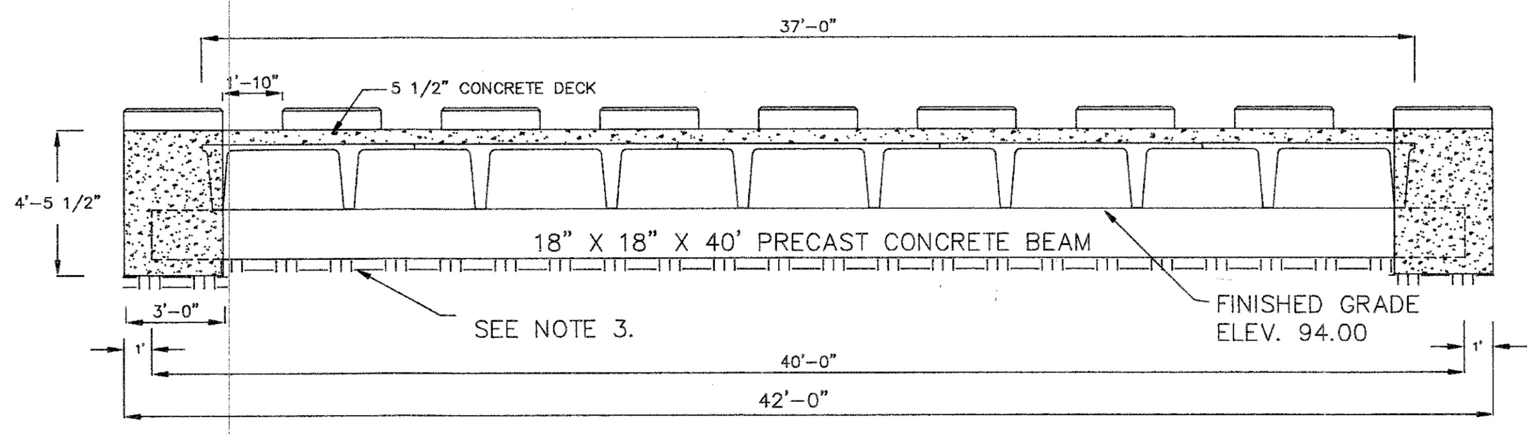
Bank stabilization and approaches: The approach road is crowned and slopes at about 2.6 percent into the crossing (figure A130b). A 1-foot thick layer of class II riprap over geotextile fabric extends 130 feet on each side, armoring the excavated slopes, road shoulders, and downstream banks from erosion. A riprap blanket 1½-foot thick was also placed between the bearing beams, as well as 4 feet upstream and 6 feet downstream from the foundations (figure A130c).

Cost: $58,000 in 1991.



END VIEW

SCALE: 3/8" = 1'



SIDE VIEW

SCALE: 3/8" = 1'

STRUCTURAL EXCAVATION
(APPROX. 102 C.Y.)

NOTES:

1. EXCAVATION FOR ABUTMENTS AND PRECAST CONCRETE PILING (GRADE BEAMS) SHALL BE IN ACCORDANCE WITH SPECIFICATION SECTION 206.

2. ALL SURPLUS MATERIAL SHALL BE DISPOSED OF, ON SITE, AS DIRECTED BY THE ENGINEER.

3. THE CONTRACTOR SHALL MINIMIZE THE DISTURBANCE OF NATIVE MATERIAL UNDER THE ABUTMENTS AND GRADE BEAMS. RECOMPACTION OF DISTURB MATERIAL SHALL BE TO THE DENSITY OF THE NATIVE MATERIAL.

4. ALL CONCRETE FOR ABUTMENTS AND CAST–IN–PLACE SLAB SHALL MEET THE REQUIREMENTS OF SPECIFICATION SECTION 552. CONCRETE SHALL BE CLASS A WITH A 28 DAY COMPRESSIVE STRENGTH OF NOT LESS THAN 3,500 PSI.

5. EXPOSED SURFACES ON ABUTMENTS SHALL RECEIVE A CLASS 2, RUBBED FINISH.

6. CURING OF ABUTMENTS AND DECK SHALL BE DONE WITH THE USE OF CURING COMPOUNDS.

7. REINFORCING STEEL SHALL MEET THE REQUIREMENTS OF SPECIFICATION SECTION 554 AND SHALL BE THE SIZE AND SHAPES SHOWN ON THE REINFORCING DETAIL SHEET.

8. PAYMENT FOR REINFORCING STEEL IS INCIDENTAL TO ITEM 552.

U.S. DEPARTMENT OF AGRICULTURE
FOREST SERVICE
R–8
SOUTHERN REGION

Drawn
Design
Checked
Reviewed

Forest: NATIONAL FORESTS IN FLORIDA
OSCEOLA R.D.

Project Name: DEEP CREEK CROSSING
FDR 237

Sheet Title: ABUTMENT DETAILS

Scale: AS SHOWN

Sheet 6 of 8

Figure A130a 1990 contract drawing, side view.

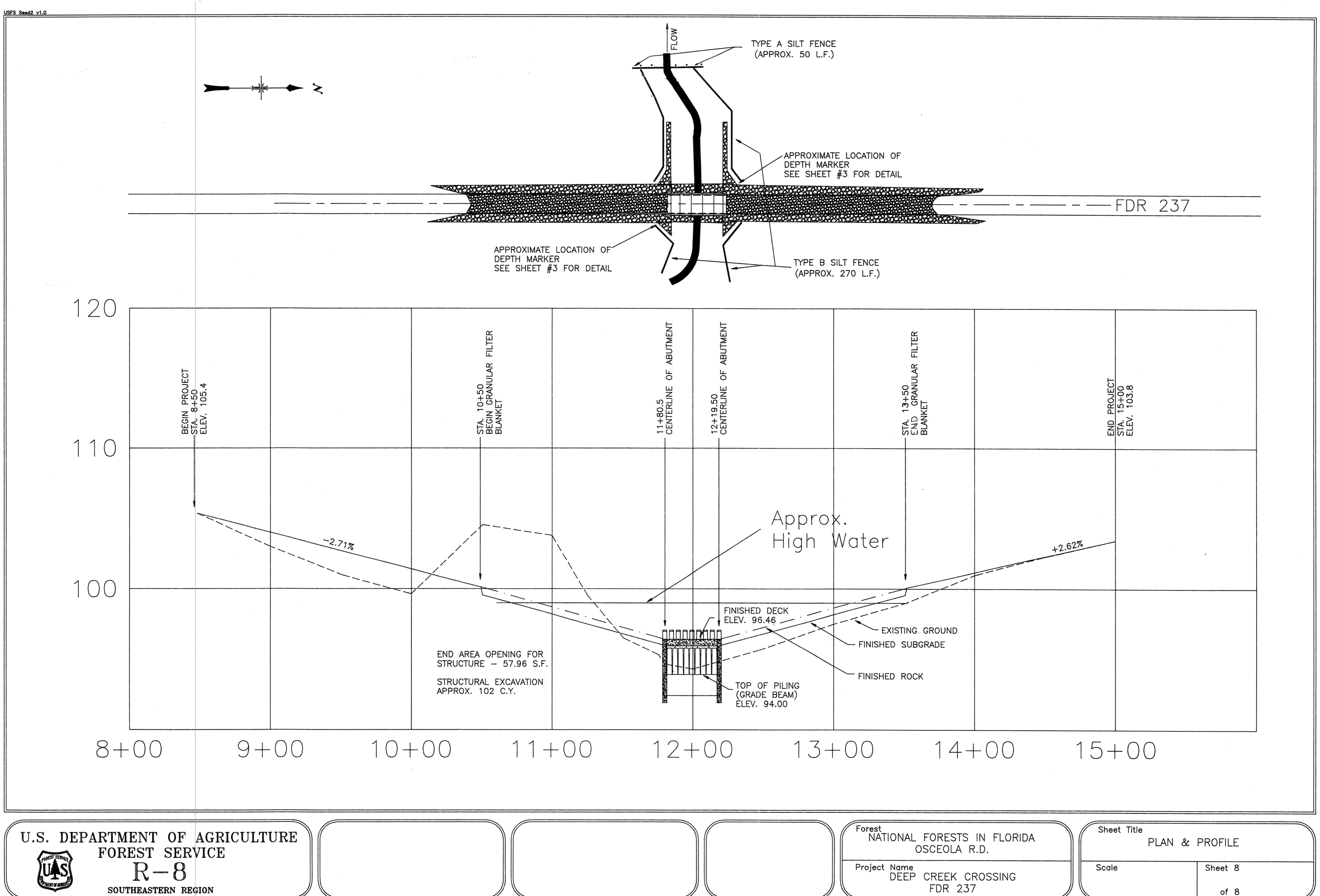


Figure A130b. 1990 contract drawing, plan and profile.

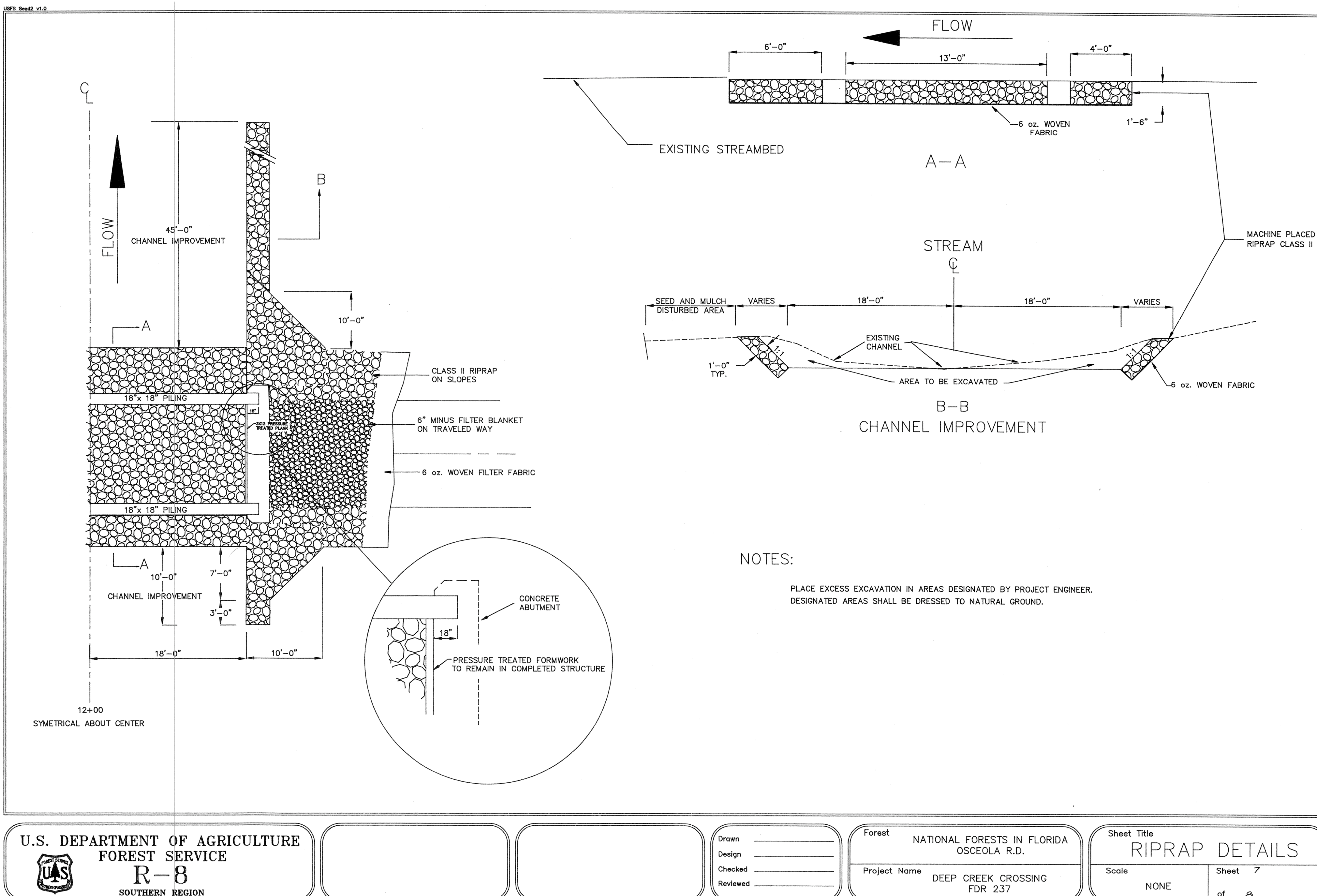


Figure A130c. 1990 contract drawing, riprap and channel improvement.

Safety: On each edge of the bridge large, bright-yellow numbers painted on 7-foot-high wood posts indicate water depth over the structure (figure A129). Flooding and fords are both common in the very low relief Flatwoods area, and residents are used to submerged roads, so no other warning signs are considered necessary here. Discontinuous curbs also provide security.

Flood and Maintenance History

The low-water bridge was constructed in 1991 and has been overtopped regularly. No maintenance has been required, although the two outer openings between T-sections are partially plugged. Because high flows can freely access the flood plain, the bridge survived large floods in 1994 and 1997 without any need for maintenance. Both of these floods caused significant damage to other structures in the area.

Figure A131. Sand and silt deposit downstream of the bridge (2003).

Summary and Recommendations

The current low-water bridge was constructed to match existing site channel dimensions. Site width was significantly wider than the natural channel due to the impacts of the previous bridge and subsequent all-terrain vehicle crossing. Sediment deposition is occurring both upstream and downstream as the stream adjusts to regain its normal width (figures A128 and A131). Given the availability of alternative access, it may be acceptable to allow this process to progress until sediment transport capacities are equalized with those in the adjacent channel. Channel narrowing can be expected to cause a few more days of traffic interruption per year.

Tommy Spencer, resources staff, and David Johnson, road manager, (Osceola National Forest) and Kathy O'Bryan, transportation systems engineer, and Will Ebaugh, hydrologist, (National Forests in Florida) contributed information and photos for this case study.

Case Study 21. Capps Low Water Bridge

Location

North central California. El Dorado National Forest, Placerville Ranger District. North Fork Cosumnes River. Meiss Cabin Road, Primary Forest Route 52.

Crossing Description

This low-water bridge was constructed in 1998 as an Emergency Relief for Federally Owned Roads (ERFO) project (figure A132). It replaced a vented concrete slab ford that plugged and caused substantial channel and flood plain damage during the 1997 flood. Because the old ford blocked sediment transport during high flows, it had caused dramatic channel aggradation and flood plain erosion. To reestablish channel stability at the site, the designers decided to bridge the entire flood plain, and to provide for overflow in case of debris jamming. The bridge has 13 concrete piers set on bedrock and the deck is square steel tubing with two smooth steel plate runways.

Figure A132. Looking downstream at the Capps low-water bridge. July 2002.

Setting

Sierra Nevada Section (M261-E). Rocks are mixed granitic, volcanic, and metasedimentary. Ponderosa pine and mixed conifer forest. Riparian vegetation includes cottonwood, alder, willow, dogwood, and cedar.

Why Was This Structure Selected?

The forest considered relocating the road, but nearby archeological resources and private property eliminated relocation as a feasible alternative.

This crossing structure was expected to accomplish the following objectives.

- Remove the sediment transport blockage associated with the old crossing structure and allow stream processes to restore a more nearly natural channel size, shape, and substrate.
- Provide room for the channel to migrate within the flood-prone area.
- Provide passage for aquatic organisms.
- Reduce the need for maintenance.

Crossing Site History

Historically, this road was a stagecoach route across the Sierra divide. It forded the North Fork Cosumnes River at this location, and probably widened the channel by breaking the banks down. Sediment deposited in the widened channel and flood flows were diverted across the rutted flood plain. With time, the flood plain progressively lowered in elevation as floods washed more material away.

Subsequent ford improvements did not solve the problem. The structure that existed prior to the 1997 flood of record was a concrete slab with an 8-foot-wide concrete box culvert, which filled with bed material and needed annual cleaning even during normal years. During floods, the ford plugged and flow spread over the flood plain, eroding and changing channel location, and washing out the road approaches. To reopen the road after floods, onsite stream-deposited material was routinely heaped up into a turnpike across the eroded flood plain, topped with an aggregate base, and either paved or oiled. This practice, combined with erosion during floods, explains why the flood-plain surface at the crossing site is several feet lower than in adjacent sections upstream and downstream of the site. Because of the widened section, sediment deposition was a serious problem, and the channel became so embedded it seemed to be paved. The vented ford washed out in 1997, during the flood of record (figure A133).

Figure A133. Capps ford after the 1997 flood. Flood flows spread out across the entire valley and road is washed out on far side.

Road Management Objectives

Forest Route 52 is maintained for passenger cars (maintenance level 3), and is used for recreation, timber haul, administrative access, and access to private land. Occasional closures due to severe weather are acceptable, but dependable summer seasonal access is required. There is little or no winter use.

Stream Environment

Hydrology: Large floods occur on the North Fork Cosumnes River during rain-on-snow events. The approximately 15 square mile watershed was mined in California's gold rush days, and early roads followed the intermittent streams up each tributary draw. (Crossing structures on these tributaries are described in case study 13.) Current roads are located on both sides of many of these draws, and are in only moderate condition. Loose bed material is readily available to all these streams because of these disturbances, and when flows rise, bedload transport can be very high. Blocking sediment transport with a ford is a particularly bad idea in this system.

Channel Description: At the crossing site, the channel is best described as a Rosgen C3 because of channel widening and flood plain modifications due to the crossing. It is a B3 or B4 upstream and downstream (figure A134), with some bedrock-controlled sections. Bankfull width is between 20 and 30 feet. The low terrace adjacent to the natural sections of the river has been lost at the crossing site, and the bridge crosses a 300-foot flood plain that is about 2 to 3 feet lower than the ground adjacent to the stream elsewhere. Even in undisturbed upstream reaches, abandoned channels and side channels are evident across the valley bottom. Clearly the stream is dynamic and prone to shifting across the valley floor.

Figure A134. Downstream view of Capps bridge showing cobble bars and debris in channel.

Because the previous structure obstructed sediment transport, bed material at the site was much finer than in up- and downstream reaches. Cobble-embeddedness was very high. The new structure has allowed fines to migrate through, opening up the cobble bed again, and improving fish habitat.

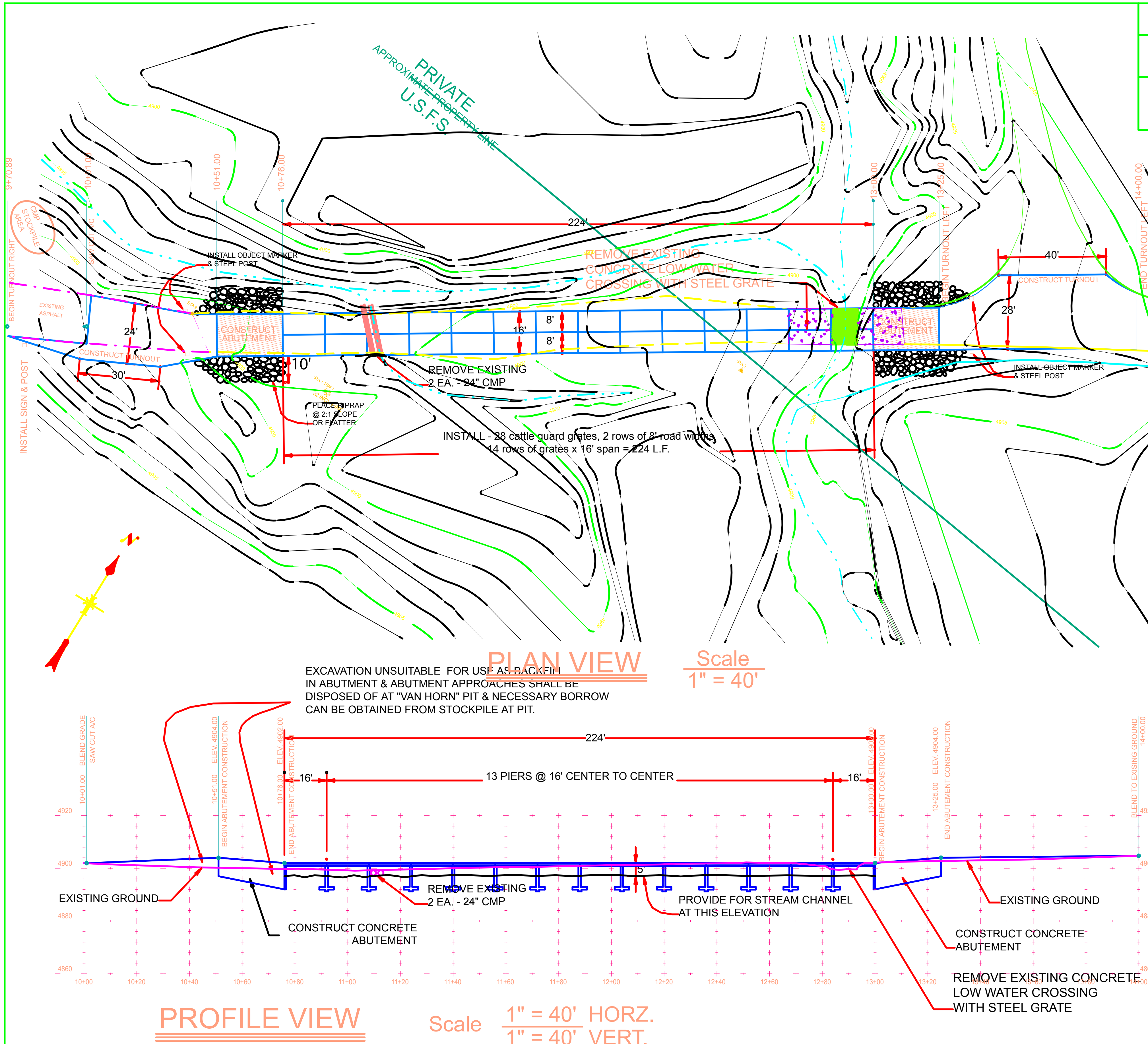
Aquatic Organisms: This structure provides passage for all species, at all life stages. By providing for free downstream transport of bed material and wood, the structure is also working to maintain downstream and onsite stream habitats. Foothill yellow-legged frogs, tree frogs, western pond turtles, and trout are among the aquatic species that are likely to use these habitats.

Water Quality: This structure was designed to restore channel functions and it helps maintain good water quality by reducing channel and bank erosion.

Structure Details

Structure: The Capps low water bridge is 224 feet long, with 13 piers spaced on 16-foot centers. The piers are up to 12 feet deep to reach

PROJECT	SHEET NO.
Capps Crossing ERFO	3 of 8
PLAN & PROFILE	



LEGEND:

- MAJOR CONTOURS
- MINOR CONTOURS
- CENTERLINE DRAINAGE
- EDGE PAVED ROAD
- EDGE AGGREGATE ROAD
- EDGE DIRT ROAD
- APPROXIMATE PROPERTY LINE
- CONTROL POINTS

0 20 40 80 120
SCALE IN FEET

GENERAL NOTES:

SPECIFICATIONS: CONSTRUCTION - U.S.FOREST SERVICE GENERAL PROVISIONS & STANDARD SPECIFICATIONS FOR CONSTRUCTION OF ROADS & BRIDGES, 1985 EDITION WITH ACCOMPANYING SPECIAL PROJECT SPECIFICATIONS.
DESIGN LOAD : HS 20-44.

CONCRETE: CLASS "A" CONCRETE WITH A 28 DAY MINIMUM COMPRESSIVE STRENGTH OF 3500 P.S.I. AND SHALL BE VIBRATED. EXPOSED CORNERS SHALL BE CHAMFERED 3/4". ALL VERTICAL SURFACES SHALL BE FORMED. ADDITIVES CONTAINING CALCIUM CHLORIDE SHALL NOT BE USED. AIR ENTRAINMENT SHALL BE 4 % TO 7 %.

REINFORCING STEEL: REINFORCING STEEL SHALL CONFORM TO AASHTO M31 (ASTM A-615), GRADE 60. MINIMUM COVERING TO FACE OF DIMENSIONS SHOWN RELATING TO SPACINGS OF REINFORCING STEEL ARE TO CENTER OF BARS UNLESS OTHERWISE SHOWN. MINIMUM COVERING TO THE FACE OF ANY REINFORCING BAR IS 2" UNLESS OTHERWISE SHOWN. WHERE CONCRETE IS PLACED AGAINST EXISTING SOIL THE MINIMUM COVERING SHALL BE 3".

STRUCTURAL STEEL: ALL STRUCTURAL STEEL EXCEPT THE FORMED RAIL SECTIONS SHALL CONFORM TO ASTM DESIGNATION A-36. FORMED RAIL SECTIONS SHALL CONFORM TO ASTM DESIGNATION A-441. ANCHOR BOLTS AND NUTS SHALL CONFORM TO AASHTO M 314-90. ANCHOR BOLTS & NUTS SHALL BE ZINC COATED BY HOT DIP OF MECHANICAL DEPOSITION. ALL WELDING SHALL BE DONE IN CONFORMANCE WITH THE LATEST EDITION OF THE AMERICAN WELDING SOCIETY SPECIFICATIONS FOR WELDED HIGHWAY & RAILROAD BRIDGES. ALL STRUCTURAL STEEL EXCEPT ANCHOR BOLTS SHALL BE PAINTED WITH ONE COAT OF RUST INHIBITIVE METAL PRIMER AND ONE COAT OF FOLIAGE GREEN BRIDGE PAINT, AASHTO M-67.

HYDROLOGY: DRAINAGE AREA = 9 SQ.MI.

Figure A135. Site plan and cross section for Capps Crossing replacement project.

bedrock. The deck consists of 16-foot-long sections of box iron grating 16 feet wide. Steel beams support the rectangular steel tube decking. The 25-foot-long concrete abutments slope down to the deck at 8 percent (figure A135).

Bank stabilization and approaches: Riprap placed at the two abutments provides protection against scouring. Near the abutment in the active channel, large long rocks were placed at an angle to help turn flow toward the middle of the stream, away from the abutment and banks. Other than the riprap, the banks will be allowed to stabilize naturally.

Cost: $300,000 in 1997.

Safety: Early cold weather in this area makes icing a hazard while the road is still open. Wooden guard rails were added to keep vehicles from sliding off the roadway (figure A136). Safety signing is limited to type III object markers on the ends of the bridge.

Flood and Maintenance History

On January 1 2006, the bridge underwent a flood estimated to have an 85-year return interval. Large amounts of debris were caught under and on the bridge, and sediment accumulated around the structure as a result. Perhaps due to sediment accumulation upstream of the bridge during the flood, flow spread over the entire flood plain and has concentrated into two principal channels, one on either side of the flood plain. Maintenance work will include debris removal and in-channel work to confine low-flow to a single channel and remove some sediment deposits.

Figure A136. Note concrete abutment with riprap, grating with tire runways, and wood curbs.

Summary and Recommendations

This site presents challenges for crossing structures because historic disturbances in the drainage--combined with recent floods--mean that very large amounts of boulder and cobble-sized material are available for transport during high flows. The bridge is an appropriate structure type for this disturbed site because it minimizes interruption of sediment and debris transport and should permit the channel to stabilize over time.

This low-water bridge is a solid heavy duty structure that is expected to sustain flooding well. In retrospect, forest personnel believe it would have been advisable to space the piers at a distance equivalent to the current active channel width to minimize the potential to block floating wood debris.

Ken Pence, engineering technician (retired); Cheryl Mulder, zone hydrologist; David Jones, engineer; and Richard Adams, facilities engineer from the Eldorado National Forest provided information for this case study.

Similar Structures In Other Locations

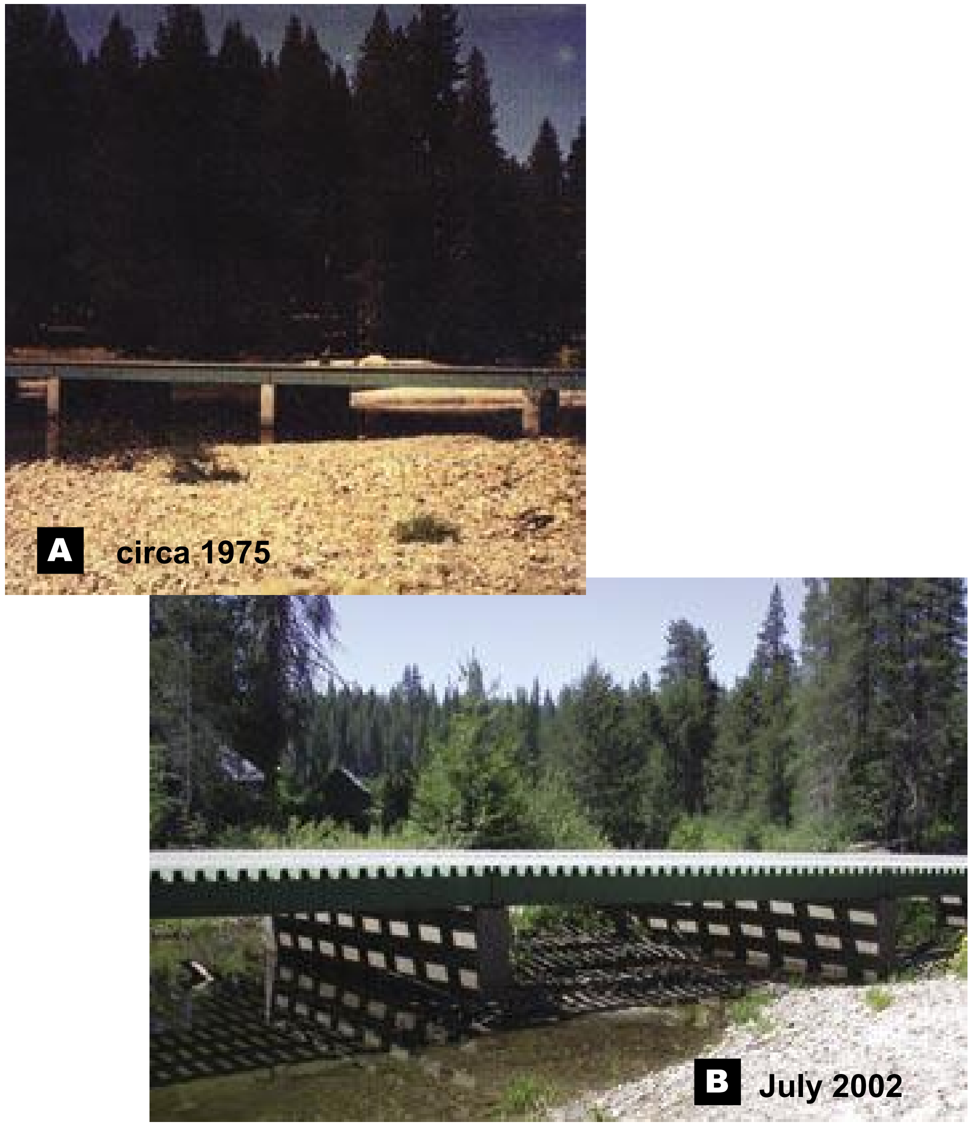
The Eldorado National Forest had experience with low-water bridges before constructing one at the Capps crossing in 1997. A very similar structure has been in existence since 1971 where the Jones Wreckum road crosses Jones Fork of Silver Creek. Originally, the crossing was probably an unimproved ford. It accesses private property.

The site is at about the same elevation as Capps, and has a similar runoff regime. According to Steve Brink, the designer, flow at this site fluctuates from 15 feet wide and 1-foot deep to 180 feet wide and 5-foot deep (Brink 1974, 2000). Crossing objectives were to support log haul and recreation, provide for free fish passage during low flows, protect good trout spawning habitat up- and downstream, and avoid flow obstructions that might cause channel shift. This bridge was designed to pass 80 percent of the estimated 100-year flow under the deck. It was overtopped the first winter without damage or any need for maintenance. It has since been overtopped at least three times, and the only maintenance on record is removal of woody debris.

The bridge rests on 10 concrete spread footings placed 5 feet below the streambed surface. The approach slabs have cutoff walls 5 feet below the streambed and were riprapped. The deck consists of twenty 8-foot by 16-foot cattleguards.

Figure A137. Looking downstream at Capps bridge with debris trapped under deck, 1988.

This reach is flatter than Capps, bed material is finer (coarse gravels about 1 to 1½ inch), and the channel appears to be more stable. The bridge is located just upstream of a right-angle bend in the river and crosses the point bar leaving enough space for natural adjustments in sediment storage. Woody debris trapped under the bridge on the point bar side has not been removed, and has contributed to sediment accumulation (figure A137). Both upstream and downstream bars have enlarged since the 1970s (figures A138a, A138b). Nonetheless, comparing current channel conditions to Brink's 1974 description, the channel does not seem to have changed much, indicating that the stream is functioning naturally and is stable. None of the pier footings are exposed.



Figures A138a and A138b. Looking downstream at the Jones Wreckum Bridge. A138a. Bridge inspection photo.

Appendix B—Site Investigation Form

Hydraulic Structure—Initial Site Examination Form

The site examination form is intended for use at sites where a new or replacement crossing structure is being planned, whether a bridge, low-water crossing, or significant culvert. The form can be used as a checklist to ensure the basic information needed for preliminary site assessment is collected. Although it is simple, a completed form assembles a good amount of site information for structure selection and design. Accurate site surveys, including channel longitudinal profile and cross sections, are also necessary to complete the design.

For simple sites, this information may be adequate for design. Complicated sites will usually require additional field surveys and site investigations.

HYDRAULIC STRUCTURE

INITIAL SITE EXAMINATION FORM

(DATA SHEET FOR FORDS, BRIDGES, AND CULVERTS) (INCLUDE SITE SURVEY, LONGITUDINAL PROFILE, AND CROSS SECTIONS)

FOREST		ROAD (TRAIL) NAME	
STRUCTURE NAME		STREAM NAME	
STRUCTURE NUMBER	LOCATION SECTION	TOWNSHIP	RANGE

A. HYDROLOGIC & HYDRAULIC DATA

1. SHOW ON A 15 MINUTE TOPOGRAPHIC MAP DRAINAGE AREA	2. NAME OF CLOSEST GAUGING STATION DISTANCE. MILES	
3A. MANNING'S ROUGHNESS COEFFICIENT (N)	3B. AVERAGE STREAMBED SLOPE 500-FT UPSTREAM: 500-FT DOWNSTREAM:	
4. DESCRIBE CHARACTER OF STREAM BED MATERIAL AND STREAM BANKS WITHIN THE 1,000-FOOT AREA		
5A. AMOUNT OF DEBRIS IN CHANNEL	5B. TYPE OF DEBRIS	
6. WATER ELEVATONS		
6A. DATE AND FLOW DEPTH AT TIME OF SURVEY	6B. ESTIMATED BASE FLOW DEPTH OCCURS MONTH	6C. ESTIMATED EXTREME HIGH WATER DEPTH (HOW DETERMINED?)
6D. CAUSE AND SEASON OF FLOODS		

B. OTHER CHANNEL CHARACTERISTICS

1. NOTE EVIDENCE OF INSTABILITY OF BANKS OR SCOUR	
2A. STRAIGHT CHANNEL, OR NOTE DEGREE OF SINUOUSITY	2B. HIGH FLOW ANGLE OF APPROACH (PARALLEL OR IMPINGING?)
3. CHANNEL STABILITY (AGGRADATION, DOWNCUTTING, LATERAL CHANNEL MIGRATION, ETC)	
4. CHANNEL CLASSIFICATION (ROSGEN OR OTHER)	
5. CHANNEL ENTRENCHMENT (RATIO = FLOOD-PRONE/BANKFULL WIDTH)	
6. UPSTREAM/DOWNSTREAM STRUCTURES AFFECTING SITE (DAMS, BRIDGES, ETC.)	
7. OTHER SITE ASSESSMENT FACTORS	

C. FOUNDATION CONDITIONS

1. CHARACTER OF SURFACE OR LOCAL MATERIALS	
2. ESTIMATED DEPTH TO BEDROCK FEET	2A. BEDROCK TYPE AND CONDITION
3. ANY SPECIAL FOUNDATION CONDITIONS? INVESTIGATION NEEDED? EXPLAIN	

D. EXISTING STRUCTURE

1. TYPE OF EXISTING STRUCTURE	1A. NUMBER AND LENGTH OF SPANS	1B. TYPE OF CULVERT	1C. SIZE
2. WATERWAY OPENING FEET WIDE OR SQUARE FEET		2A. WATERWAY ADEQUATE? ☐ YES ☐ NO	
3. STRUCTURE AFFECTED BY DEBRIS ☐ ICE ☐ DAMAGE ☐ SCOUR ☐		4. DOES STRUCTURE CONSTRICT THE NATURAL CHANNEL YES ☐ NO ☐	
5. CONDITION OF EXISTING STRUCTURE			

E. PROPOSED STRUCTURE

1. BRIDGE OR LOW-WATER CROSSING TYPE	1A. LOADING (JUSTIFY IF OTHER THAN HS 20)
1B. WIDTH	1C. SUBSTRUCTURE OR SPECIAL NEEDS
2. TYPE OF CULVERT	2A. SIZE
2B. CULVERT DESIGN ISSUES?	
2C. CORROSION OR ABRASION CONCERNS?	2D. TYPE OF FILL MATERIAL TO BE USED

F. MISCELLANEOUS DATA

1. TIME AND DURATION OF CONSTRUCTION SEASON	2. RIPRAP IS AVAILABLE YES ☐ NO ☐	2A. DISTANCE FROM SITE AT MILES
2B. DESCRIPTION OF RIPRAP MATERIAL		
3. TRAFFIC CONTROL AND SAFETY NEEDS		
4. ROADWAY ALIGNMENT AND GRADE (ADEQUATE?)		
5. CHANNEL OR STRUCTURE ALIGNMENT CHANGES RECOMMENDED (SHOW ON COPY OF SITE PLAN)		
6. ARE DIKES OR BANK PROTECTION REQUIRED TO CONTROL FLOW (SHOW ON COPY OF SITE PLAN)		
7. DESCRIPTION OF ON-SITE CONSTRUCTION MATERIAL TO BE USED		
8. STORAGE AND/OR WASTE AREAS AVAILABLE FOR CONSTRUCTION (LOCATION, SIZE, AND DESCRIPTION)		
9. WHAT IS THE MAXIMUM LENGTH OF GIRDERS THAT CAN BE HAULED TO THE SITE? FEET		
10. METHOD OF CONSTRUCTION CONTRACT ☐	FORCE ACCOUNT ☐	TIMBER PURCHASER ☐
11. OTHER REMARKS AND SPECIAL RECOMMENDATIONS		

G. FISH AND OTHER WILDLIFE PASSAGE CONSIDERATIONS

1A. IS FISH PASSAGE REQUIRED? YES ☐ NO ☐	1B. IF YES, WHAT SPECIES AND LIFE STAGES?	2. IS PASSAGE FOR OTHER SPECIES REQUIRED? (TERRESTRIAL, CRAWLING, SWIMMING) YES ☐ NO ☐ WHICH?
3. SPECIAL/IMPORTANT CONSIDERATIONS FOR HABITAT PROTECTION?		
4. FOREST BIOLOGIST RECOMMENDATIONS		

PREPARED BY:	**DATE**	**FOREST ENGINEER REVIEW:**	**DATE**

FIELD SITE SKETCH, LONGITUDINAL PROFILE, AND CROSS-SECTIONS

Adapted From: Form R5-7700-71

Appendix C—Rosgen Channel Types

These illustrations are reprinted by permission from Rosgen 1996.

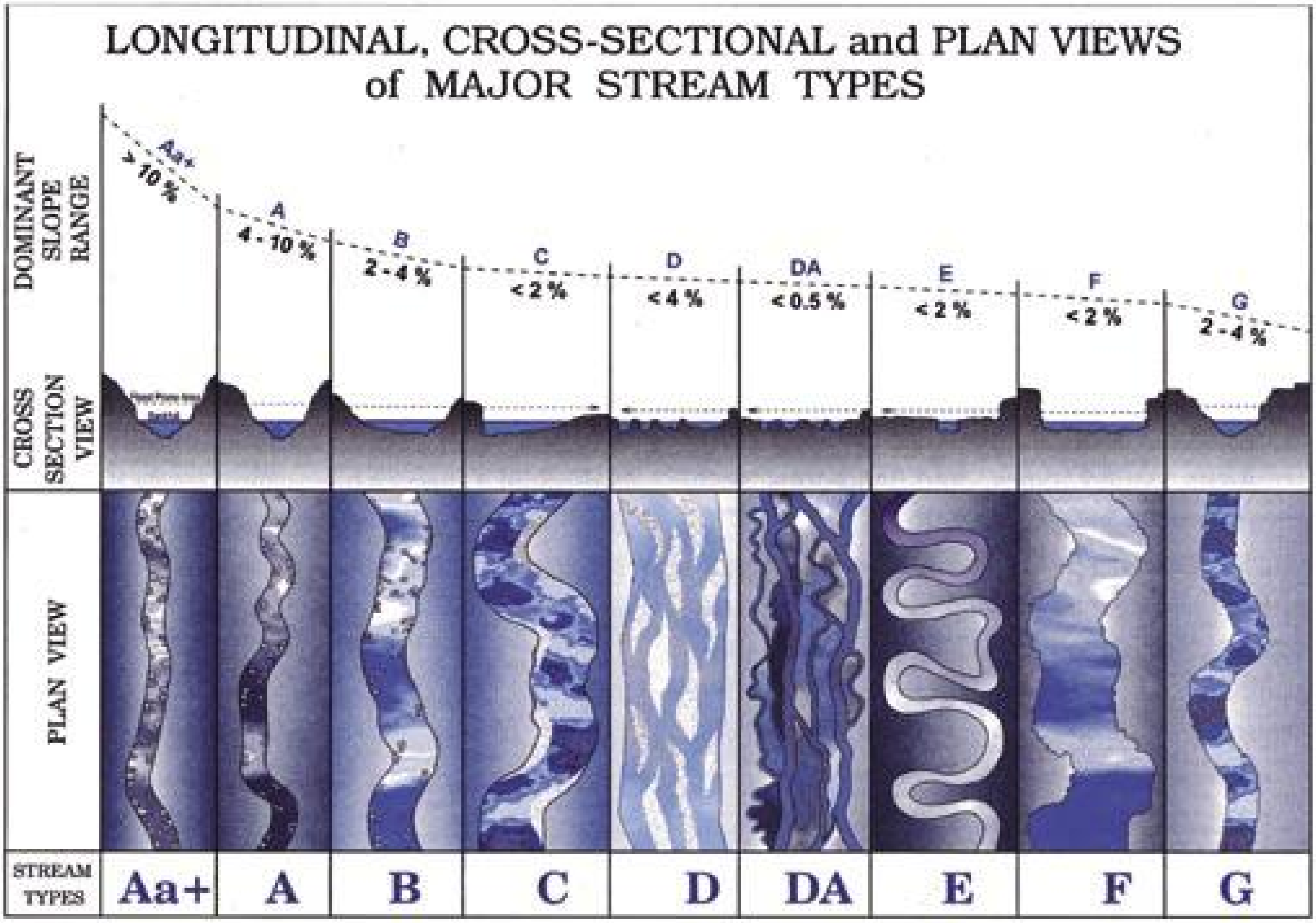


Figure C-1 illustrates how the major stream types (A-G) are delineated based on entrenchment, sinuosity and slope ranges.

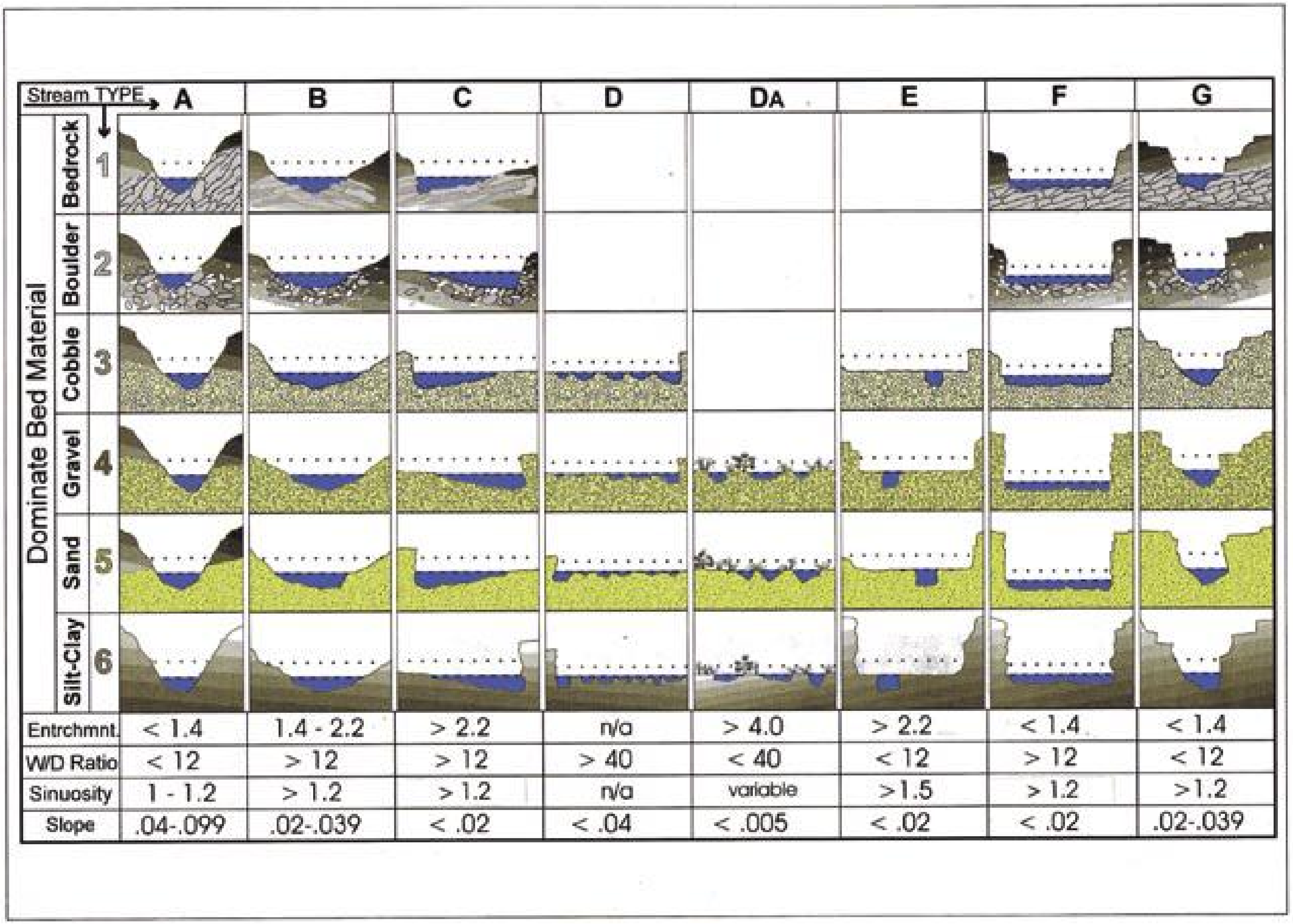


Figure C-2 shows the cross sectional forms typical of the steam types as they vary with channel materials of different size, from bedrock and boulder to silt-clay. It also indicates the values of the variables that define each stream type. (Rosgen 1996)

Appendix D—Low-Water Crossing Effects on Water Quality

Most of the small body of scientific literature about ford effects on water quality is related to sediment, the most common pollutant from road and stream crossing sources. It is quite difficult to generalize the conclusions from those papers because researchers use different methods in different studies and because of the site-specific nature of the effects. Furthermore, research is lacking that would tie ford-related sediment changes directly to impacts on aquatic species and habitats. [Numerous references summarize the effects of sediment on aquatic species and their habitats, including Bilby 1985; Bilby et al.1989; Vaughan 2002; and Furniss et al.1991.]

In an excellent summary of crossing effects on water quality, Taylor (1999) concluded that unvented fords have more effects on water quality than do culverts, and that bridges have fewer detrimental effects. The research leading to that conclusion compared suspended sediment concentrations both upstream and downstream from each crossing type on flowing streams during construction, reconstruction, and traffic use. Although results varied quite a bit, they nonetheless showed that, for culverts and fords, sediment increased downstream during active construction and occasionally during a subsequent rainfall. Traffic usually produced detectable increases downstream. The longer-term effects of fords on water quality appeared to depend on factors such as type of surfacing on the ford and its approaches, vehicle type and use level, and time since disturbance for reconstruction or maintenance, among other things (Taylor 1999).

Traffic through unimproved fords has been shown to produce sediment by several processes (Brown 1994). These processes include:

- Waves from vehicles eroding banks.
- Ruts concentrating surface runoff during storms.
- Water washing off vehicles (as they emerge from the water) eroding the approach as it runs back into the stream.

Erosion on the ford approaches can, of course, be mitigated by using best management practices (BMPs) (section 4.11).

Driving across an unprotected streambed also mobilizes sediment that is already present but would not otherwise be transported during low flows. Sample et al. (1998) showed that, compared to a natural (unimproved) ford, much less sediment appeared downstream of a hardened ford (streambed excavated and replaced with compacted rock and gravel) after vehicles crossed.

Note that these studies did not consider the potential catastrophic impacts that culvert crossings can have when culvert capacity is exceeded and the roadfill fails. Properly designed ford crossings may be a chronic impact, but do not pose the catastrophic risk of sediment inputs that culverts do.

For chemical pollutants, the situation may be different. As vehicles drive through water, oil, grease, and other chemical pollutants can wash off. Pollutants that have been identified in highway rights-of-way, which could conceivably enter the water, include lead, zinc, cadmium, and polychlorinated biphenyls (PCBs) from tire wear; asbestos, copper, chromium, and nickel from brake-lining wear; and oil and grease (Hyman and Vary 1999). The authors are not aware of any evidence that these constituents cause detectable or significant water quality problems at fords.

There is no evidence to suggest that paving a ford is likely to put water quality at risk due to petroleum hydrocarbons leaching from the asphalt. A study at the USDA Forest Service Coweeta Hydrologic Laboratory found total petroleum hydrocarbons (TPH) in very low (<0.5 parts per million) concentrations in runoff from a 2-year-old paved forest road (Clinton and Vose, 2003). (There is no surface water quality standard for TPH.)

Preliminary monitoring results from three streams on the Fishlake National Forest in Utah show how off-highway vehicle (OHV) traffic through fords affects turbidity, streambed fines, and concentrations of volatile organic compounds and total TPH (Deiter, 2006). Deiter measured downstream turbidity and numbers of vehicles crossing an unimproved ford over several years, and established a relationship between the two parameters (fig. D-1).

Turbidity attenuated rapidly with distance downstream from the Dry Creek study crossing (fig. D-2), and pebble counts demonstrated that the percent of fines in the streambed near the crossing increased after a 6-day OHV event (200 to 500 crossings). No information is available on whether the increase persisted after flushing flows or how it affected the aquatic community.

Although naphthalene and gas- and diesel-range organic compounds were detected during the OHV event, all were below levels of concern for ambient surface water. Deiter concluded that, for the hydrocarbon parameters measured, OHV traffic did not appear to cause significant damage to the aquatic environment.

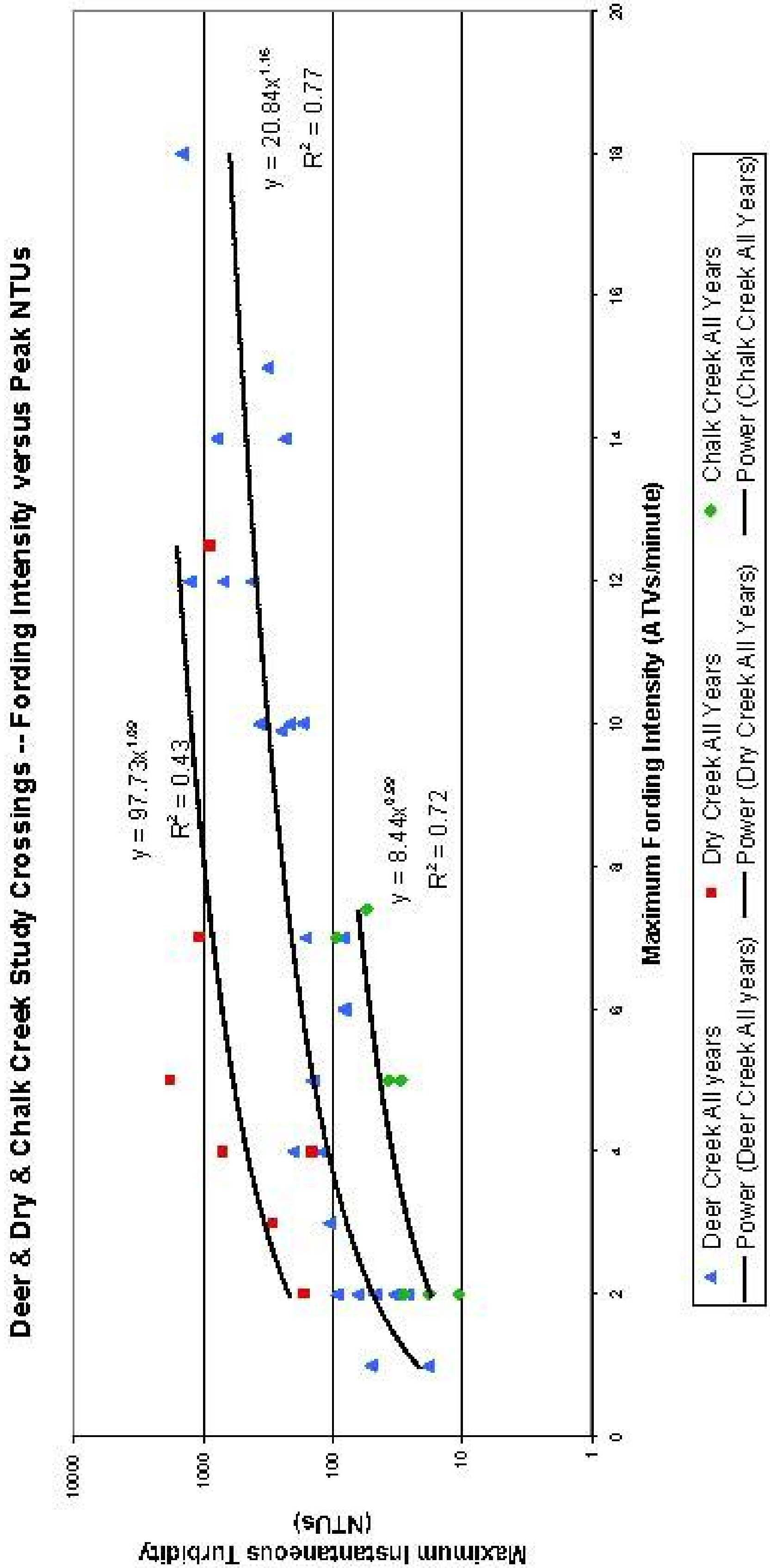


Figure D-1. Fording intensity is moderately well-related to turbidity. These data represent turbidity measurements taken as waves of riders passed the crossing at times when turbidity was at background levels (i.e., water quality was not affected by previous riders) (Deiter 2006).

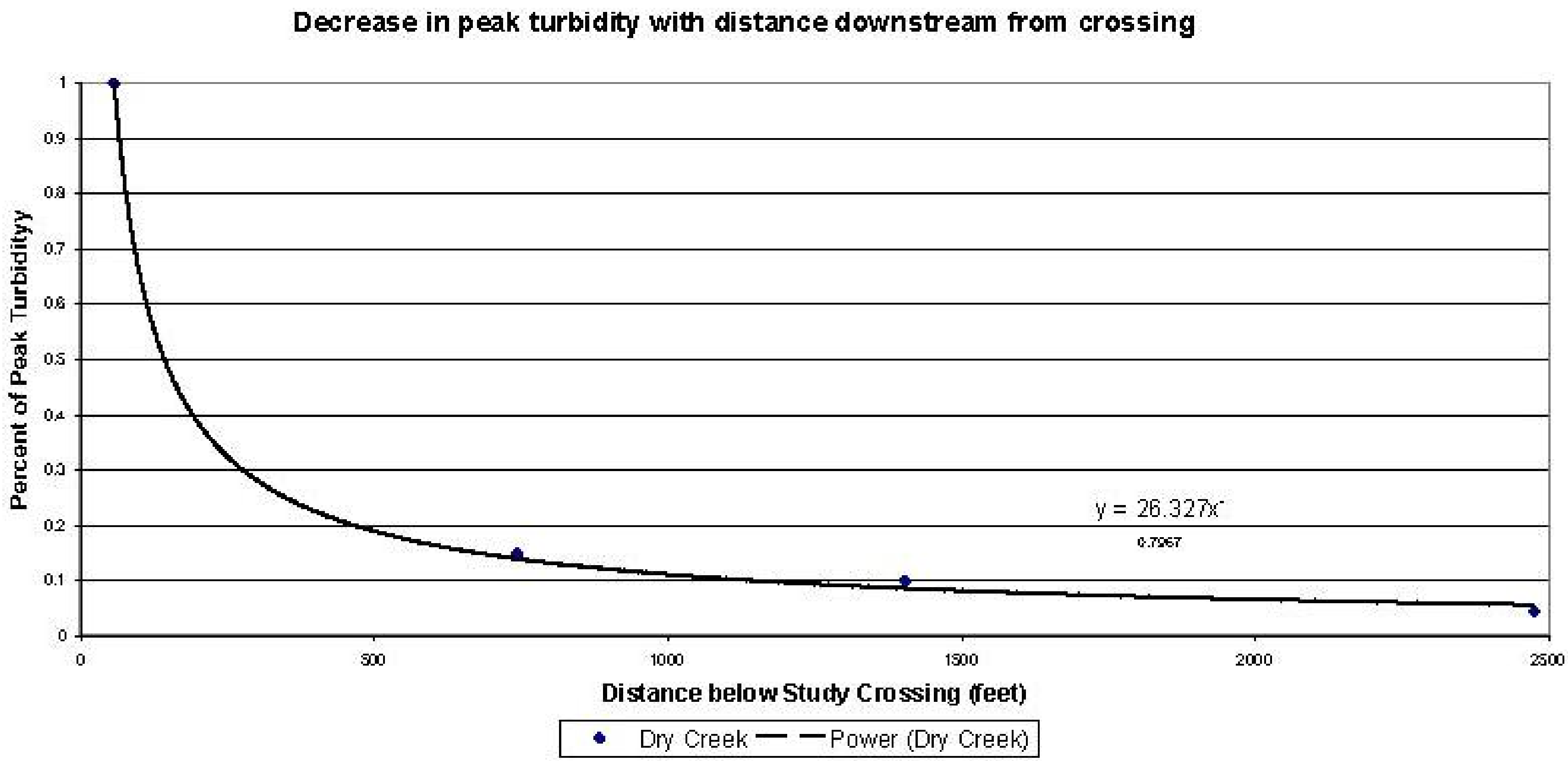


Figure D-2. Turbidity decrease with distance downstream. Dry Creek has four unimproved fords along a fairly uniform 1/2-mile length. These data represent turbidity measured at a downstream ford (the study ford) as a wave of riders crossed fords at different distances upstream. Peak turbidity data are reported as a percentage of peak observed at the study ford (study ford data shown as 100 percent). The other fords are at 750, 1,400, and 2,480 feet upstream of the study ford. (Deiter 2006)

Appendix D—Low-Water Crossing Effects on Water Quality

There are no demonstrated instances of OHVs transferring whirling disease to uninfected streams, and the likelihood of that happening is not thought to be large (Wilson 2006). However, fine sediment enrichment, such as the increase in streambed fines that Deiter did demonstrate, could improve habitat conditions for one of the hosts of whirling disease. Hypothetically, this could worsen an infection where it already exists (Wilson 2006).

Using the structure location and design recommendations in this guide will help protect water quality by properly siting a structure and then fitting it to the site. Standard BMPs also apply here (as at all road-stream crossings), and include:

- Proper crossing location.
- Timing of construction.
- Good structural design.
- Disconnecting the road from the stream by
    - Armoring approaches.
    - Draining the road to the forest floor before runoff can reach the stream.
    - Providing sediment traps or filter areas at ditch outlets

In addition, water quality protection at low-water crossings includes hardening the crossing surface itself and protecting streambanks from vehicle backwash or overflow during floods. Section 4.11 goes into more detail on long- and short-term water quality protection at low-water crossings.