

Stream Simulation

Steps and Considerations in Site Assessment

Sketch a planview map

Topographic survey

- Site and road topography.
- Channel longitudinal profile.
- Channel and flood-plain cross sections.

Measure size and observe arrangement of bed materials

- Pebble count or bulk sample.
- Bed mobility and armoring.
- Bed structure type and stability (steps, bars, key features).

Describe bank characteristics and stability

Conduct preliminary geotechnical investigation

- Bedrock.
- Soils.
- Engineering properties.
- Mass wasting.
- Ground water.

Analyze and interpret site data

- Bed material size and mobility.
- Cross section analysis.
 - Flood-plain conveyance.
 - Bank stability.
 - Lateral adjustment potential.
- Longitudinal profile analysis.
 - Vertical adjustment potential.
- General channel stability.

Document key design considerations and recommendations.

RESULTS

Geomorphic characterization of reach.

Engineering site plan map for design.

Understanding of site risk factors and potential channel changes over structure lifetime.

Detailed project objectives, including extent and objectives of any channel restoration.

Design template for simulated streambed (reference reach).

Figure 5.1—Steps and considerations in site assessment.

After verifying that the site is suitable for a crossing and will probably be suitable for stream simulation, the next step is to conduct a thorough site assessment. In this phase, you will collect the topographic and other data necessary for designing both the stream-simulation channel and the crossing structure and road approaches. Crossing-removal projects require virtually the same set of data and observations.

Interpret the additional information gathered here to predict how the structure and stream will interact, and to design a stable structure that avoids or minimizes adverse effects to the stream over the long term. Document your key considerations, findings, and recommendations. This work requires close communication among team members who are skilled in biology, geomorphology, hydrology, and engineering. A thorough understanding of channel form and **fluvial** processes—the basics of which are in appendix A—is essential for interpreting the site assessment information.

5.1 COLLECTING SITE DATA

Data collection for site assessment consists of surveying channel, valley and road topography, and tying the survey to observations of geomorphic and other features, including subsurface materials. Much of the assessment is aimed at understanding the site and the stream processes that will have to be accounted for in design of the new crossing. You need this understanding to predict channel changes expected over the structure's lifetime and design for them. Again, the level of effort and detail should correspond to the complexity of the site and the risks associated with placing a structure there.

The second goal of site assessment is obtaining a model for design of the **simulated channel**—that is, characterizing the reference reach. However, the **reference reach** must have a slope very similar to the slope of the simulated channel, and that slope will not be known for sure until the **project profile** design is complete (section 6.1.2). The actual reference reach cannot be identified with certainty until after that first design step. There are two ways to handle this logistically:

1. Enough data can be collected during the site assessment to characterize several potential reference reaches at different slopes. This avoids the need to revisit the site and collect additional data once the reference reach is selected during design (chapter 6).

Stream Simulation

2. After analyzing the project area survey and determining one or more potential slopes for the simulated streambed, identify one or more applicable reference reach(es) from the longitudinal profile, and return to the site to characterize their cross-section dimensions, **entrenchment**, bed material, etc.

Section 5.5 goes into detail on selecting the reference reach. Channel morphologic data needed for the reference reach are summarized there.

Good documentation of the field observations is essential for interpreting the survey data, and a complete sketch map is a key complement to the narrative field notes.

5.1.1 Sketch Map

Often the site sketch map will have been started during the initial site reconnaissance (section 4.4). More information should be added as site assessment progresses. The sketch map helps in evaluating road and channel alignments, and interpreting survey results. Draw the map approximately to scale, and illustrate the spatial relationship of the channel and flood plain features and their relation to the road-stream crossing. As you walk through the reach drawing the map, take the opportunity to flag **key features**, cross sections, **bankfull** elevations, **flood-prone zone** limits, etc., to ensure their inclusion in the topographic survey.

The sketch is a plan view of the **project reach**, showing:

- Channel pattern (straight, meandering, or braided). On existing roads, attempt to estimate the location and pattern of the natural channel before the road was built.
- Channel and road alignments relative to each other.
- Channel width and variations in width.
- Channel units (pools, riffles, steps, etc.).
- Valley and flood plain features, such as **side channels**, width of the flood-prone zone, evidence of past flood elevations, **terraces**, valley slopes, **abandoned channels**, etc. It is sometimes possible to use abandoned channel segments to visualize the natural channel location and **planform** through existing crossings.
- Valley features that might influence construction, such as wetlands, old roads, utilities, and property boundaries.

- Important stream features such as large boulders or bedrock, large woody debris structures, gravel bars, submerged vegetation, vegetation changes, eroding banks, on-bank trees, bank irregularities, bankfull elevation markers.
- Location of detailed measurements, such as cross sections, pebble counts, and photo points.
- Survey instrument setup locations, benchmarks.
- Possible reference reaches (see section 5.5).

(For additional information and explanation regarding constructing a site sketch map, see Harrelson et al. 1994.)

Newbury Creek Site Assessment—Sketch Map

The sketch map in figure 5.2 shows a crossing on Newbury Creek on the Olympic National Forest that we will follow through the site assessment process (figures 5.8 - 5.11 and 5.17).

The dotted lines bordering the stream channel on the sketch indicate the edges of the valley bottom, where the flatter valley surface meets the steeper side slopes. Note that the stream is closely bounded by a high terrace (GLFL) upstream of the culvert, and there are several places where bedrock is exposed in the channel. Downstream of the culvert, the valley broadens and a low terrace and flood plain (FPLT) border the channel. The crossing is located at a transition where the bedrock-controlled channel changes to an alluvial one that is less confined.

Upstream of the culvert, plane-bed segments are mixed in with pool-riffle segments (see appendix A for descriptions of these channel types). Downstream of the culvert, the channel type is pool-riffle, with riffles dominating. Gravel bars on the inside of bends are narrow (that is, little sediment is stored in the channel), and woody debris is not present in large amounts. Log weirs installed in the mid 1980s and early 1990s to increase pool habitat are both upstream and downstream of the crossing.

The road crosses the stream at a slight bend in the channel. Upstream of the road, a riprap blanket on the left bank (facing downstream) indicates there have been some erosion problems.

Later we will see how all of these observations enter into the site assessment recommendations for design.

Stream Simulation

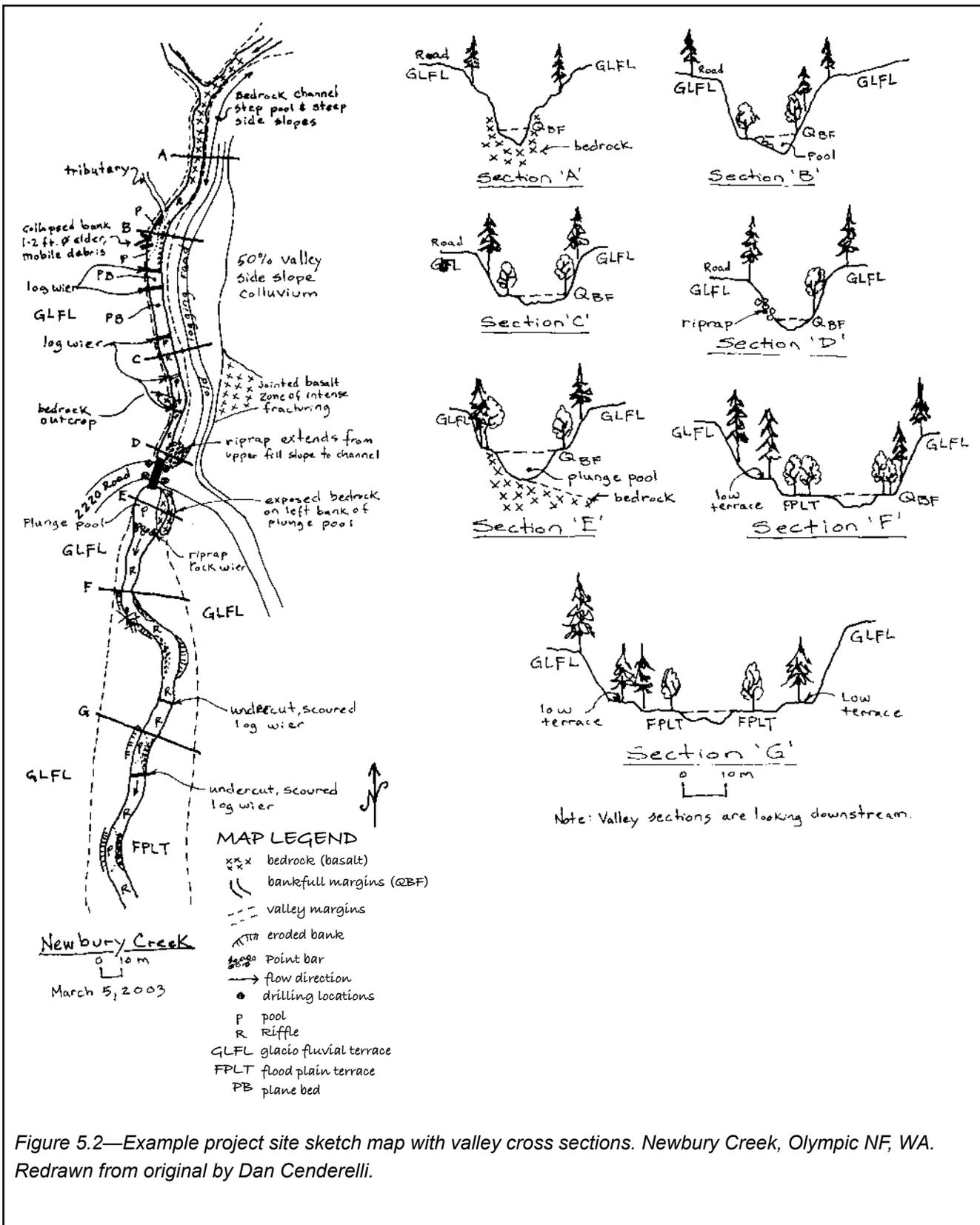


Figure 5.2—Example project site sketch map with valley cross sections. Newbury Creek, Olympic NF, WA. Redrawn from original by Dan Cenderelli.

5.1.2 Topographic Survey

The topographic survey has two overlapping objectives. It needs to include:

1. The detailed topographic data the project engineer needs to prepare the site plan, structural design, and the construction contract.
2. Geomorphic information required for designing the simulated streambed and tying it into the adjacent stream sections. Generally, this will involve a longer length of channel than traditional engineering site surveys at road-stream crossings.

Sometimes these two objectives are considered distinct from each other and two surveys are done separately. However, there are good reasons for doing a single integrated survey. First, any surveys must use the same elevation controls and benchmarks. Second, different team members have the expertise to observe different types of features and conditions. Working together on the survey is an excellent opportunity to exchange information and arrive at a common interpretation of site conditions and limitations.

This topographic survey can be seen as a standard engineering site survey expanded to include a longer reach of stream that may not be surveyed to the same level of detail. The engineering site survey is typically a radial survey in which points are not necessarily taken along straight transects. The product is a contour map. This part of the survey must extend far enough upstream and downstream from the road to support planning for alignment changes, channel restoration, and temporary road or stream diversions during construction. On the other hand, channel longitudinal profiles and cross sections, which are used for simulated channel design, are displayed as linear plots. If the radial survey covers the entire area in sufficient detail, the profile and cross sections can be generated from the digital elevation models. As the survey moves away from the worksite itself, however, it is more common to survey only those points needed for the longitudinal profile and cross sections. In either case, good notes and sketch map annotations are essential for identifying what each point is; without them the linear plots can be extremely difficult to interpret.

Topographic Survey Methods

The standard engineering site survey collects an array of three dimensional points that, when plotted, is detailed enough to create a contour map that accurately represents the landform and site features. The key is look at the terrain and visualize the locations of the points that will accurately depict the shape of the terrain, both horizontally and vertically, and then survey those points so that the topographic map accurately represents the actual terrain in the field. Be sure to include not only the obvious slope breaks in the channel, etc., but also include points that define swales and high areas in the general landform.

There are several methods accurate enough for site topographic maps:

Traverse and cross sections. One method is to survey numerous cross-sections of the channel and valley at selected locations along a traverse. Be careful using this method—a cross section must be taken at every horizontal or vertical change along the stream to accurately draw a terrain model from the cross sections. The cross section method is not as accurate as the radial survey; it works best when the landform is fairly regular.

Radial survey. The recommended method is to survey key points that are not necessarily along straight transects; instead, each three dimensional point is defined by azimuth, distance, and elevation from a control point or set of control points. The array of points defines the topography and features on the map. This type of survey usually is done with a total station, which combines a theodolite, electronic distance meter, and data storage device in the same instrument. Data collected with a total station is electronically transferred to a computer and the contour map is quickly generated using software.

Combining the radial survey with the cross-section method can be efficient when the channel survey extends beyond the area where a contour map accurate enough for site layout purposes is needed. In this case, use the radial survey close to the crossing where accuracy is more important, and survey linear cross sections further out.

During the site survey, keep good notes and annotate the sketch map. The survey includes the following work items:

- Establish two horizontal reference points for each control point. (A control point is where the survey instrument is set up.) Two reference points per control point allow the set-up location to be relocated later. Often it is convenient to locate reference points at each end of the roadway outside of the construction work area.
- Establish vertical controls using temporary benchmarks. Benchmarks should be reoccupiable during and after construction.
- Clear vegetation, but limit vegetation removal to only what is necessary for facilitating safe travel and seeing the survey target. (Avoid destabilizing banks and removing large amounts of stream cover.)
- Survey all topographic break points.
- Collect enough topographic points to accurately detail the site (both road and stream), including locations of hazard trees or trees to retain, probe/boreholes, utilities, and property lines.
- Survey channel and valley features (**thalweg**, water's edge, top and bottom of banks, foot of valley slope or terraces, key **grade control** features, steps, gravel bars, bedrock exposure, etc.) in accordance with guidance in sections 5.1.3 and 5.1.4. Take more points around bends than in tangent sections, and take points at the top and bottom of banks vertically very close together if you plan to use **HEC-RAS** or another step-backwater model.
- Ensure enough ground and stream coverage to allow for potential road or stream realignment.

After completing the field survey, most surveyors and designers use a digital terrain or contour modeling program—such as AutoCad Land Development Desktop, Terramodel, Surfer, or Eagle Point—to create a topographic map for the site. As these software packages use break lines to control the interpolation between points, topographic break points (top and base of bank, toe of roadfill, etc.) must be accurately identified and surveyed. Be sure to plot the surveyed points on the map so that the accuracy of the contour lines that the program generates can be checked. If the design engineer does not conduct the survey, (s)he should ground-proof the contour map before starting final design.

Stream Simulation

This guide does not go into further depth on standard engineering surveying procedures that are well documented elsewhere (see appendix A in USACE 2006). Instead, this guide focuses on the survey data and observations needed for designing the simulated streambed. These measurements and observations include:

- Channel longitudinal profile, key grade controls, scour depths.
- Cross-section channel geometry: top of bank, bottom of bank, etc.
- Width and elevation of valley surfaces; flood plain inundation frequency and depth.
- Streambed and bank materials.
- Channel and bank stability, sediment and **debris** processes.

5.1.3 Longitudinal Profile

The longitudinal profile is perhaps the single most valuable tool in the stream-simulation design process. It shows the natural channel gradient, the local gradient variability, the features controlling channel gradient, the depth and variability of scour, the length and spacing of **channel units**, such as pools, riffles, and steps, the length and depth of any accumulated sediment upstream from the culvert (channel aggradation), and the length and depth of channel scour downstream from the culvert (channel degradation). The longitudinal profile is necessary for determining the appropriate channel elevation and design gradient through the crossing, identifying a reference reach with a similar gradient, and determining the range of potential vertical streambed adjustment (**vertical adjustment potential**).

5.1.3.1 What and where to survey

Use survey equipment capable of 0.01-foot precision to survey the longitudinal profile. This kind of precision is required for surveying benchmarks and water surface slope. Take ground shots to tenths of a foot. Include the inlet and outlet invert of the existing structure, road fill boundaries, and the center point of the road.

Most longitudinal profiles have highly variable local slopes reflecting different channel units, such as pools, riffles, steps, and cascades (figure 5-3). The survey should include enough points to clearly delineate these

units and the **streambed structures** (steps, pool tail crests, etc) that control their elevations. As described in appendix A.5.5, these channel units typically occur in repeating sequences, with regular spacing between them. Delineating units on the longitudinal profile enables us to mimic their dimensions and spacing if channel units, such as steps, are constructed inside the culvert, and it permits us to tie the constructed streambed into the adjacent channel units. Table 5-1 lists channel points and features to survey and describe in the survey notes.

Given the importance of selecting the survey points and making accurate observations about them, the person who will be primarily responsible for interpreting the survey and designing the simulated channel should run the rod. For each survey point, identify the local channel feature (e.g., pool, riffle crest, base of step, etc.), and note other relevant characteristics, such as size, packing, shape, and stability of the particles. These notes are critical for interpreting the longitudinal profile survey later.

Generally, points for the longitudinal profile should be along the thalweg—the deepest part of the channel and the main thread of flow. However, in some channels the thalweg is substantially longer than the channel centerline. In a meandering channel, for example, the thalweg swings to the pool near the outside of each bend, and thalweg slope can be much less than slope calculated from centerline length. In such cases, survey both thalweg and centerline points, distinguishing them with separate codes. Channel slope calculations will use the centerline points.

Steep channels often have randomly distributed scour holes that are not in the main center of flow. On these channels, represent the thalweg by selecting points along the general trend of deepest flow rather than zigzagging across the channel from hole to hole. Also survey centerline points, especially at grade controls like step crests, and use the centerline distances to calculate channel slope between grade controls.

Stream Simulation

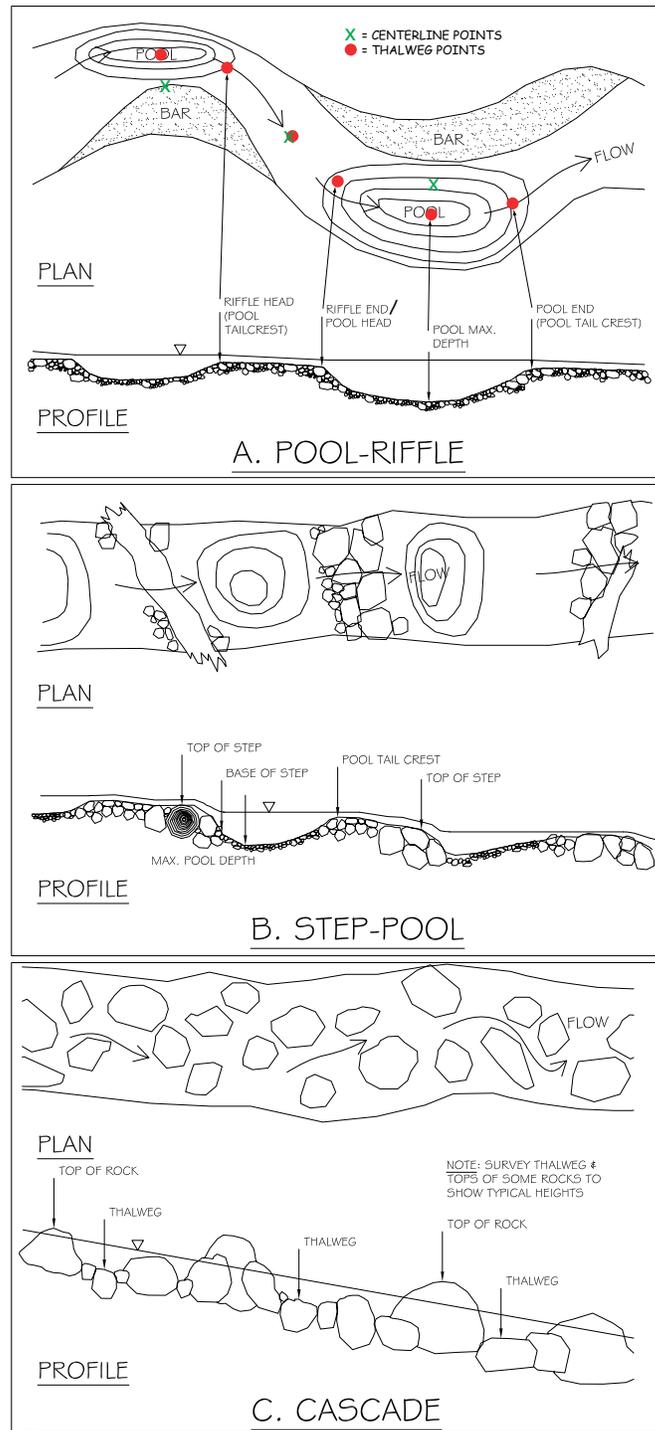


Figure 5.3—Typical measuring points needed to define the longitudinal profile for a pool-riffle channel (a), step-pool channel (b), and cascade channel (c). The plan view sketches show the approximate location of the main thread of water to survey. In the cascade channel, one would occasionally take a point on top of a rock to indicate the general height of the bed material.

Table 5.1—Longitudinal profile points and observations.

Profile points (include all major slope breaks)	Notes
Beginning (riffle head or pool tail crest) and end of riffles (figure 5.3a).	Note riffle head (pool tail crest) material, size and mobility.
Top and bottom of rock or wood steps (figure 5.3b).	Note step material, size, embedment, stability.
Beginning, end (pool tail crest), and maximum depth of pools (figure 5.3a and b)	Note what is causing the pool: a channel bend, bedrock outcrop, woody debris jam, a step formed by boulders, cobbles, woody debris, etc.
Other Features	
Features controlling grade and/or retaining sediment: large woody debris, small embedded wood, large rocks, beaver dams, etc.	Note size, durability of material, and mobility.
Changes in bed material size	May be associated with steps, embedded wood, mid-channel bars, bedrock outcrops, local aggradation above undersized culvert, etc. Characteristics like lower gradient and general lack of bed diversity distinguish aggraded areas above culverts from the rest of the channel.
Tributary junctions	Note tributary width, any sediment accumulation at junction.
Zones of bank instability	It is usually not necessary to survey these; just note their presence, height, materials, riparian vegetation, as needed.
Cross-section locations	Select cross sections along the longitudinal profile to characterize channel variations in width, depth, slope, bed material size, etc.).
Bankfull or ordinary high water elevations at various points along the profile	See box “Identifying Bankful Elevation” (section 5.1.4.2). Some jurisdictions require showing ordinary high water elevations on the site plan map.
Elevation and extent of sediment accumulation above undersized culvert	Field evidence might include gravel or sand bars. Bed may appear featureless or simplified as compared to the rest of the channel (due to burial of features).
Depth and extent of incision downstream of culvert	Field evidence might include coarser bed material than upstream of culvert; banks higher than upstream and possibly unstable; wider channel than upstream.

Stream Simulation

5.1.3.2 Length of the longitudinal profile

The profile should be long enough to display on paper the general profile of the reach, including any grade breaks. If the profile extends beyond the detailed survey area (section 5.1.2), ensure the surveys are tied together with a common datum.

At most sites, the channel longitudinal profile extends 20-30 channel widths in each direction from the culvert. Generally, this ensures the profile meets the following criteria:

- Extends well beyond the influence of the existing crossing structure.
- Includes several sequences of repeating bedforms, for example pools and riffles, to get a good representation of their length, spacing, and slope. Including the range of variability in channel slopes, scour depths, and bedforms gives you a good chance of including a segment that can be used as a reference reach.
- Extends beyond the length of stream expected to adjust (usually to downcut) when the existing structure is replaced. Crossings with large elevation drops might require longer surveys because a longer reach of stream might adjust to the crossing replacement. Wherever possible, end the survey at stable points that will limit vertical adjustment, such as bedrock outcrops or other stable features

The reference reach is discussed in detail in section 5.5. The reference reach has characteristics (most importantly slope) similar to those of the crossing segment if the road were not there. Generally, the reference reach is upstream and outside the influence of the existing crossing, and is included in the longitudinal profile. In fact the longitudinal profile is often long enough to include several options for the reference reach. In some cases, however, you may need to look for a better reference reach at some distance from the crossing. The actual reference reach will be selected later (section 6.1.3) based largely on the design slope through the crossing.

5.1.3.3 Grade controls

Grade controls are key structural features that control channel elevation and grade, dissipate flow energy, and store sediment. On different channels, these grade controls might include steps, pool-tail crests (riffle crests), bedrock outcrops, large woody debris structures, beaver dams, or debris flow or landslide deposits. In stream-simulation design, it is important to know how mobile or immobile the key grade controls are relative to the life of the crossing structure, and evaluating their stability is an important part of the survey. If grade controls are highly unlikely to move over the life of the crossing structure, even during large floods, the design can rely on a stable longitudinal profile. If the grade controls move relatively frequently, the design will need to accommodate vertical adjustment in the channel. In this context, mobile bed structures do not necessarily imply an unstable channel. For example, a stable fine gravel bed stream is likely to be highly mobile and to adjust under even moderate flows; on average, though, it retains its equilibrium dimensions and slope (see appendix A, section A.3). Evaluating bed mobility is discussed further in section 5.1.5.

Stability of these grade-control structures depends on material strength and durability, size and orientation of the particles or wood pieces, and the feature's relationship to nearby structures (table 5.2). As the survey moves along the channel, the person holding the rod should document bedform length and width, as well as particle size, packing and embedment. They should also qualitatively evaluate the stability of the bed structures relative to the lifespan of the crossing. Manmade structures like diversion dams may play the same roles as natural structures, and the possibility that such structures might be removed will also need to be considered in design.

Table 5.3 lists specific types of channel-bed structures and describes characteristics for each type that lead to a qualitative rating as high, moderate, or low stability. The table offers an example of a rating system for **key feature** stability—a system that has proved useful in Alaska. Modify the table as needed to fit your area.

In low-gradient, fine-grained channels with highly mobile streambeds, there may be no persistent grade-control structures. Any combination of channel bends, submerged and embedded wood, bank irregularities or other bank **roughness** features, for example, overhanging or submerged vegetation, may control slope and roughness.

Stream Simulation

Table 5.2—Factors contributing to channel-bed structure stability.

Material strength
<ul style="list-style-type: none">• Durable vs. nondurable rock.• Shape of the substrate – degree of angularity or roundedness.• Condition of wood (sound or decayed – degree of decay).• Diameter of wood (longevity).
Orientation and size of particles and pieces
<ul style="list-style-type: none">• Key pieces (boulder, small cobble, wood, a combination of wood and rock) are large. Logs are well-anchored in the bank, so that the stream cannot cut around the end.• Particles are imbricated and/or embedded rather than loose and readily available for transport.• Wood has roots attached.• Length of the wood in relation to stream width (logs are longer than stream width).
Relationship to other bedform structures
<ul style="list-style-type: none">• Structures are/are not subjected to undermining if adjacent structure is lost.• Immobile structures in the reach govern the extent of vertical and lateral adjustments.

Table 5.3—A qualitative method for determining channel-bed structure stability.

Structure composition	Stability Rating	Structure Characteristics
Bedrock	High	Bedrock ledges or falls span entire stream width
Boulder-cobble steps	High	Boulder-cobble steps span entire width of stream. Rocks are tightly keyed in place, and keyed-in material extends below base of scour pool below step.
Cobble-boulder or cobble-gravel pool tail crests or riffle crests	High	Cobble-boulder or cobble-gravel pool tail crests or riffle crests span the entire width of stream. Particles are tightly packed, embedded into the channel bed, and coarser than the remainder of the channel bed.
Log	High	Wood is sound and well anchored, spanning entire stream width.
Composite log and rock	High	Wood is sound and well anchored, may or may not span entire stream width. Rock pieces are well keyed in place and bridge gaps so that composite structure controls width from bank to bank.
Boulder-cobble steps, cobble-gravel steps	Moderate	Steps do not span entire width of stream or are loosely keyed in place. Keyed-in rocks may not extend below base of scour pool below step. Alternatively, step key pieces are not in contact with each other.
Cobble-boulder or cobble-gravel pool tail crests or riffle crests	Moderate	Pool tail crests span entire width of stream, but the largest particles are similar in size to those elsewhere observed along the channel bed. Alternatively, particles are moderately packed and/or moderately embedded into the channel bed.
Log	Moderate	Wood is rotten and punky. It may span entire stream width, but anchoring is susceptible to bank scour and movement during high flood events.
Composite log and rock, beaver dams	Moderate	Wood is rotten, punky, not anchored well, or does not span the entire stream width. Rock pieces are not well keyed in place and subject to movement at higher flood events. Rock bridges gaps so that structure extends from bank to bank, but there are indicators of lateral scour. Beaver dam is well constructed with a good distribution of large logs, small sticks and mud (but consider the possibility that even a stable dam could break during the life of the crossing structure).
Cobble-gravel steps or pool tail crests	Low	Steps do not span entire width of stream, and/or are composed of loosely packed materials. Pool tail crests are constructed of material no coarser than rest of stream bed.
Log	Low	Wood is very rotten and punky, may or may not span entire stream width, and anchoring is poor and susceptible to bank scour and movement during bankfull flood events. Indications of movement are visible where pieces are anchored into the bank.
Composite log and rock, beaver dams	Low	Wood is very rotten and punky, or structure is made of loosely packed pieces that are poorly anchored. Structure does not span entire stream width. Rock is small in size and subject to movement at bankfull flood events. Beaver dams are poorly constructed or old and inactive. Large key logs are not present.

Stream Simulation

Where wood is present, describe its size, condition, mobility, and function. See section 5.1.6.3 for details on describing wood in the project area and reference reach.

5.1.4 Cross Sections

Cross sections represent the channel and flood-prone area as they vary with local slope, entrenchment, materials, etc. When viewed together, the plan view map, the longitudinal profile and cross sections provide a three-dimensional perspective of valley and channel topography. Relating the cross sections to the longitudinal profile and to bed-material observations helps one understand how the channel works in terms of erosion, deposition, and sediment transport. The goal is to understand the extent and causes of variability in channel width, depth, and particle sizes throughout the reach. Data from one or more cross sections in the reference reach will be used to design the simulated streambed.

Cross sections also provide information on the height and stability of banks. The question of whether to allow upstream incision at crossings where the downstream channel has incised should always take these variables into consideration.

As with the longitudinal profile, survey channel cross sections to at least 0.1 foot. Either ensure the topographic survey is detailed enough to generate accurate cross sections from the digital elevation model, or survey the cross sections individually. If cross sections are taken outside the topographic survey area, ensure the surveys use a common datum.

5.1.4.1 Location and number of cross sections

At existing crossings, survey cross sections immediately upstream and downstream from the culvert to show the geomorphic effects of the existing crossing on channel conditions, channel and flood plain relationships, and construction accessibility. These cross sections will be important for designing smooth transitions at the inlet and outlet of the new crossing structure.

Base the number of cross sections for the project area as a whole on the variability in channel characteristics and on risks at the site. Understanding the variability in channel dimensions like width and depth is very important in properly sizing the simulated channel as well as the new structure. Channel dimensions vary depending on many factors, such as **entrenchment**, composition of the bed and banks, large woody debris, valley form, channel planform, channel gradient, and flood history. On relatively uniform channels, surveying two or three cross sections upstream and downstream from the crossing may be sufficient to adequately characterize the channel and its variability. On complex channels, to properly characterize the site, understand the risks, and provide a design template additional cross sections upstream and downstream from the crossing will be needed. Consider measuring cross sections on a representative range of channel units, such as riffles, pools, steps, runs, etc., and widths. Those measurements will provide various options for a reference reach and will help you understand the variability within the reference reach.

Be sure to cover the entire reach that may be part of the final project, including locations where you might install grade control structures or restore the channel. In some cases where the entrenchment ratio and apparent **flood-plain conveyance** are high, the designer may use a hydraulic step-backwater model such as **HEC-RAS** for quantifying flood-plain conveyance at different flood stages. If so, the designer should evaluate the terrain in the field, and locate the number of cross sections needed to accurately represent reach and flood-plain geometry in HEC-RAS.

5.1.4.2 Typical cross-section measuring points

Each cross section should include all major topographic slope breaks. Survey and describe all features (see table 5.4 and figure 5.4) that pertain to the cross section. Of these features, bankfull elevation is one of the most important.

Stream Simulation

Table 5.4—Cross-section survey points and observations.

Survey and observation points: channel (include all major slope breaks)	Notes
<i>Top and bottom of banks</i>	<i>Sediment characteristics, vegetation type</i>
<i>Channel thalweg</i>	<i>Ensure cross-section location is shown on longitudinal profile.</i>
<i>Left and right bankfull elevations</i>	<i>Defines bankfull width; allows surveyors to estimate elevation of the floodprone zone. (See textbox “Identifying Bankfull Elevation” page 5—20)</i>
<i>Left and right edges of active streambed</i>	<i>Width of channel devoid of vegetation.</i>
<i>Changes in bed and bank materials</i>	<i>Bedrock, gravel bars, colluvium, etc. Note bank stability, bank vegetation type, rooting density, and depth.</i>
<i>Undercut banks</i>	<i>Measure dimensions of the undercut bank (depth and height). Small streams with dense vegetation can have ½ to ⅓ of their area in undercuts, enough to affect discharge and sediment entrainment estimates and the simulated-channel width.</i>
<i>Left and right edges of water at time of survey</i>	<i>If you measure flow at time of survey, these measurements permit calibrating hydraulic models for the cross section.</i>
Survey and observation points: flood plain and valley bottom	
<i>Edges of flood-plain channels and terrace(s) if applicable</i>	Terrace edges, toe of valley slope, top and bottom of flood-plain channel banks, etc. To ensure good coverage of floodable areas, include the entire floodprone zone: extend the cross sections to an elevation that is double the maximum bankfull depth measured from the channel thalweg (see figure 5.5).
<i>Side channels, flood swales, vegetation type transitions</i>	<i>Note evidence of flood-plain conveyance: scour, vegetation washed away, large woody debris accumulations on the flood plain. Describe the roughness elements on the flooded area: vegetation type and density, ground debris, topographic irregularity, etc.</i>
<i>Flood high water marks</i>	<i>Fine sediment on top of vegetation; debris caught in or wrapped around shrubs or trees; flood water line on trees or other flood-plain features.</i>

Chapter 5—Site Assessment

An example of the features to include in a cross-section survey appears in figure 5.4.

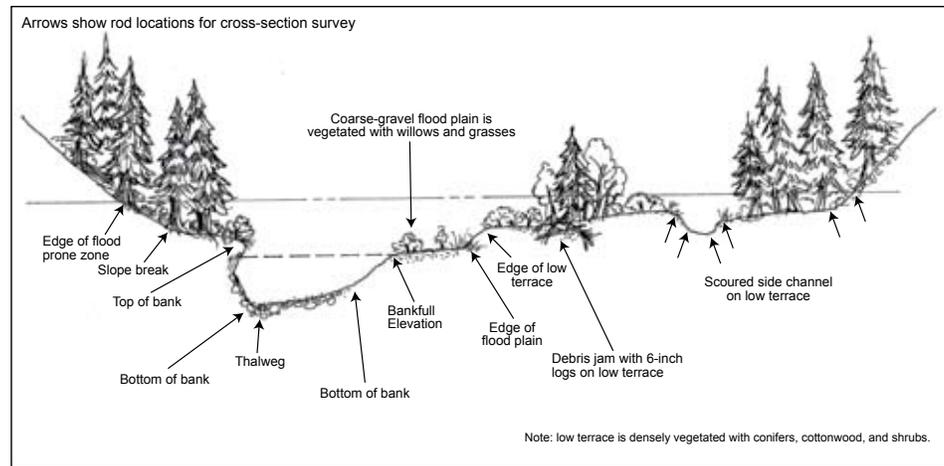


Figure 5.4—Schematic channel cross section showing recommended survey points.

Include the flood-prone area in the surveyed cross sections by extending the cross sections to an elevation that is double the **maximum bankfull depth** measured vertically from the channel thalweg (Rosgen 1996). This will encompass the frequently inundated flood plain (if one exists) and permit calculation of the entrenchment ratio (see appendix A section A.3.4). If the channel is confined or entrenched, the cross-section endpoints may be on the valley slope or a terrace.

Identify surveyed points in the survey notes, with descriptive comments. Since the cross section represents the channel segment, descriptions need not be limited to the cross-section line. The notes should describe the general character of the channel segment upstream and downstream of the cross section. They should also describe flood-plain features and characteristics, and flood-plain features should be included on the site sketch.

Understanding the interaction between the main channel and the adjacent valley surfaces is crucial in designing a crossing that obstructs flood-plain functions as little as possible. Where a flood plain is present, identify side channels, flood swales, and wetlands that should be considered during design. Make note of any indicators of recent flood elevations you find. There also may be evidence of beaver activity, rapid bank erosion, and lateral channel shift across the flood plain. Look for relict channels that

Identifying Bankfull Elevation

Bankfull elevation is the point where water fills the channel just before beginning to spill onto the flood plain. Bankfull discharge is the flow in the channel (cubic feet per second) when the water surface is at bankfull elevation. Bankfull discharge typically occurs every 1 to 2 years (Leopold et al. 1964), but its frequency of occurrence can vary depending on channel type, hydrologic regime, and watershed conditions. Bankfull is recognized as a surrogate for the range of flows that maintain channel shape and size (Emmett 2004). It is often referred to as the effective discharge of a stream: the flow responsible for moving the most sediment (Dunne and Leopold 1978) and maintaining channel form. This is why bankfull flow width is the minimum structure width required for simulating and maintaining channel form and functions through a crossing.

Strictly speaking, bankfull applies only to alluvial streams with flood plains. In alluvial stream types, use some or all of the following indicators for recognizing bankfull elevation, depending on the situation (Harrelson et al. 1994):

- Elevation of the edge of an active flood plain (flood plain may be present as discontinuous patches).
- Elevation associated with the top of the highest depositional features such as point- and mid-channel bars.
- Changes in slope on the banks [figure 5.5(a)].
- Changes in particle size of bank materials (from coarser to finer).
- Changes in vegetation types (from moss to lichens, from grass to alder, etc.).
- Stain lines on rock and scour lines in moss and lichens.

Be careful when using vegetation as a geomorphic indicator as vegetation in some channels is inundated by bankfull flows. Depositional features should be the primary geomorphic indicator for identifying bankfull flow in alluvial channels.

Not all indicators will be present at each cross section. They vary with channel type, and false or confusing indicators have to be sorted out at each site. Flagging and surveying many bankfull elevations along a substantial length of channel helps to eliminate misleading indicators and is essential for accurate identification. The ideal method for consistently identifying bankfull elevations is to plot the bankfull longitudinal profile using points where bankfull was confidently identified. Then—where the profile crosses any cross section—that is the bankfull elevation at that cross section (Emmett 2004).

In **entrenched** and nonadjustable **channels** (bedrock or strongly **cohesive materials**), **ordinary high water (OHW)** level is used instead of bankfull

for stream-simulation design purposes. OHW marks are characteristic of frequent high flows that are sustained long enough that the vegetation or bank material is distinctly different from the adjoining higher ground. OHW marks in nonadjustable channels include many of the same features in the list for alluvial channels: stain lines on rocks, high points of depositional features, and vegetation changes. In figure 5.5(b), OHW is taken as the elevation of the boundary between the moss (which survives long submergence) and woody vegetation.



Figure 5.5—(a) Bankfull elevation on an unentrenched alluvial channel. (b) Ordinary high water elevation in an entrenched coarse-grained channel without depositional features.

There are numerous guides to using channel physical features for identifying bankfull elevations (e.g., Leopold et al. 1964; Williams 1978; Dunne and Leopold 1978; Harrelson et al. 1994; Rosgen 1994; Knighton 1998). The Forest Service has produced several multimedia presentations describing the techniques and procedures for identifying bankfull flow for different channel types in different parts of the country (USDA Forest Service 2003; USDA Forest Service 2005).

Stream Simulation

may be blocked by the road fill, and consider whether they can and should be reconnected. Also note the smoothness or roughness of the flood-plain surface, because these characteristics influence the velocity of **overbank flows**. Together with entrenchment ratio and slope, roughness controls the volume of water conveyed on the flood plain (flood-plain conveyance). Figure 5.5(a) is an example of a rough flood plain, where grasses, shrubs, and trees slow overbank flows.

Field evidence of high flood-plain conveyance following a flood might include:

- Scoured flood-plain swales and side-channels.
- Scoured flood-plain surface.
- Impact scars high in trees or logs suspended above banks.
- Accumulations of large woody debris and/or sediment on flood plain.

Recognizing if and how an existing crossing has altered the natural channel's location and length can be important for correctly interpreting channel response, and designing the layout for the replacement. Often the aerial photo or the sketch map suggests the predisturbance planform. In the field, look for old abandoned channel segments, berms, or any other evidence that the channel was moved or that the culvert replaced a bend.

Cross sections also can help distinguish reaches where **channel incision** has occurred downstream of a crossing. In this case, the crossing structure is acting as a grade control protecting upstream reaches from **headcutting**, and the downstream reach may be quite different in cross section than the upstream reach. Compared to the channel upstream from the crossing, an **incised channel** downstream from the crossing may have:

- A lower **width-depth ratio**.
- Higher banks, with older vegetation higher on the bank.
- Over-steepened, failing banks.
- Cut into weathered bedrock, clay, or other nonalluvial material below the valley **alluvium**.
- A flat bed in cross section.
- No buried debris within the bed.
- Less gravel accumulation.
- Coarser bed material or a more armored bed.

5.1.5 Channel Types and Bed Mobility

Channel-type classification is a fundamental step toward understanding both current conditions and future channel changes. Classifying the channel—using both the Montgomery and Buffington and the Rosgen systems (see appendix A, section A.6)—can provide insights on the dominant geomorphic processes associated with the reach, and on the type and intensity of future channel response to a new or replacement structure, or to structure removal. For example, bedrock, cascade, and step-pool channels are **transport** channels that convey most of the sediment supplied to them and undergo minimal channel changes in response to all but very large disturbances (Montgomery and Buffington 1993, 1997). In contrast, plane bed, pool-riffle, and dune-ripple channels are **response** channels that may undergo substantial changes in response to disturbances (appendix A, table A.1).

In transport channels, the larger bed-forming rocks or logs are generally quite stable. They do not move in frequent floods, although finer bed material does move over or around them during bankfull and larger events. Because these bed structures—essential for energy dissipation—do not self-form in frequent floods, they need to be designed and constructed in the simulated streambed.

Response channel beds mobilize at flows from slightly above bankfull to much smaller flows, depending on the bed particle size and structure. For highly mobile channels, such as dune-ripple and fine-grained pool-riffle types, bed features are usually not constructed in the simulated channel, because they are expected to self-form during the first high flows after construction.

For intermediate channels, such as coarser pool-riffle and plane bed types, the frequency of bed mobility depends on such things as **armor**ing and **imbrication**. Evaluate the mobility of these channels in the field and determine whether bed structures should be constructed in the simulated channel. The decision will depend not just on bed mobility, but also on risk. In a high-risk channel—say, where the watershed has recently burned—the team might lean toward constructing bed structures to be sure energy dissipation functions are in full operation immediately.

Stream Simulation

Design of stream-simulation channel-bed material varies depending on bed mobility in the natural channel, and the bed material sampling method also depends on it. Bed mobility is a distinguishing characteristic of Montgomery-Buffington channel types and they are used in the following discussion for that reason. Appendix A describes them more fully. For channel types with intermediate mobility (the coarser pool-riffle and plane-bed types), the team should judge mobility before sampling the bed material, and select the sampling method accordingly.

5.1.6 Channel-bed and Bank-material Characteristics

Characterizing bed and bank material and structure helps the team predict how the channel might respond to disturbances in the future, or how it might recover from past disturbances.

Two other specific objectives for characterizing bed and bank composition and structure are:

1. To design bed material sizes and arrangement for the simulated streambed.

The bed-material size distribution in the reference reach is the basis for the stream-simulation bed material mix. Likewise, the size of rocks or wood making up key energy dissipation and grade control features in the reference reach is the basis for sizing any stabilizing features in the stream simulation bed.

2. To understand bed material sizes and mobility in the reach upstream of the crossing.

As bed material is eroded from the simulated channel during high flows, the upstream reach must be able to resupply similar particle sizes at similar flows. If not, the simulation will not retain its intended bed characteristics. The bed may coarsen or be washed out.

Often, both these objectives can be achieved by sampling the streambed and describing banks in the reach upstream of the crossing and outside the crossing's area of influence. However, even when the reference reach is not upstream, the team will still need to assess bed material sizes, channel roughness, and bed mobility upstream of the crossing to assure they approximate those of the reference reach. The assessment need not be quantitative, but the team should satisfy itself that the upstream reach will indeed resupply the simulated streambed.

The bed and bank characteristics that are of primary interest in stream-simulation design are those of the reference reach. One strategy for data collection is to wait until the reference reach is selected before collecting detailed data. The alternative is to take enough data, while you are already onsite studying the reach, to support several possible reference reach selections.

5.1.6.1 Sampling strategies and methods

Sediment sizes vary longitudinally, laterally, and vertically across the channel bed, reflecting the spatial variability of **channel units** (for example, channel margin, thalweg, pools, riffles), small-scale bedforms (for example, particle clusters, **transverse bars**, longitudinal bars), and bed layers (for example, armor, subarmor).

For the purpose of designing the simulation bed material, the sample should represent the entire reference reach. Be aware of the variability in particle size distribution between different channel areas along the reference reach, and sample those areas proportionally to their coverage (Harrelson et al. 1994; Rosgen 1996; Bunte and Abt 2001).

For detailed flow modeling, bed-material sampling may need to be stratified by channel units, such as pools, riffles or steps. It may take several samples to represent the range of variability present (Reid et al. 1997; Wohl 2000; Bunte and Abt 2001). Data specific to a channel-unit might be needed, for example, if a designer wants to estimate the flow that mobilizes specific grade control structures in the natural channel (see section 6.4). The number of samples needed depends on the complexity of the channel and the objective. The designer/analyst should specify the amount and type of data that is required.

This section relies heavily on information from Bunte and Abt (2001) “Sampling Surface and Subsurface Particle Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics and Streambed Monitoring,” published by the Forest Service, Rocky Mountain Research Station. The book is readily available from Rocky Mountain Research Station, Fort Collins, CO. We strongly recommend reading the many pertinent sections, especially those on sampling methods, rock size measurement techniques, sample sizes, and armoring.

Stream Simulation

Except as described below for different channel types, bed surface material is normally characterized by measuring particles in place using the pebble-count method, and sampling in a grid pattern. Measure 100 to 400 particles selected either systematically along a measuring tape or from the toe of the boot in a heel-to-toe walk (Wolman 1954; Bunte and Abt 2001). For well-sorted (poorly graded) streambeds, 100 particles are sufficient; for poorly-sorted (well graded) streambeds, up to 400 particles are necessary.

The grid is formed by spanning the channel with a measuring tape repeatedly along the channel at close intervals. The sampling interval along the transect is one to two times the diameter of the largest particle. The grid method is the preferred sampling technique for pebble counts in cobble and boulder materials as well as gravel, because it reduces the bias against sampling the very small and very large particles. For purposes of stream-simulation bed design, pebble counts should include the channel bed between the base of each bank, and exclude the banks themselves. Review Bunte and Abt (2001) for details about selecting and measuring particles and laying out the sampling scheme. If the pebble count represents an entire reach, ensure the tape placements adequately cover the range of variability present in the reach.

Pebble count results are reported as a cumulative frequency distribution of particle sizes. In conventional notation, D_{50} (reported in millimeters) represents the median particle size; fifty percent of all particles are finer. Likewise, 84 percent of all particles are finer than D_{84} . The pebble count parameters most commonly used in stream simulation bed design are D_{95} (representing the largest mobile particles), D_{84} , and D_{50} . Where immobile particles function as key energy dissipation and grade control features, their sizes also are used in design.

Distinguishing alluvial particles (those moved by the current river) from rocks that are not mobile is important. Immobile rocks may have fallen or slid into the stream during a landslide or **debris torrent**, or they may have been transported by ice-rafting. These rocks are generally much larger than the largest alluvial rocks, commonly two to three **particle size classes** larger. If they are mistaken for the largest mobile particle size, the simulated bed may end up with much coarser bed material than the reference reach. Nonalluvial material can be recognized by its limited distribution along the channel, and by its larger size. Rocks derived from the adjacent hillslopes (by landslides, rockfalls, etc.) are usually angular to subrounded, rather than round, and may therefore look out of place in the stream. Section 5.1.6.2 describes data collection for nonalluvial material and other key features.

Table 5.5 summarizes the recommended methods for characterizing bed sediment in different channel types for stream-simulation design purposes. The channel types are described in more detail in appendix A, section A.6.1.

Table 5.5—Bed sediment sampling and observations for different Montgomery and Buffington (1997) channel types.

REFERENCE CHANNEL TYPE	TYPICAL CONDITIONS					RECOMMENDED SEDIMENT SAMPLING METHOD FOR BED DESIGN
	Bed material	Dominant roughness & structural element	Slope ¹	Entrenchment	Streambed mobility	
Dune-ripple: high mobility	Sand to medium gravel	Sinuosity, bedforms, banks. Small debris may provide structure.	Low	Slight	Termed "live bed"; significant sediment transport at most flows	<ul style="list-style-type: none"> Visual estimate representing whole reference reach or Bulk sample/sieve Note role of wood in stabilizing bed
Pool-ripple and plane-bed: mobile	Gravel, may be slightly armored	Bars, pools, grains, sinuosity, banks	<1.5%	Slight	Near bankfull	<ul style="list-style-type: none"> If fine gravels (up to 16 mm), same as dune/ripple Grid pebble count² If armored, note armor thickness and packing. Visually estimate percent fines in subsurface layer
Pool-ripple and plane-bed: intermediate mobility	Gravel to cobble, usually armored	Grains, banks	<4%	Slight to entrenched	Features controlling streambed elevations (riffle crests) mobilize at flows greater than bankfull	<ul style="list-style-type: none"> Grid pebble count If armored, note armor thickness and packing. Visually estimate percent fines in subsurface layer Measure dimensions of 10-25 of the largest rocks on upstream portion of riffle crests. <p>* Note imbrication, embeddedness, consolidation, particle shape</p>

¹ Slope is not diagnostic of Montgomery and Buffington channel types. Ranges given here include extremes. Typically, pool-riffle channels are <1.5%; plane bed channels are 1.5% to 3%, and step-pool channels are 3% to 6.5%. Forced channels can have steeper slopes.

² For the grid method, measurement points are spaced at one to two times the diameter of the largest particle. Transects are also located at that spacing.

Stream Simulation

REFERENCE CHANNEL TYPE	TYPICAL CONDITIONS					RECOMMENDED SEDIMENT SAMPLING METHOD FOR BED DESIGN
	Bed material	Dominant roughness & structural element	Slope ¹	Entrenchment	Streambed mobility	
Step-pool	Cobble to boulder	Steps, pools, banks. Debris may be an important component of streambed structure.	3–8%	Moderately entrenched to entrenched	Fine material moves over larger grains at frequent flows. Bed-forming rocks move at higher flows depending on size; often $>Q_{30}$.	<ul style="list-style-type: none"> Grid pebble count. Measure 10–25 step-forming rocks individually. Sample enough to get a range representative of all the steps in the reference reach. If steps are on wood, measure wood diameter and step height.
Cascade	Boulder	Grains, banks	$>3.5\%$ (usually $>6.5\%$)	Entrenched	Smaller bed material moves at moderate frequencies (floods higher than bankfull). Larger rocks are immobile in flows less than $\sim Q_{50}$.	<ul style="list-style-type: none"> Grid pebble count.
Bedrock	Rock with sediment of various sizes in transport over rock surface	Bed and banks.	Any	Any	Bedload moves over bedrock at various flows depending on its size. May be thin layer of alluvium over bedrock. Wood can strongly affect sediment mobility.	<ul style="list-style-type: none"> Visually characterize alluvial material patches or use pebble count. Note features controlling sediment accumulation (e.g., wood).
Channels in cohesive materials	Silt to clay	Sinuosity, banks, bed irregularities	Any	Any	Fine sediment moves over immobile bed at moderate flows depending on its size. May be thin layer of alluvium over immobile bed.	<ul style="list-style-type: none"> No estimate needed—bed cannot be constructed of cohesive materials.

¹ Slope is not diagnostic of Montgomery and Buffington channel types. Ranges given here include extremes. Typically, pool-riffle channels are $<1.5\%$; plane bed channels are 1.5% to 3% , and step-pool channels are 3% to 6.5% . Forced channels can have steeper slopes.

Dune-ripple and fine-grained pool-riffle channel types: high mobility.

Streambeds composed primarily of medium gravel and finer materials (less than 16 millimeters) are generally dune-ripple or pool-riffle channel types. Visual estimates of dominant particle size classes are normally sufficient on these channels. Estimate maximum particle size, and percentages of the bed covered by different size classes, such as coarse gravel, medium gravel, fine and very fine gravels, sand, and silt/clay. (Particle-size classes are defined in appendix A, table A.1.) Platts et al. (1983) recommended doing this along transects, visually estimating the particle-size class that comprises the largest part of each 1-foot section. Visual estimation is adequate in these fine-grained channels because it is generally not necessary to design the simulated bed material as carefully as in less mobile streambeds. The fine particles move at very frequent flows (below bankfull), and the simulated streambed reshapes itself rapidly as new material is transported into it from upstream.

If more certainty about the particle size distribution is needed, then use bulk-sampling and standard laboratory sieve analysis to characterize the entire particle-size distribution for medium-gravel and finer channels. See Bunte and Abt (2001), section 4.2.2, for recommended sampling procedures.

Pool-riffle and plane-bed channel types: mobile. Streambeds in these channels mobilize at flows near bankfull, and bed features are expected to form naturally in the simulated channel within a short period of time after construction. In these mobile channels, the bed-material sample should represent the whole reference reach. Use the grid pebble-count method, tailoring the number of individual particles measured to the variability in bed material sizes.

Not all pool-riffle and plane-bed channels are mobile, so evaluate as many mobility indicators as possible. Besides small particle sizes, indicators of relatively frequent mobilization include the absence of algal stains or moss on particles, steep faces and a lack of vegetation on bars, and loose bed material. Be careful if doing this evaluation shortly after a large flood; particle packing is looser after the bed mobilizes during such a flood. If it has been some time since a high flow, lesser flows will have reworked the streambed particles so that they are more tightly packed (Reid et al. 1985).

The degree of armoring also influences streambed mobility. Gravel-bed streams frequently have surface layers that are coarser than the

Stream Simulation

subsurface (appendix A, figure A.6). In such armored channels, the size and packing of the armor layer strongly influences streambed mobility, while the subsurface fines limit flow infiltration and control subsurface flow. Inspect the material underneath the surface and compare it to the surface to determine whether a streambed is armored (appendix A, figure A.6). If it is armored, the subsurface has a much higher content of fines (particles less than 2 millimeters in diameter including silt and clay). The armor layer median particle size (D_{50}) is usually 1.5- to 3-times larger than the subsurface material, and can be up to 4-times larger (Reid et al. 1998; Bunte and Abt 2001). Characterizing both armor and subarmor layers is important for designing realistic bed material for the simulation. Figure 5.6 illustrates the difference between surface and subsurface material in a gravel-cobble stream in Colorado.

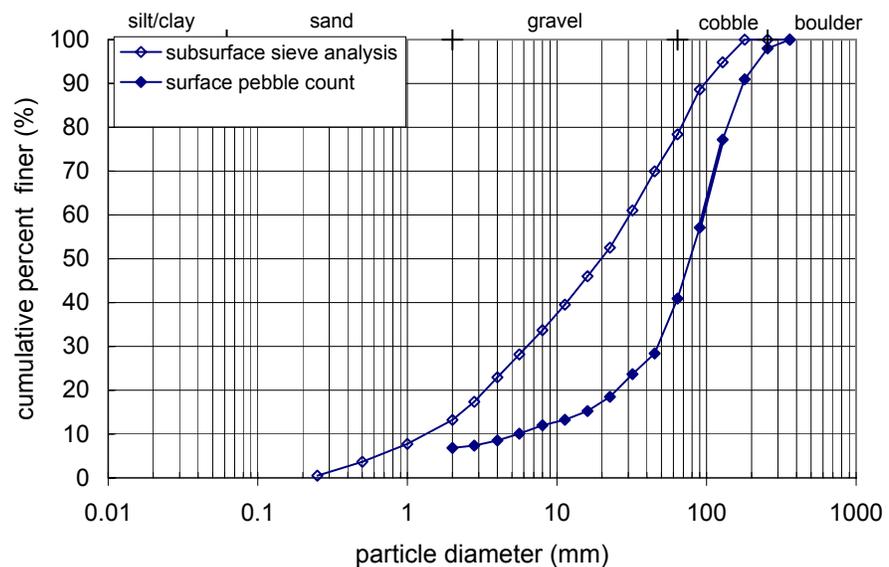


Figure 5.6—Surface armor and subsurface particle size distribution curves for the South Fork Cache la Poudre River (data from Bunte 2004). The surface armor was characterized by a pebble count. The subsurface was bulk sampled and sieved. Although the subsurface has a higher content of fines, it also includes the full range of coarser sizes found in the surface armor.

Visually estimating the subsurface fines content is usually adequate for stream-simulation design purposes. Sometimes you may be able to find an exposed scour pool, where you can clear off the exposed surface from a bank and estimate the content of fines. Otherwise, remove the coarse armor layer (usually one to two particles thick) from a bed area 1.5 to 2.0 square meters (16 to 22 square feet). If the area is submerged, use a

plywood shield to protect it from flowing water (Bunte and Abt 2001, p. 209). Estimate the percent area covered by fines, including fine gravels, sands, silts, and clay. These estimates will determine the content of sand (less than 2 millimeters) and silt/clay (less than 0.063 millimeters) in the simulation bed mix. Note any unusual situations, such as a layer of cobbles overlying very fine sediments.

Pool-riffle and plane-bed channel types: intermediate mobility. In steeper, coarser pool-riffle channels, where particle sizes increase to very coarse gravel and cobble, streambed mobility is likely to decrease. This is especially true for **imbricated**, embedded, consolidated or heavily **armored streambeds** (see section 4.4, table 4-2). Particle shape and angularity also affect mobility: mobilizing angular particles requires higher **shear stresses** than mobilizing spherical particles of similar size (Reid and Frostick 1996). Flat, disc-shaped particles are usually well imbricated, making them more resistant to **entrainment** (Carling 1992).

As in the mobile channels, measure bed material using a pebble count method that samples the different channel units proportionally to their areas within the reach. In these coarser channels, tightly packed or embedded rocks making up the heads of riffles (or pool-tail crests) may be stable up to flows much larger than bankfull. It's important to distinguish these less mobile grade controls where they exist. The whole-channel pebble count includes the riffle crests where the grid crosses them, but a separate assessment of the larger particle sizes comprising the upper segment of the riffle crests is also needed, so that these key features can be constructed in the simulated channel. Measuring 10 to 25 of the largest rocks on the riffle crests is probably sufficient. (Figure 5.8 shows an example of bed material evaluation in an intermediate-mobility pool-riffle channel.) Also note any other characteristics that influence mobility. If the rocks are tightly imbricated, embedded, or packed, particle size alone may not be an adequate index of stability of the grade controls. Where rocks are highly asymmetrical, it may be necessary to measure the long, short, and intermediate axes to describe their relative dimensions and create appropriate specifications later.

Step-pool and cascade-channel types: low mobility. Assess particle sizes on these channel types using grid-based pebble counts covering the entire streambed. For step-pool channels, measure on the order of 10-25 step-forming rocks, separately if necessary. Again, for highly asymmetrical particles, measuring dimensions of all three axes may be necessary to write a good specification. Where steps are formed by wood, measure log

Stream Simulation

diameters. Ensure a good representation of the range of sizes of the step-forming rocks or wood in the reach as a whole. Measurements of the step-forming features comprise the first estimate of rock size for the steps in the stream simulation design bed. Design the overall bed mix from the whole-channel pebble count that includes the step-forming rocks only where the grid crosses them.

5.1.6.2 Key features

In stream-simulation practice, the term key feature means any element on the streambed or banks that is large and immobile enough to control channel slope and dimensions, affect water velocity and flow direction, and/or retain sediment over a fairly long period of time. Key features often play crucial roles in maintaining the stability and diversity of the streambed and stream banks. Key features are either permanently immobile or, as in the case of the pool-tail crests and steps mentioned above, they are low-to-intermediate mobility grade controls that cannot be expected to form naturally within a culvert in a reasonable period of time. In addition to bedforms like steps, they include large wood, rock outcrops, large living tree roots, large boulders, etc.

Key features are characterized separately from the alluvial material so their functions can be replaced in the stream-simulation channel. They should be shown on the site sketch map and surveyed and noted during the topographic survey. Where water drops over a feature, include the height of the drop in the surveyed longitudinal profile. It will probably be used directly in the simulated channel design. Field notes should cover type, condition, size, function, and stability of each key feature (see section 5.1.3.3). Possible functions include providing grade control, hydraulic roughness, and bank stability. In some cases, key features may prevent the channel from shifting laterally or widening.

Table 5.6 is an example of a form that can be used to summarize the field notes describing wood and other key features.

5.1.6.3 Wood

Note: all wood is included in table 5.6 even when it may not be a long-lasting key feature. The table classifies the wood by size, and describes each category in terms of diameter, length, condition (rotten or sound), amount or spacing, and function. This is simply a handy way to summarize the field observations for later reference during design. Where logs or trees are true key features, their size and stability should be noted individually and they should be located on the site sketch.

Chapter 5—Site Assessment

Table 5.6—Example key-feature summary table.

KEY FEATURE SUMMARY					
Key feature	Size	Function	Spacing	Plunge height (bed elevation change)	Condition & mobility/ stability
<i>Wood debris and live trees</i>	<i>6"-15"</i>	<i>G</i>	<i>@ 15'</i>	<i>0.4'-0.7'</i>	<i>Rotten— low stability</i>
	<i>10"-15" tree diameter</i>	<i>C</i>	<i>continuous on left bank</i>		<i>Live tree root systems</i>
	<i>36" tree diameter</i>	<i>R,C,B</i>	<i>@ 20' both banks</i>		<i>Live tree root systems</i>
<i>Large boulders</i>	<i>40" x 23" x 15"</i>	<i>R,C,B</i>	<i>irregular</i>		<i>immobile</i>
	<i>37" x 18" x 18"</i>	<i>R,C,B</i>	<i>irregular</i>		<i>immobile</i>
<i>Bedrock</i>	<i>None</i>				
<i>Bedforms (steps, clusters, pool tail crests, etc.)</i>	<i>Steps are formed by wood (6"-15")</i>	<i>See above</i>			

Function key: Grade control, Roughness, Bank stability, lateral Confinement

Stream Simulation

Wood need not be a long-lasting key feature to exert strong effects on channel morphology. For example, **woody debris**, living trees and roots, and other roughness elements can reduce bed-surface particle size by dissipating some of the boundary shear stress that would otherwise be exerted on the bed. Because the shear stress on the bed is less, the bed responds by becoming finer than it would otherwise be (Buffington and Montgomery 1999a).

Even small pieces of wood can affect the channel. In sand and fine-gravel-bed streams, buried fine woody debris can stabilize the bed at a steeper slope than it would otherwise sustain. Make sure to note the frequency and size of the fine debris if it is present and playing this role. If the stream-simulation bed design does not include the stabilizing effects of the small wood, the bed material may scour.

5.1.6.4 Bank materials and morphology

Streambanks can be relatively straight and uniform, or irregular with localized sections projecting into the channel. Woody vegetation and rock projecting from banks into the channel can have a substantial effect on channel form and processes by increasing **flow resistance**, obstructing or deflecting flow, stabilizing banks, and influencing erosional and depositional processes on the streambed (Poff et al. 1998). Bank irregularities also influence channel margin habitat for aquatic species by creating lateral scour pools and depositional zones. These habitats can be critical for passage of weak-swimming species that need slow and/or shallow water along the channel margin.

Mimicking the diversity, roughness, and shape of the channel margins and banks is important for simulating the degree of hydraulic roughness in the reference reach and for satisfying aquatic organism passage objectives. Where bank irregularities are important for edge habitat, bank stability, or channel roughness (figure 5.7), measure their spacing and length, that is, the distance they extend out into the channel. Note the type (large woody debris, standing trees, rock) and size of material that forms the bank protrusions. These features can be simulated with rock.



Figure 5.7—Channel margin diversity in Ore Creek, Oregon.

Understanding bank stability is also important when considering the effects of potential downcutting after a culvert replacement. Because there is often an elevation differential across older culverts, some adjustment of the longitudinal profile is likely during or after replacement with a stream-simulation culvert. If the replacement structure causes the upstream channel to degrade, the stability of the banks becomes an issue. Their stability may affect the decision about whether or how to control any headcutting that may occur (see section 5.3.3).

Qualitatively evaluate bank stability by observing:

- Bank materials and their layering.
- Rooting depth, density, and root sizes.
- Large, stable woody debris on banks.
- Live trees and shrubs that may overhang the banks.
- Evidence of active bank erosion such as vegetated chunks lying near the edge of the streambed.

5.1.7 Preliminary Geotechnical Investigation

The initial assessment phase (chapter 4) included collecting existing information on site geology from geological reports, watershed analyses, or past projects in the area. Usually these reports provide only general geological information. Complete a field geotechnical investigation to evaluate if a more detailed study of subsurface material properties is needed, and to help determine the cost and feasibility of the proposed project. The geotechnical site investigation assesses the spatial variability and physical characteristics of soil and bedrock, and the presence of ground water.

The list that follows summarizes the geological and geotechnical observations that may be needed. These observations apply to any site, whether steam-simulation design is used or not. Techniques are not discussed in detail because they are standard engineering practice. Ensure the geotechnical data are tied to the common datum of the topographic site survey.

Bedrock.

- Location, elevation.
- Type, durability, dip, strike, orientation, thickness (these characteristics become important at bridge or open-bottom arch sites).
- Structural features (fracture and joint patterns, width, depth, orientation, continuous or discontinuous, extent, shear, and fault zones).
- Weathering (distribution and extent).

Soil.

- Type (Unified Soil Classification System).
- Physical characteristics (thickness, cementation, occurrence).
- Engineering properties of the materials at the site.
- Durability.
- Plasticity.
- Load-bearing capacity (friction angle, cohesion, unit weight).
- Permeability.

Mass-wasting risk at the site (Benda and Cundy 1990).

- Debris flow.
- Slides and rock falls.

Ground water

- Occurrence and distribution.
- Relationship to topography.

Chapter 5—Site Assessment

At most sites, sufficient subsurface data can be collected using simple hand methods (probing, hand augering, drop hammer, shallow excavations, etc.) Probing is a simple method of estimating some subsurface conditions, such as relative density of subsurface material, depth to bedrock, depth to probe refusal, and type of subsurface material (Williamson 1987). It is appropriate on most low-volume forest roads where no pavement is planned and the design structure is a culvert.

The probe is ½-inch galvanized steel pipe (actual dimensions are approximately ¾-inch outside diameter) and uses an 11-pound slide hammer for driving the probe into the soil. Stouter probes—such as stainless steel—may be needed in coarse-bed channels where rock is likely to be encountered. Probe immediately upstream and downstream of the existing structure and laterally across the stream (at least to bankfull width), including the area that the structure will cover. If bedrock is encountered during excavation, probe beyond bankfull width to develop more accurate estimates of excavation quantities. To assess localized changes in subsurface material and bank composition, extend the probing to the banks away from the fillslopes. Probe in scour holes to obtain information deeper in the subsurface. If riprap precludes probing near the culvert outlet, probe farther downstream and in the bank areas near the outlet. Include probe site locations on the site sketch, and flag them for the topographic survey. Using the surveyed surface elevations of each probe hole, calculate the elevation of the probed depth. For a more in-depth discussion of probing, see Williamson (1989).

During low-flow conditions, the plunge pool immediately downstream from an undersized culvert often has well-exposed scoured banks. Descriptions of sediments in the banks may provide insights into the material beneath the existing culvert. The vertical stratigraphy of the plunge pool sediments can highlight geotechnical concerns, such as the load-bearing capacity of the underlying sediments (how much weight the material can support), dewatering (how much ground water is expected and whether flow diversion is feasible), and susceptibility of the sediment to scour. Bank seepage can indicate potential problems with ground water during construction.

The results from the preliminary investigation may indicate the need for a more intensive, detailed geotechnical investigation involving core drilling, seismic surveying, and/or ground penetrating radar to fully characterize the geology at the road-stream crossing. Such an investigation may be desirable anyway if the site has high associated risks and costs. For example, if the replacement structure might be a bridge or an open-bottom

Stream Simulation

arch, and the preliminary geotechnical investigation shows that there is soft material at the site, a detailed geotechnical investigation will be required.

5.1.8 Road Travel-way and Construction Considerations

Logistical constraints affect what you can do at any site. During the site assessment and preliminary design, identify all the limitations that could constrain design. A list of common constraints follows:

- Vertical constraints: Maximum road grade, and fixed or required elevations influence structure type and clearance and impact the site layout.
- Horizontal constraints: Issues of site visibility and maximum or minimum curve radius can affect site layout.
- Right of way and property boundaries: These affect the length of stream segment that can be regraded, along with the type and length of structure that can be installed.
- Utilities and property developments: These can affect the ability to reconfigure the site.
- Material constraints: Unavailability of materials may require a compromise on material used or an alternative design solution to stream simulation.
- Site access: Access issues may affect the type of equipment you can use, as well as the feasibility of regrading the channel profile. The availability of space for storing materials can also affect the construction schedule.
- Road closure and detour feasibility: The importance of a road for public travel and access during construction may constrain construction activities.
- Time constraints: Regulatory limitations to protect threatened or endangered species may limit the ‘work window’ to a few weeks out of the year. This can preclude some construction techniques, such as building cast-in-place concrete footings.

These logistical constraints may limit the extent of regrading or the type of structure, forcing a less-than-ideal solution for the site. For instance, a narrow right-of-way may force a steeper-than-ideal project profile to limit the footprint of the work.

The site assessment should answer other construction-related questions as well:

- Are the existing crossing embankment materials suitable for backfill? (See section 7.3.4.)
- What onsite materials (trees, downed logs, **riparian vegetation**, topsoil, large rocks) are suitable for possible inclusion in the stream-simulation design or stabilization plan?
- Are there nearby areas that might be suitable for treating dirty water by filtration through soil and vegetation? (See section 7.8.4.)
- What is the **diversion potential** at the site? Where would diverted water go?
- Where might topsoil and construction materials be stockpiled?
- Will streambank stabilization measures be necessary upstream or downstream? If so, what kinds of measures are needed?

5.2 ANALYZING AND INTERPRETING SITE DATA

5.2.1 Interpreting Sediment Processes and Mobility

Site assessment documentation for bed mobility should include:

- Channel types upstream and downstream of the crossing.
- Apparent bed mobility in upstream reach, and mobility indicators: degree of armoring, imbrication, bed structures, dominant particle sizes.
- Evaluation of whether grade controls need to be constructed in the stream simulation design bed.

Information for the reference reach should include:

- For gravel and coarser channels, particle size distribution curve(s) including particle sizes of grade controls if necessary.
- A visual estimate of subsurface fines.
- A qualitative description of the degree of armoring and the apparent stability of the armor layer (determined by packing, particle shape, etc.).
- For highly mobile streambeds, qualitative evaluation of particle sizes: maximum mobile particle size, dominant class, range of sizes present.
- Key feature type, size, function.

Stream Simulation

In all cases, describe any effects of the existing crossing structure on bed material sizes to help in predicting channel response to removal or replacement.

The composition and characteristics of bed and bank material can provide insight on the frequency of sediment transport, channel stability, and sediment supply. These insights are important during design when decisions must be made about regrading the project profile, realigning the crossing structure or the adjacent reaches, and designing streambed structures that move at similar flows to the reference reach.

Newbury Creek Site Assessment—Bed Material

Figure 5.8 shows pebble-count data from a riffle in a potential reference reach downstream of the existing culvert at the Newbury Creek site [see figure 5.2 and 5.10(b)]. The bed is well-armored, tightly packed, and imbricated. Well-established moss can be seen on the largest particles, suggesting that riffle particles do not move very frequently. The channel type is pool-riffle with intermediate mobility. Riffle-crest particles were measured separately. A sample of 10 of the largest rocks on the riffle crest averaged 244 millimeters in diameter, which is in the large cobble range. The surface layer has less than 1-percent sand and finer material, but a visual estimate of subsurface **fin**s is about 20 percent.

Field notes indicate that gravel bars on the insides of bends are narrow, woody debris is not present in large amounts, and little sediment is stored in the channel. From the initial assessment, there is a low-gradient meadow a short distance upstream of the crossing reach. The meadow reach traps most sediment moving down Newbury Creek, and the supply of sediment to the crossing reach is fairly low. Aggradation is unlikely to be a major issue at this site.

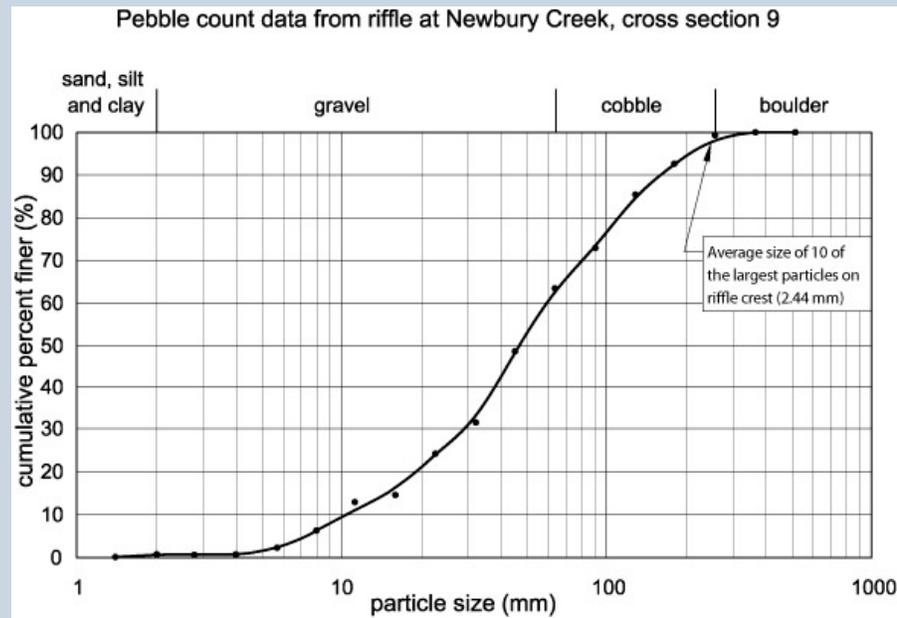


Figure 5.8—Particle-size distribution curve from a potential reference reach in the vicinity of cross sections 8 and 9. Cross sections are located on figure 5.9.

5.2.2 Analyzing the Longitudinal Profile

Plot the surveyed longitudinal profile and cross sections, and annotate them from the survey notes to help interpret the relationships between channel characteristics and stream processes. Locate the cross sections and bed material site(s) on the longitudinal profile, as well as the grade controls and other features that were identified in the field (table 5-1). Channel slope typically varies considerably along the longitudinal profile, directly reflecting the influences of large woody debris, slope and bank failures, bedrock, bedforms, and spatial variability of bed-material sizes. Integrating all of this information allows assessment of how streambed elevations and the longitudinal profile may change over the life of the project.

Usually, plotting the profile and cross sections with a vertical exaggeration (VE) between 2 and 10 makes them easier to interpret, as it makes segments with different slopes stand out from each other. Beware of using large VE's, however, especially on streams with steep (greater than 6 percent) slopes and high steps. Too much VE can give the misleading impression of many short channel segments.

Stream Simulation

On the cross-section plots, show bankfull width and floodprone width, and identify key geomorphic features. Plotting all the cross sections at the same scale makes it easier to visualize changes in cross section dimensions along the channel.

The following steps are a systematic way of analyzing the longitudinal profile. Having the annotated cross sections handy will help with the analysis and interpretation.

1. Visually identify pools and grade controls. Identify geomorphic controls on pool formation (e.g., log, boulder weir, channel bend, culvert outlet plunge pool, etc.). Document the type and stability of the grade controls.
2. Delineate slope segments by drawing straight lines connecting successive grade controls. End a segment when the next grade control does not fall on the straight line. Calculate segment gradients, and combine adjacent segments when their slopes do not differ by more than 20 to 25 percent. For each of the final segments, determine (a) segment length, (b) the number and distance between grade controls, and (c) maximum pool scour depth.
3. Identify the length and depth of aggradation and degradation associated with the existing crossing. Identifying these areas of local aggradation and degradation helps in assessing the response of the channel to the existing structure, and predicting the channel's response to a new structure.
4. Identify the shape of the longitudinal profile to interpret the dominant geomorphic processes occurring at the crossing, and predict channel adjustments after the replacement structure is installed. Section 5.2.2.1 describes profile shapes and their implications for stream-simulation design.
5. Determine upper and lower vertical adjustment potential lines for the streambed through the crossing as if no crossing structure was present (section 5.2.2.2).

Newbury Creek Site Assessment Longitudinal Profile Analysis Steps 1 Through 3

Figure 5.9 is the annotated longitudinal profile for Newbury Creek (sketch map is shown in figure 5.2). The longitudinal profile plot identifies the surveyed cross sections, and it shows channel features such as log weirs (installed in the 1980s and early 1990s to improve aquatic habitat), bankfull and flood plain surface elevations, and exposed bedrock. Bedrock occurs at the base of pools associated with log weirs upstream from the crossing.

Figure 5.10 shows two typical cross sections upstream and downstream of the crossing (locations are on the longitudinal profile). The upstream cross section (a) is substantially more entrenched, bounded by the adjacent slope on one side and a high glaciofluvial terrace on the other. The downstream channel (b) is less entrenched; the adjacent surface is a low terrace only slightly higher than bankfull elevation.

Step 1. Pools are identified on figure 5.9, as are grade controls, which include bedrock steps, moderate-to-high stability pool-tail crests (the heads of riffles) and low-to-moderate stability log weirs. Pool-tail crests are designated high stability when composed of tightly packed and embedded boulders and cobbles. Pool-tail crests of more loosely packed cobbles and gravels are considered moderate stability (see table 5.3).

Upstream of the road, the channel is relatively straight (figure 5.2), and the primary controls on pool formation are obstructions created by bedrock steps and log weirs. Downstream of the road, the channel is more sinuous and the primary controls on pool formation are channel bends and obstructions created by log weirs that have partially failed (compare figures 5.2 and 5.9).

Stream Simulation

segment	elevation change (ft)	segment length (ft)	gradient	% gradient difference between successive segments	maximum residual pool depth (ft)	number of grade controls	distance between grade controls (ft)
A	0.94	53.17	0.0178	n/a	1.54	2	53.2
B	0.41	81.53	0.0050	-71.9	0.34	2	81.7
C	2.68	185.21	0.0145	190.4	1.07	4	62.0, 101.7, 21.6
D	1.78	92.69	0.0193	32.9	2.29	3	57.7, 34.8
E	0.73	11.01	0.0665	245.2	0.99	2	11.2
culvert	0.27	72.09	0.0037	-94.4	4.38	2	72.2
F	5.70	234.28	0.0243	55.15	0.82	3	145.7, 88.6
G	1.27	66.25	0.0192	-21.0	1.70	2	66.3
F,G	6.97	300.53	0.0232	-4.6 ^a	1.70	4	145.7, 88.6, 66.3
H	4.69	151.32	0.0309	60.8 ^{b,c}	0.68	3	92.2, 59.1

a. Percent gradient difference when compared to slope segment F.

b. Percent gradient difference when compared to slope segment G.

c. When compared to combined slope segments of F and G, the percent gradient difference is 33.3%.

- channel-bed profile
- pool
- top of bank/floodplain
- cross section location
- grade control
- 2
- ptc-H pool tail crest, high stability
- ptc-M pool tail crest, moderate stability
- st-H step, high stability
- lw-M log weir, moderate stability
- lw-L log weir, low stability
- slope segments (A,B,C,D,E,F,G,H)

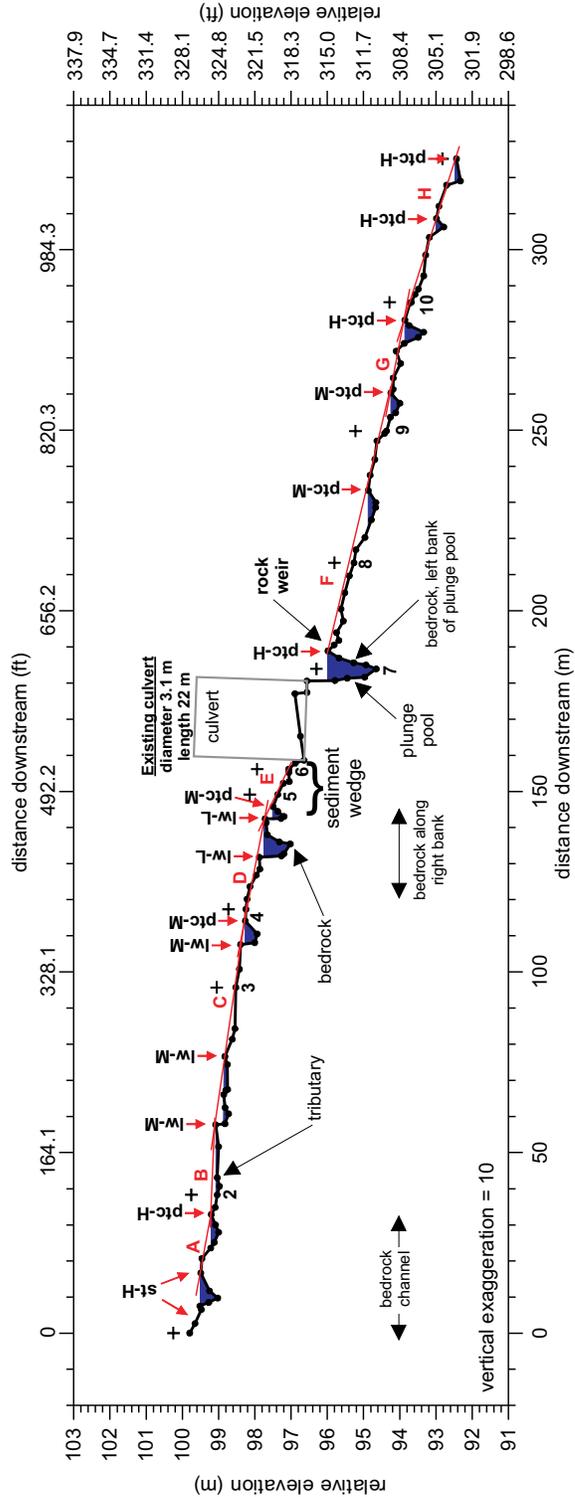


Figure 5.9—Longitudinal profile of Newbury Creek, Olympic National Forest, showing various channel features.

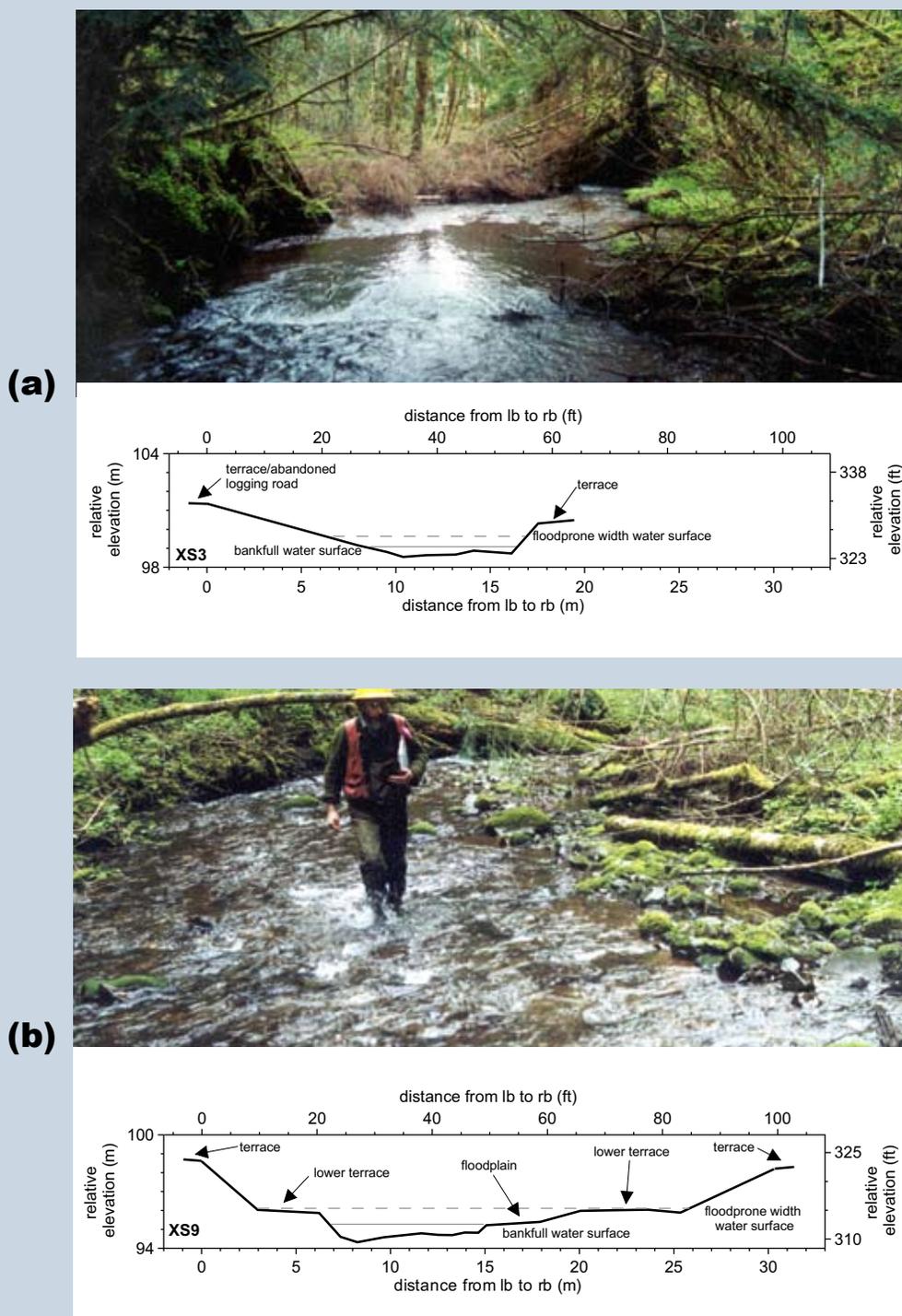


Figure 5.10—Newbury Creek cross-section profiles and photos. (Cross-sections are plotted looking downstream and their locations are shown in figure 5.9.) (a) Looking downstream toward cross sections 3 and 4 (photo taken between cross section 2 and cross section 3). Two log weirs are visible. In the background a bedrock outcrop is exposed on the right bank of the channel. (b) Looking downstream at cross section 9.

Stream Simulation

Step 2. The channel upstream of the road has five segments ranging from 0.5 to 6.7 percent slope. Downstream of the road, three segments were initially identified. Segments F and G were combined because their slopes differ by only 21 percent and the segments are the same channel type. Grade control spacing and maximum residual pool depth for each segment are summarized in the table in figure 5.9.

Step 3. Like most undersized culverts, the one at Newbury Creek has an area of sediment deposition immediately upstream of the inlet. Low sediment loads (due to the upstream meadow) and the steep, confined channel keep the sediment wedge small. Nonetheless, because the culvert is nearly flat (0.4 percent), some minor deposition has occurred in the culvert.

The plunge pool downstream of the culvert outlet is much deeper than other pools. Residual pool depth is 4.4 feet, about twice the residual depth of pools that form naturally elsewhere in the channel. The plunge-pool tail crest is a constructed rock weir of angular rocks (riprap) much larger than the native bed material (600 to 750 millimeters) (figure 5-11).

Steps 4 and 5 of the Newbury Creek longitudinal profile analysis are in sections 5.2.2.1 and 5.2.2.2, respectively.



Figure 5.11—Outlet of existing culvert on Newbury Creek, Olympic National Forest, Washington.

5.2.2.1 Identify longitudinal profile shape

Bedforms, woody debris, bedrock, etc, are not the only possible controls on channel slope. Slope also may vary where the crossing is located at a geomorphic transition, where the downstream channel has incised, or where the crossing itself has modified channel slope by causing sediment deposition upstream.

Many forest roads are located at geomorphic transitions—natural terrain breaks such as the edge of a valley at the base of the hillslope, or on a natural bench. These terrain breaks [figure 5.12 (c), (d), and (e)] can create an abrupt change in stream slope, influencing the shape of the profile and affecting sediment transport along the channel. Project teams need to identify these transitions and understand their potential effects on sediment transport and channel stability to accommodate them in the design.

Uniform

A uniform profile has no slope transition, making this the ideal crossing situation [figure 5.12 (a)]. Even where the profile is uniform, though, aggradation upstream of an undersized culvert [figure 5.12 (b)] can reduce the local slope. Such a profile can be mistaken for convex [figure 5.12 (d)] if the surveyed longitudinal profile does not extend beyond the aggradation, or if the aggradation is not recognized. Field evidence of aggradation upstream of an undersized culvert can include a relatively high gravel deposit in the center of the channel above the existing structure, a widened and/or divided channel, bank erosion, or a bar deposit just upstream from the culvert with finer sediment than at other locations. An aggraded reach may also appear simpler and more homogenous because structural features such as steps may be buried by sediment. **Backwater** aggradation is not limited to uniform profiles, of course. It can occur upstream of any undersized culvert.

Concave

A concave transition is an abrupt slope transition from steep to flatter [figure 5.6 (c)], such as on a flat valley bottom near the toe of a hillslope. Such an area is a natural depositional zone, where sediment accumulation through the crossing structure can reduce the structure's hydraulic capacity (see figures 4.7 and 4.8). Occasionally, sediment deposition can also plug the channel, and cause the stream to cut a new channel in a different location. If the excavation for a replacement structure cuts into the bed of the steeper reach and no upstream grade control exists, upstream headcutting and additional sediment deposition may result.

Stream Simulation

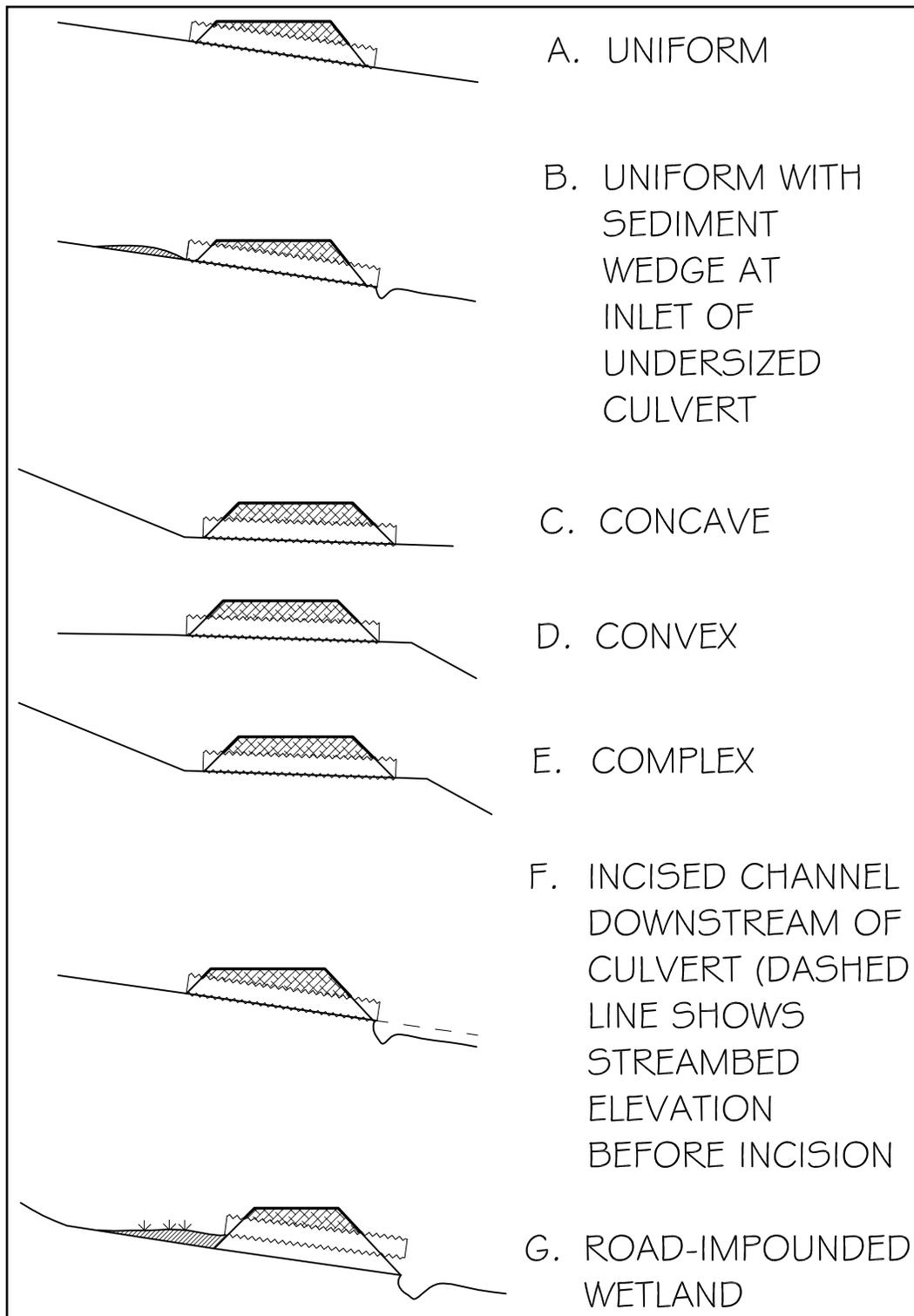


Figure 5.12—Longitudinal profile shapes: (a) uniform; (b) uniform reach affected by local scour and aggradation due to undersized culvert; (c) concave transition; (d) convex transition; (e) complex transition; (f) incised channel; (g) road-imponded wetland.

Convex

A convex transition is a slope transition from a mild slope to a steeper one [figure 5.12 (d)]. Depending on how close the crossing is to the grade break, flow acceleration resulting from either the structure or a disturbance during construction can destabilize bed structures that control the downstream grade. Destabilization, in turn, could create a headcut that might migrate upstream through the structure and undermine it.

Complex

A complex transition is a profile with both a convex and concave shape [figure 5.12 (e)]. This type of transition has both the upstream problems of the concave type and the downstream problems of the convex type.

A road crossing placed at a convex or concave site may exacerbate the natural tendency toward aggradation or degradation if the crossing constricts the stream, or construction disrupts key grade controls. This can lead to a perpetual need for maintenance and the chronic channel disturbance associated with it. Consider road relocation away from concave or convex sites. Even though relocation may appear expensive, it may sometimes be cheaper than long-term costs associated with maintaining a poorly located crossing.

Local scour versus regional incision

Longitudinal profiles at culverts often show that the culvert is perched, but the elevation differential can have several causes: the downstream channel may have incised since the culvert was installed [regional incision, figure 5.12 (f)]; high velocity flow from the culvert outlet may have scoured a local plunge pool [figure 5.12 (b)]; or the culvert may have been placed too high during construction [figure 5.12 (g)]. Distinguishing local scour from regional incision is important, because the scale of the design solutions will be very different (see also section 6.1.2.1).

The vertical offset between the upstream and downstream channel bed profiles is a primary tool for determining whether degradation at the culvert is a local effect or the result of larger-scale channel incision (review appendix A). In figures 5.12 (b) and (g) and 5.13 (a), channel scour is local. When the downstream profile is extended upstream beyond the influence of the culvert, the profile aligns vertically with the upstream channel. The culvert is perched, but the perch is caused by local scour. In contrast, in figure 5.12 (f) and 5.13 (b), when the downstream profile is extended, it is approximately parallel to the upstream channel but at a lower elevation. A longitudinal profile with this channel-bed offset identifies an incised channel where the existing culvert is functioning as a grade control.

Stream Simulation

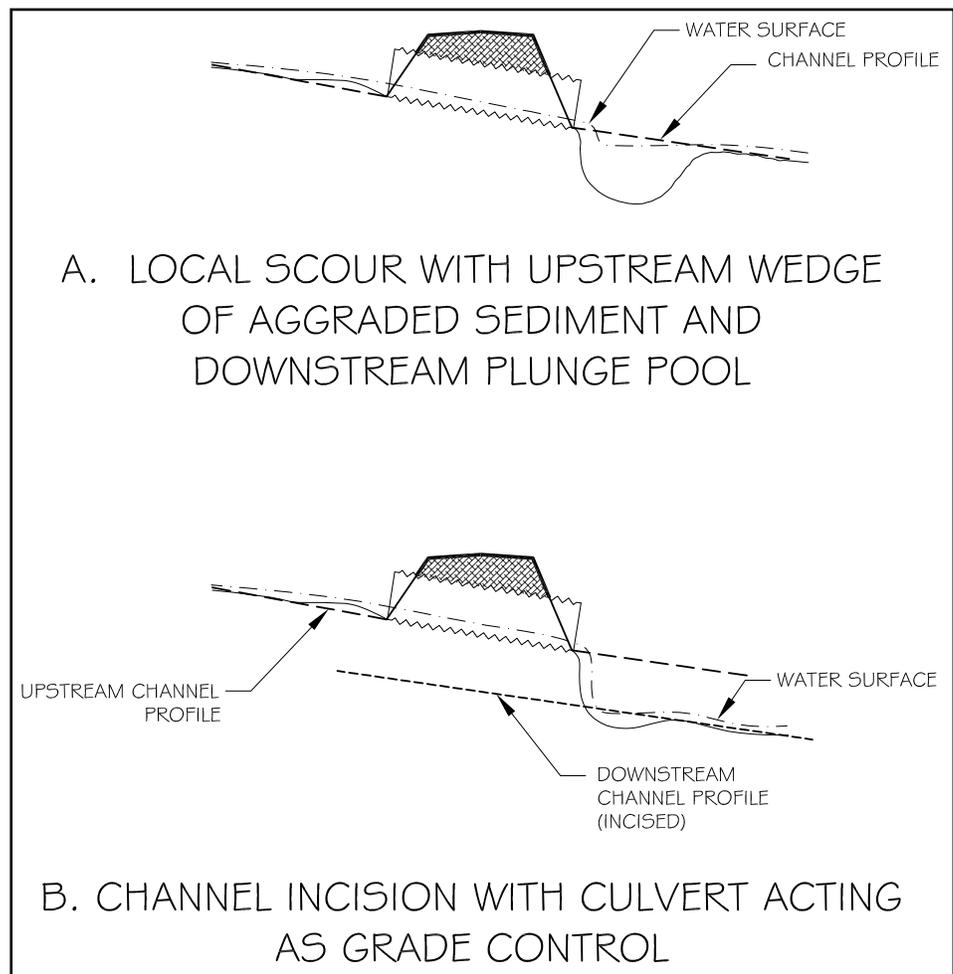


Figure 5.13—Distinguishing (a) downstream local scour from (b) channel incision.

Channel-bed offsets on either end of a culvert can also occur from other causes. For example, a natural slope transition can sometimes appear as an offset (figure 5.12 (c), (d), or (e)). Abrupt changes in streambed elevations also occur in steep streams where bedrock or large logs control steps. If the existing culvert was placed on top of an earlier failed culvert, the upstream channel could have massively aggraded, and both road and streambed profiles are higher than otherwise. Or, the culvert could have been constructed on a bedrock ledge. In all these cases, it is less likely that the upstream and downstream profiles would be parallel. Field observations and historical information about the crossing will help define which of several possible causes is responsible for the change in streambed elevation.

Cross sections are an excellent way to verify whether a downstream reach is incised (see appendix A, section A.7.2). An incised channel downstream from a crossing structure where the crossing is functioning as a grade control will have different cross-section characteristics from the unincised upstream channel (see end of section 5.1.4.2). Bed material also is likely to be different—possibly coarser—with less accumulation of gravel or fines.

Newbury Creek Site Assessment

Longitudinal profile analysis step 4, identify profile shape

At first glance, the Newbury Creek longitudinal profile (figure 5.9) leads one to suspect that the downstream reach may have incised. When a straight line along the downstream grade controls (the longitudinal profile) is extended upstream of the culvert, it is substantially lower than the upstream streambed. However, several pieces of evidence suggest this is not a case of channel incision. For one, the cross sections (figure 5.10) indicate that the banks downstream are not higher than those upstream; in fact, the downstream reach is less—not more—entrenched. There is no evidence of bank instability and no indication that either bed or banks have adjusted to a lowering of the channel bed.

The evidence confirms what the site sketch (figure 5.2) suggested—that the crossing is located at a geomorphic transition. The valley is narrow and controlled by bedrock upstream from the crossing, and the valley is wider and alluvial downstream from the crossing. The road crosses the stream at the head of the alluvial valley. The longitudinal profile shape is complex due to local steepening immediately upstream from the crossing, where bedrock outcrops in segment D constrict the channel for a short distance.

See figure 5.17 for step 5 of the longitudinal profile analysis for the Newbury Creek site.

Stream Simulation

For incised channels, verify the cause, scale, extent and stage of incision if at all possible. For design of any crossing, it is important to know whether incision is actively progressing, stabilizing, or recovering. If the cause is an upstream-migrating headcut, comparing the downstream reach to the channel evolution model (appendix A, section A.7.2) can help determine the stage of evolution. If the cause is a local influence, such as removal of woody debris or loss of a local grade control, then, with time, the bed may aggrade naturally back to its original profile. To accelerate the recovery process, the crossing project could include restoring the incised section to grade.

Road-impounded wetlands

Some road crossings with culverts that are undersized or that were installed too high cause ponding upstream (figure 5.12(g)). The ponding causes sediment deposition, which reduces the supply of sediment to the downstream channel. At these sites, the longitudinal profile usually shows an aggradation wedge, bed material is likely to be distinctly finer upstream than downstream, and vegetation may be different. The team will need to choose whether to preserve the wetland area, remove it, or allow it adjust naturally to a stream simulation replacement culvert. Because of a general loss of wetland habitat in some basins, resource managers are often motivated to preserve these wetland areas.

To preserve the wet area and provide some measure of aquatic organism passage, a design method other than stream simulation is usually needed. Stream simulation may not be possible in these cases because simulating the natural channel slope, form, and processes through the crossing would cause incision in the upstream wet area when some or all of the accumulated sediment is remobilized. On the other hand, if you design an over-steepened channel to preserve the wetland, the channel would not be self-sustaining because the sediment sizes necessary for sustaining the steeper slope could not be transported through the wetland to the channel. (Refer to appendix B for design methods other than stream simulation. Use these methods where the channel through the crossing must be substantially steeper than the natural channel, and achieving stream simulation objectives is unlikely.)

5.2.2.2 Determining vertical adjustment potential

One of the first steps in stream-simulation design involves selecting the gradient and elevation for the streambed that will be constructed—that is, the project profile. (See section 6.1.2.2 for detailed discussion of project profiles. It might be a good idea to review that section now, to get an idea

of how the design uses the interpretations discussed here.) Before selecting the project profile, however, the team needs to predict the elevations between which the stream bed might vary over the service life of the structure: the vertical adjustment potential (VAP). The upper and lower VAP lines represent respectively the highest and lowest likely elevations of any point on the streambed surface in the absence of any crossing structure. This section describes the considerations that go into forecasting the VAP lines for the structure's lifetime. There is no cookbook approach to selecting the upper and lower VAP lines; they are based on the team's interpretation of conditions and processes in the stream that might affect the elevation of the channel in the future.

Depending on channel type and condition, processes that can change the streambed elevation, whether permanently or temporarily, include:

- Channel incision caused by downstream base-level change.
- Increased flows or sediment inputs resulting from land management changes or climatic events in the watershed.
- Aggradation or degradation at a slope transition.
- Erosion and deposition of key features like boulders, steps, and large woody debris.
- Channel scour and fill during floods and debris flows.
- Headcutting upstream of a larger replacement culvert, as aggraded sediment is mobilized.
- Pool formation.

Try to predict what types of changes might occur and estimate how the channel might respond to those changes. Consider first the potential for large-scale, long-term channel change, such as deposition due to debris flow, or regional channel incision due to base-level changes downstream. Then consider local changes, such as movement of one of more key features or formation of a debris jam. Predicting how such changes may affect bed elevations is necessarily subjective; use every available piece of field and historical evidence available. Be conservative where the probability of vertical adjustment is high, such as where large amounts of wood are in the channel, or where channel incision is expected. If you are uncertain how the channel might change in the future, design conservatively and consider getting additional expertise to help predict future conditions.

Stream Simulation

In channels where large wood or rock steps control bed elevation, if these key features do not move, they will control the lower limit of vertical adjustment for the lifetime of the replacement structure. On the other hand, loss or outflanking of one or more of these key features could cause a large change in bed elevation over some length of stream as the channel adjusts toward a new equilibrium. The length of stream affected depends on the stability of the adjacent grade controls and on the depth of channel bed lowering. Usually, the material from the failed step moves only a short distance downstream, filling in the downstream pool and reorganizing the bed to form a new grade control. See the Fire Cove Road VAP analysis, figures 5.14 and 5.15.

If the key features are less stable, project how bed elevations are likely to change when they move. In intermediate and low-mobility channels, some amount of channel-bed fluctuation will always occur as wood pieces or rock grade controls enter or move through the channel, or as bedforms and bend locations change. Debris jams or buried small debris can temporarily retain sediment upstream, and they may form a scour pool downstream. If the debris moves, how will the stream adjust? Generally, the height of the grade controls, (log or rock steps, pool-tail crests, debris accumulations) indicates the scale of bed adjustment expected after one or a series of grade controls moves.

In stable channels where the bed surface as a whole is not expected to change (e.g., due to **base level** lowering or changes in flow), the depth of ordinary pools is a reasonable estimate of the lowest likely bed elevation in any slope segment. Unusually deep pools formed by large key features would not be considered in this analysis since they would not form inside a culvert. The depth of surveyed pools, however, represents only a snapshot-in-time of a dynamic channel that undergoes scour and fill during high flows. Limited research has shown that, in armored gravel-cobble bed streams, flood scour depths are on the order of twice the thickness of the armor layer, or about twice D_{90} (Bigelow 2005; Haschenburger 1999). It makes sense in these cases to expect that—temporarily at least—the bed may be that much lower than the bottoms of pools. If the level of risk warrants, the lower VAP line can be lowered to account for that.

Channel incision that affects long stream reaches can occur due to a variety of causes. Downstream influences include in-stream gravel mining or channel straightening that cause a headcut to begin moving upstream; upstream causes might be an upstream dam that reduces sediment loads, or any land management activity that reduces infiltration and increases peak runoff rates. Predicting the lower VAP line under these conditions requires

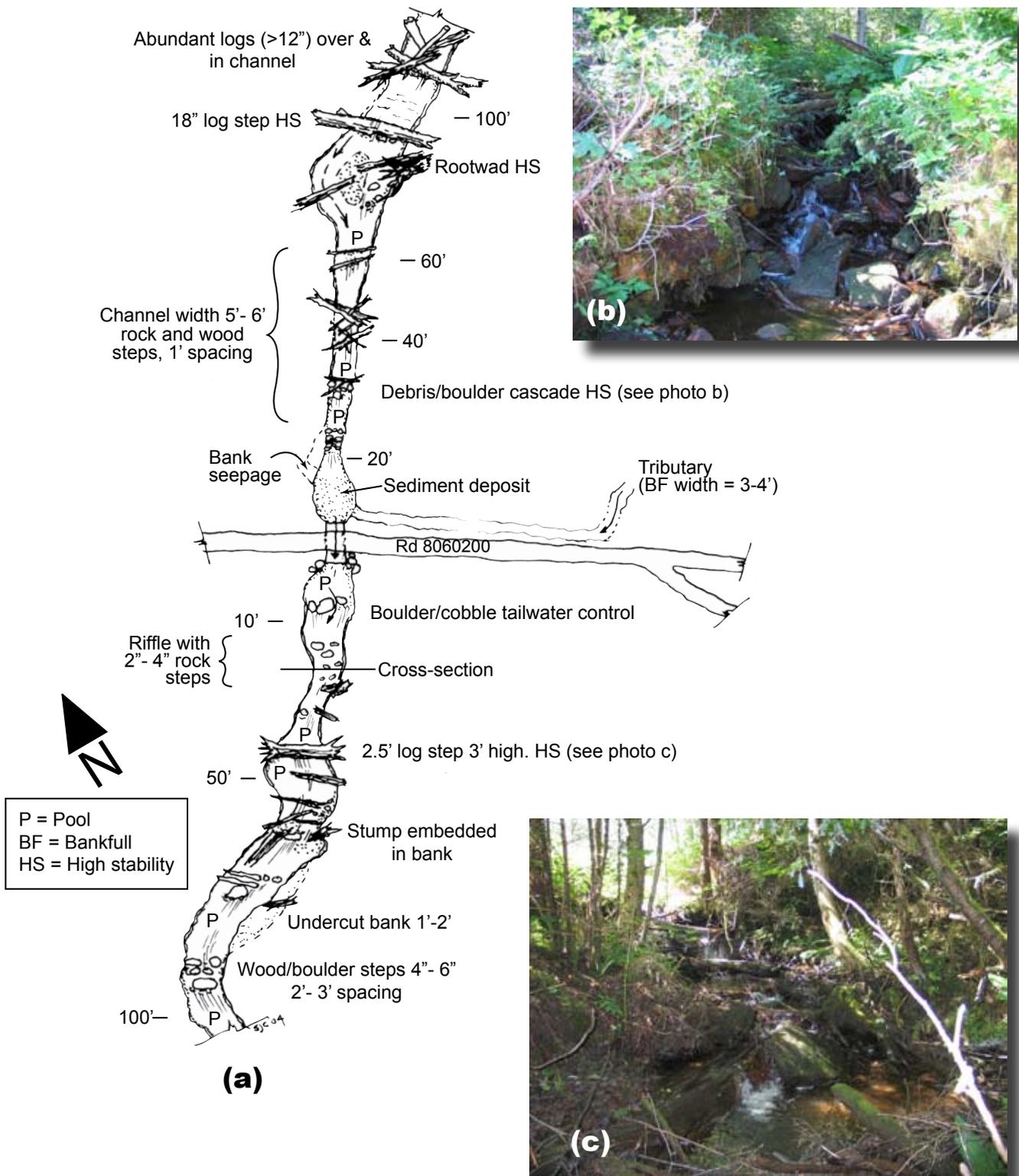


Figure 5.14—Fire Cove Road crossing, Tongass National Forest, Alaska: (a) site sketch; (b) looking upstream from the crossing at a high-stability step/cascade; (c) downstream of the crossing looking upstream at a high-stability log step (road is in light background area).

Stream Simulation

The Fire Cove Road crossing on the Tongass National Forest is a good example of predicting vertical adjustment potential (VAP) in a steep stream with large log steps (figure 5.14). In this example, no regional channel incision or aggradation is expected. The solid, well-embedded 2.5-foot diameter log about 50 feet downstream of the culvert [figure 5.14(c)] is a key feature controlling the grade. Just upstream of the culvert is a high-stability feature: a debris-and-boulder cascade where bed elevation is unlikely to change. Figure 5.15 shows two alternatives for the lower VAP line at this site. VAP line 1 assumes the stable downstream log does not move over the lifetime of the project. VAP line 2 indicates how deeply new pools in the project reach could scour if the log does move. Headcutting would end at the high-stability cascade section even if the downstream grade control is lost.

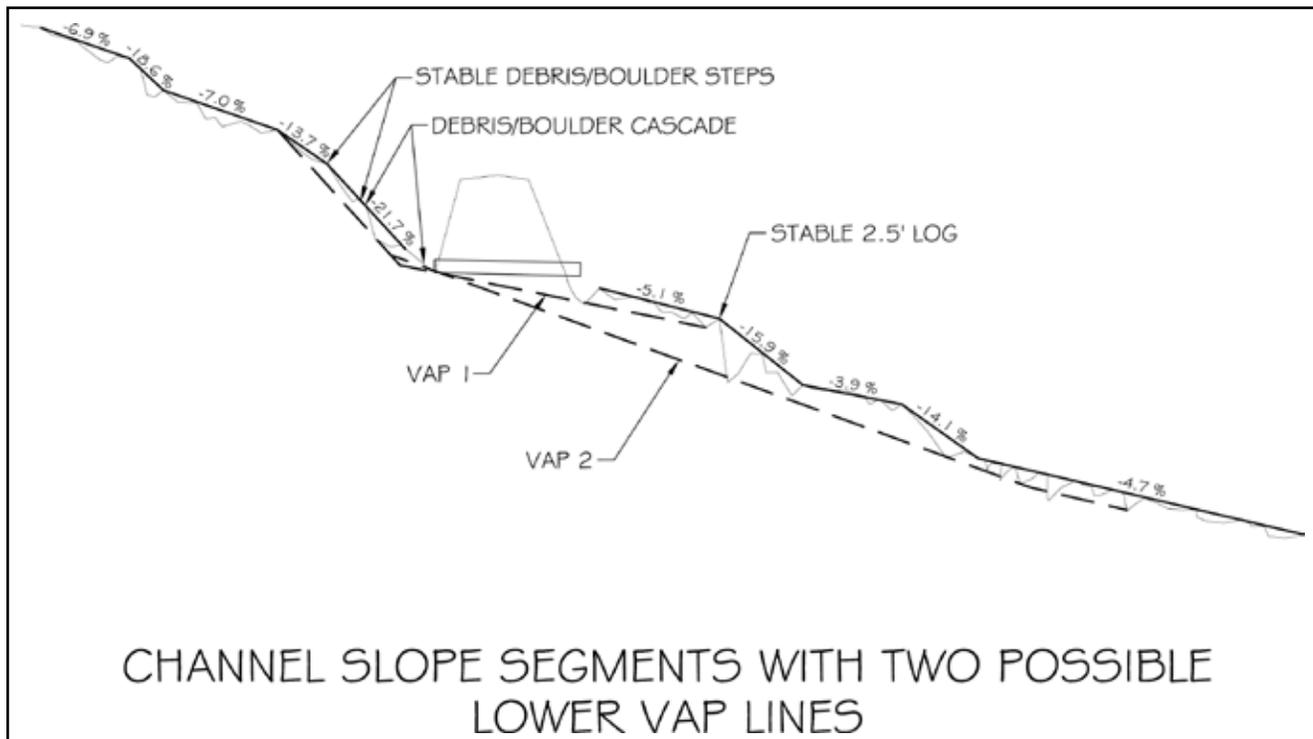


Figure 5.15—Longitudinal profile with two possible lower VAP lines for the Fire Cove Road crossing. Either of the two lower VAP lines could be used depending on how stable the downstream control is judged to be. In chapter 6, we will see how this crossing was actually designed (figure 6.7).

estimating how much of this large-scale incision may occur at the crossing site, and then adding the depth of pool scour to that estimate.

Also think about any features or processes upstream that may cause the channel to rise. Some examples are:

- Headcuts, bank failures, landslides, or debris flows occurring upstream may create a potential for large amounts of sediment deposition in the structure. Debris released by the headcut can exacerbate the deposition problem. (See Benda and Cundy 1990, for a method of predicting the risk of debris flow deposition).
- Formation of a debris jam and sediment accumulation behind it can easily cause local bed elevations to rise.
- Evidence of recent aggradation or heavy bedload movement may indicate the channel is aggrading, or it may be recovering from aggradation.
- If the channel is unnaturally lacking in debris, consider whether trees falling into the stream in the future might retain sediment and raise the channel-bed elevation.
- Crossings located on tributaries near their junctions with a larger river may experience aggradation if they are backwatered by high flows in the river.

Using all the information, draw at least two lines on the longitudinal profile to show the range of possible future bed elevations at the site (figure 5.16). Delineate the lines for channel segments outside the influence of the existing structure, and then connect them through the project reach as though no structure were there. Draw them approximately parallel to the average grade of each slope segment unless bedrock or other immobile controls dictate a different slope.

The scenarios represented in figure 5.16 illustrate how the VAP lines were delineated in three different hypothetical cases. Figure 5.16 (a) shows the longitudinal profile of a 10-foot-wide stream crossing a road in a 4-foot culvert. The channel profile shape is uniform, and the stream is in dynamic equilibrium. Watershed conditions are stable; there is no reason to expect regional channel incision due either to headcut migration from downstream or to changes in flow or sediment loads. The channel is an armored gravel-cobble pool-riffle channel with some woody debris. Pools not associated with large key features or the existing undersized culvert are a maximum of 2 feet deep. The lower VAP line is at 2.8 feet below the

Stream Simulation

existing profile, 0.8 foot being added as a safety factor for potential scour during floods. The depth of potential scour is estimated as twice the D_{90} size of 0.4 foot.

The upper VAP line in figure 5.16 (a) is at the top of the 2.5-foot-high bank because debris accumulations in this vicinity can extend that high. The top of the bank is the maximum elevation to which sediment could aggrade behind such an accumulation.

Figure 5.16 (b) shows the same channel after a 2.5-foot headcut moved up from downstream and was stopped by the existing culvert. The incised channel profile is 2.5 feet lower than the undisturbed (upstream) channel profile projected downstream. Here, if the culvert were not in place, the headcut could continue to move upstream causing incision up to 2.5 feet. Thus, the lower VAP line is 2.8 feet below the *incised-channel* longitudinal profile. Downstream of the road, a 3-foot-high debris jam of small trees that were undermined by bank erosion constitutes one piece of evidence for locating the upper VAP line at 3 feet above the incised channel profile (below the top of the bank). Again, if the culvert were not in place, the headcut would continue migrating upstream, and upstream VAP conditions would be essentially the same as those downstream.

Figure 5.16(c) is a very different scenario, a concave profile. The road is located where a steep (8 percent) step-pool channel meets the valley floor of a larger river. Downstream of the transition zone, the stream meanders across the valley on a 2-percent grade to join the river. The steeper channel currently appears stable, but the height and composition of the banks at the valley edge show that the channel has deposited substantial sediment and debris there during past floods. Private property makes road relocation impossible here.

The upper VAP line in this example is drawn at the top of the 2-foot-high banks in the valley section, and at the top of the higher banks in the slope transition section. We are presuming that at least short reaches of channel can fill to the top of the bank behind debris accumulations. The lower VAP lines in each channel segment are below the bottoms of the pools by a depth of two times D_{90} .

As shown in figure 5.16(c), where a channel has distinct gradebreaks, VAP lines can be drawn in segments. The high- and low-potential profiles might not be parallel where some feature will limit the possible channel elevation from going higher (e.g., flood-plain elevation) or lower (e.g., bedrock). Drawing several possible profiles—to show the range that might be expected at the site, given the existing grade controls and how they might change—is helpful. Where substantial uncertainty in the degree of potential vertical adjustment exists (e.g., in a channel with a highly mobile bed and good potential for debris jam formation), you might increase the range of potential vertical adjustment to offset the risk of error. Note your assumptions and relevant observations on the profile.

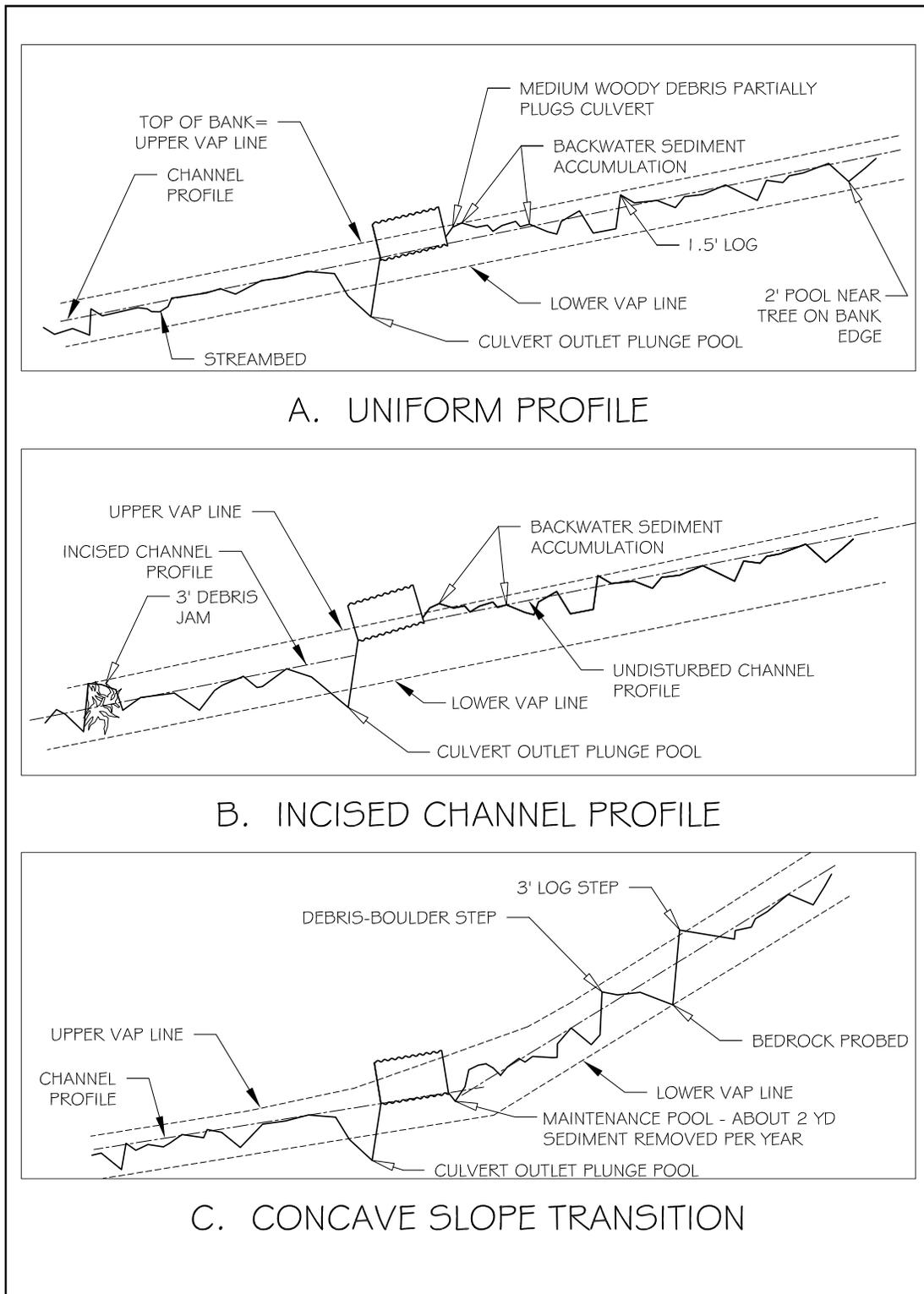


Figure 5.16—Range of vertical adjustment potential for three longitudinal profile types: (a) uniform profile, (b) incised channel profile, (c) concave slope transition. The “channel profile” lines are the “slope segment” lines drawn in step 2 of the longitudinal profile analysis (section 5.2.2).

Stream Simulation

Newbury Creek Site Assessment Longitudinal profile analysis step 5, determine vertical adjustment potential

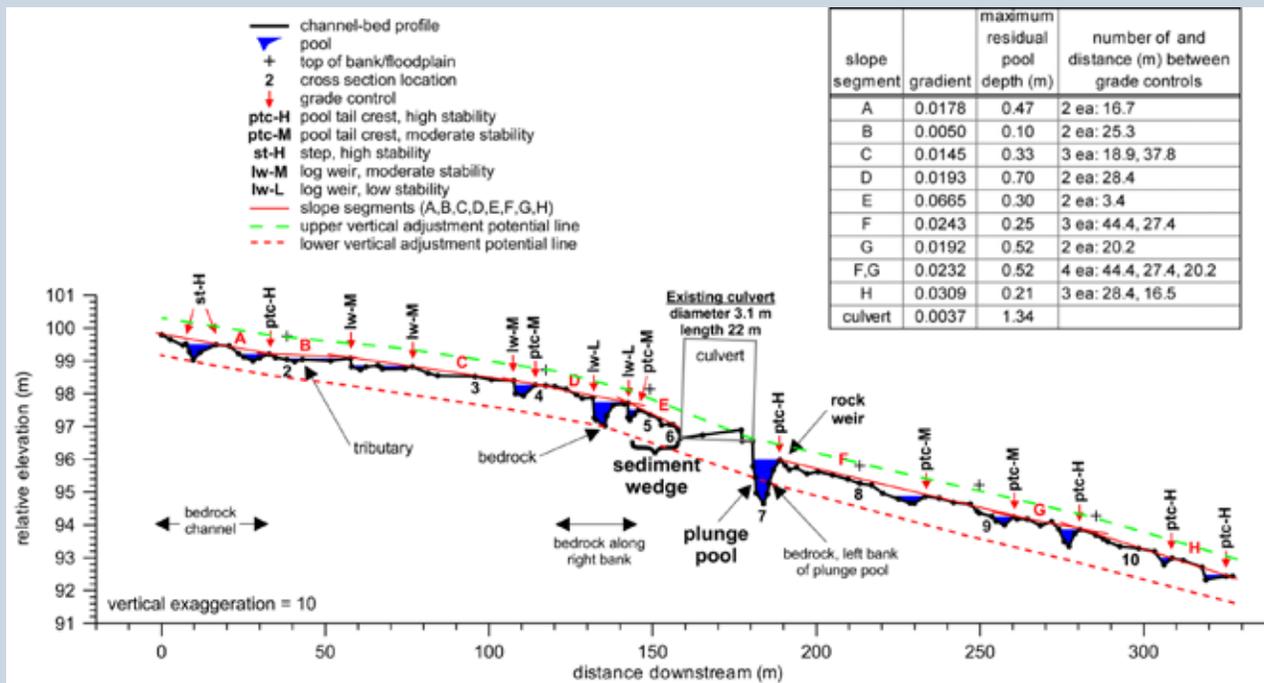


Figure 5.17—Newbury Creek longitudinal profile showing vertical adjustment potential.

As noted in the previous Newbury Creek sidebar (section 5.2.2.1), the channel downstream of the crossing has not incised, and there is no reason to expect incision in the future. Therefore, the lower VAP line includes only the maximum residual depth of pools (1.6 feet) for each slope segment, plus the anticipated flood scour depth (1.3 feet, twice the D_{90} of 0.65 foot). The lower VAP line is therefore 2.9 feet below and parallel to the slope segment lines except where bedrock forces the projected lower VAP line higher (segments A and D, and cross section 7).

The upper limit of vertical adjustment potential is taken as the top of the bank, and again the line approximately parallels the slope segment lines. Near the culvert inlet, the line is lower than the upper bank because backwater from the undersized culvert has caused the streambed to aggrade there. When the culvert is removed, the aggraded material is expected to erode and the streambed should stabilize at its natural, lower elevation.

5.3 PROJECT SITE RISK ASSESSMENT

Continuing to build on the initial assessment and the longitudinal profile analysis, assess all risks at the site. Use all available data and observations to interpret current project site conditions, predict potential channel changes, and identify significant risks that the design will have to deal with. Review the site suitability determination in light of your more in-depth understanding of the site.

Sometimes, design issues are associated with specific channel types (see table 5.7). For example, slightly entrenched channels have wide flood plains which can convey high flows during floods. Such road-stream crossings have risks associated with flood-plain constriction and **lateral channel migration**. Other risks can pertain to any channel type, depending on watershed and reach conditions.

5.3.1 High Flood-plain Conveyance

When it occurs, high flood-plain conveyance (i.e., a high flow on the flood plain during floods) is an important factor affecting design. When flood-plain conveyance is high and overbank flow occurs frequently, it may be necessary to install other flood-plain drainage structures under or across the road. The objective is to avoid funneling overbank flows through the main crossing structure, which would destabilize the simulated streambed in the culvert. Alternatively, a bridge or viaduct could be considered as a replacement structure.

To determine whether high flood-plain conveyance is an important issue at the site, estimate the depths and velocity of recent overbank flows. Use observations of past flood elevations and flood-plain scour and deposition features (section 5.1.4.2), together with historical flood data. Flood-plain vegetation and erosional and depositional features observed during the cross-section surveys may indicate recent overbank flow depths and should give a qualitative indication of the frequency and intensity of overbank flows. The presence of flood swales or side channels, for example, indicates enough overbank flow to cause significant scour. These channels, which can convey large amounts of flow, also may be important refuge or juvenile habitat for aquatic species. Identify them as key locations for flood conveyance and, where appropriate, aquatic organism passage. Be sure to evaluate whether evidence of overflow on the flood plain upstream

Stream Simulation

Table 5.7—Crossing design issues associated with specific channel characteristics.

CHANNEL CHARACTERISTIC	COMMON MAJOR ISSUES FOR CROSSING DESIGN	SPECIFIC RISKS	POSSIBLE DESIGN SOLUTIONS (SEE ALSO TABLE 6.7)
<i>High flood-plain conveyance, frequent overbank flow</i>	<p>Crossing may constrict flood-plain flow, increasing velocities through crossing structure.</p> <p>Road approach may block flow in flood plain, causing backwater ponding.</p>	<ul style="list-style-type: none"> • Simulated bed may not be sustainable. • Depositional/erosional processes that maintain flood-plain habitats can be interrupted. 	<ul style="list-style-type: none"> • Add overbank flow surfaces inside culvert. • Widen simulated channel. • Add flood-plain culverts and/or road dips for floodrelief and flow distribution. • Add flood-plain culverts or road dips. • Consider permeable roadfill (6.5.1.1).
<i>Channel migrating laterally across valley floor</i>	<p>Alignment may change over time so that stream approaches inlet at a greater angle. Bank and roadfill erosion is progressive as alignment worsens.</p>	<ul style="list-style-type: none"> • Increased probability of sediment/debris blockage at inlet. • Culvert capacity may be reduced due to aggradation or inlet energy losses. • Bed scour can occur in stream simulation culvert inlet. 	<ul style="list-style-type: none"> • Relocate crossing. • Widen crossing structure. • Build inlet transition (6.1.1.4). • Build structure that can be moved in future.
<i>Large elevation drop across existing structure caused by downstream incision</i>	<p>Preventing upstream incision requires over-steepening the structure's profile and/or adjacent reaches.</p> <p>Lowering the crossing to the level of the downstream channel may initiate a headcut moving upstream.</p>	<ul style="list-style-type: none"> • Some aquatic species may not pass steepened crossing. • Simulated streambed may not be sustainable if upstream reach does not provide amount or size of sediment required. • Habitat loss or degradation upstream. • Upstream channel incision can isolate stream from flood plain. • Upstream channel incision can destabilize banks. 	<ul style="list-style-type: none"> • Reconsider designed project profile (6.1.2.3). • Design steepened profile using appropriate permanent grade controls (Appendix B.2). • Restore incised channel to original grade. • Extend length of project to permit controlled incision upstream. Consider moderate-stability grade control structures upstream to control rate of headcut migration. • Restore downstream channel to original grade. • Mitigate specific risks.
	<p>If channel is still incising, dimensions, elevation and grade may change over the structure lifetime.</p>	<ul style="list-style-type: none"> • Crossing structure and/or grade control structures may become perched or fail. 	<ul style="list-style-type: none"> • Wait to replace crossing structure until incision has stopped. • Size culvert (or foundation) to accommodate possible range of profiles (see section 5.2.2.2). • Add downstream grade controls to control incision (6.1.2.3). • Restore channel to original grade.

Table 5.7—Crossing design issues associated with specific channel characteristics (continued).

CHANNEL CHARACTERISTIC	COMMON MAJOR ISSUES FOR CROSSING DESIGN	SPECIFIC RISKS	POSSIBLE DESIGN SOLUTIONS (SEE ALSO TABLE 6.7)
<p><i>Channels transporting high volumes of woody debris or sediment, or subject to debris flows</i></p>	<p>Crossing structure may plug and fail.</p>	<ul style="list-style-type: none"> • Road and aquatic habitat damage. • Frequent maintenance may be needed. • Traffic interruptions may be long. 	<ul style="list-style-type: none"> • Consider structures with removable tops for clean-out. • Harden approaches and fill for overtopping. • Prevent stream diversion if crossing is overtopped.
<p><i>Concave transitions (6.1.2.2) including braided streams and alluvial fans</i></p>	<p>Channel may aggrade and/or shift location.</p>	<ul style="list-style-type: none"> • Sediment deposition may reduce culvert capacity. • Debris may block inlet. • Stream may move across fan or valley away from culvert. 	<ul style="list-style-type: none"> • Relocate crossing away from transition or alluvial fan. • Build structure that can be moved in future. • Use wider, higher crossing structure (e.g., bridge). • Adjust project profile to intermediate grade (section 6.2.2.2). • Avoid destabilizing steeper upstream reach during construction. • Size structure to accommodate vertical adjustment potential.
<p><i>Convex transition (6.1.2.2)</i></p>	<p>Downstream bed may be destabilized during construction or during floods.</p>	<ul style="list-style-type: none"> • Headcut moves upstream through culvert. • Habitat loss or degradation upstream. • Upstream channel incision can isolate stream from flood plain. • Upstream channel incision can destabilize banks. • Crossing structure and/or grade control structures may become perched or fail. 	<ul style="list-style-type: none"> • Reevaluate vertical adjustment potential; consider lowering VAP line to accommodate risk of headcutting. • Construct new grade controls or reinforce natural controls. • Widen structure to avoid concentrated outflow.

Stream Simulation

Table 5.7—Crossing design issues associated with specific channel characteristics (continued).

CHANNEL CHARACTERISTIC	COMMON MAJOR ISSUES FOR CROSSING DESIGN	SPECIFIC RISKS	POSSIBLE DESIGN SOLUTIONS (SEE ALSO TABLE 6.7)
Channels with large key features (large wood, boulders) controlling slope and roughness (6.1.2.2)	Key features must be simulated inside the structure.	<ul style="list-style-type: none"> Simulated key features are of different material (i.e., rock simulates logs) and may not function the same (eg., diversifying water velocity, retaining sediment). Simulated features may trap sediment and debris to form a dam. 	<ul style="list-style-type: none"> Select materials and construct key features carefully. Use shorter, wider crossing structure.
Bedrock	Key features (wood) may stabilize alluvial veneer over bedrock in reference reach.	<ul style="list-style-type: none"> Alluvial veneer may not be self-sustainable in culvert without stable key features. 	<ul style="list-style-type: none"> Span channel without disturbing streambed and banks. Construct fixed key features to retain alluvium.
Cohesive material (silt/clay)	Bed construction inside pipe is not practical because silt/clay material cannot be moved and stabilized.	<ul style="list-style-type: none"> Constructed bed (or no bed) may not simulate natural channel and aquatic species may not be able to move through. 	<ul style="list-style-type: none"> Span channel without disturbing streambed and banks.

of the road crossing might simply be the result of flow constriction at an existing undersized crossing. If so, a larger structure may be all that is needed to solve the problem.

Flood-plain observations will also help in selecting a roughness factor for flood-plain flow estimation, if you intend to use a model such as WinXSPRO or HEC-RAS.

5.3.2 Lateral Adjustment Potential and Alignment

On streams with a high potential for lateral channel migration, the channel's angle of approach to the crossing structure may become more acute over time. As described in appendix A, a poor alignment is an especially important risk factor in streams transporting woody debris. Evidence of past channel shifting (e.g., an acute angle of approach to the culvert inlet, bank erosion on one bank) can help in evaluating the risk to the replacement structure. Also consider factors, such as current bank stability (section 5.1.6.4), land use and vegetative condition, and probable future land use changes.

Understanding the natural channel's (pre-disturbance) pattern is essential for proper layout of a stream-simulation installation. Culverts shorten and steepen channels when they replace a bend. In the case of a stream-simulation culvert, such an increase in channel slope could put the simulated streambed at risk. Using the sketch map and field observations, try to detect the natural channel location and pattern. This would be the starting point for designing the replacement crossing alignment.

It is especially important to consider natural **channel pattern** where a crossing must be located on a meandering stream. Several options are described in section 6.1.1 for minimizing risk by keeping the crossing short, aligning it with the stream, and providing efficient transitions. Preview that section and consider the various alignment options (figure 6.4) while still in the field. Observations of bed and bank stability are vital in selecting the least damaging option. If a skewed culvert-to-channel alignment is being considered, bank materials and stability will determine whether bank stabilization measures are needed near the inlet or outlet. Where channel straightening cannot be avoided, the channel may respond by eroding either its banks or its bed. Try to predict likely channel responses to such changes by considering the relative resistance of bed and bank materials.

5.3.3 Headcutting Potential

Even in a uniform longitudinal profile, simply replacing an undersized culvert with a larger one set lower in elevation can cause the adjacent stream reaches to adjust. Sediment accumulated above the old culvert remobilizes, although usually the adjustment is not large enough to create a problem. Where the downstream reach has incised, however, headcutting upstream of the replacement structure (section 5.2.2.2) can be substantial enough to affect buried infrastructure, destabilize streambanks, modify aquatic habitats, etc. Decide whether to control such a headcut or allow it to progress upstream, considering the trade-offs between the extent and duration of impacts, versus the benefit of allowing the channel to evolve to a natural self-sustaining condition.

Deciding how to handle any expected headcutting requires answers to questions such as the following:

- How much headcutting is likely if no controls are implemented? How far upstream might it go?
- What effects will the expected headcut have on streambed and banks? How long will they last?
- Should headcutting be prevented?
- Should headcutting be allowed to occur at an uncontrolled rate?
- Should the rate of headcutting be slowed by temporary grade controls?

Before making these decisions, be aware of the types of effects headcuts can have. Bates (2003) identified the following physical, biological, and infrastructure issues for teams to consider when determining whether to control a headcut or allow it to occur.

Extent of headcut

The upstream distance that a headcut can travel depends on the stream slope, bed composition, sediment supply to the reach, and the presence of stable debris and/or large rock in the channel. The extent of headcutting is usually less in coarse-grained or debris-laden channels than in finer-bedded streams, because the headcut is more likely to encounter a stable grade control that prevents it from moving further upstream. A channel with a high supply of mobile bed material will reach equilibrium more rapidly than a channel with a low rate of sediment supply.

Condition of upstream channel and banks

Where a reach has aggraded above an undersized culvert, the channel can stabilize and return to its natural condition after some headcutting occurs through the aggraded area. If the upstream banks are already marginally stable, however, the degrading channel can undermine and destabilize them.

Habitat impacts of upstream channel incision

Allowing a large headcut to travel freely upstream can damage aquatic habitats. For example, a newly incised channel may be narrow and confined, with habitat diversity and stability reduced because the channel cannot access its flood plain during high flows. Although the channel may evolve back into its initial configuration (appendix A, figure A.28), substantial bank erosion and habitat instability may persist for a long time, up to a century in some cases (figure 5.18). Where bedrock is shallow, a headcut may expose it; and, if no debris or sediment structure is left, the stream will have difficulty trapping new sediments to recover habitat diversity and stability. Some bedrock (such as siltstone) is easily erodible once exposed. A headcut can also cause enough incision to leave side channels perched, inaccessible, or dry. Avoid headcuts in such areas. Restoring incised stream channels may require substantial channel reconstruction with wood and/or rock structures.



Figure 5.18—Major channel instability occurring on the Homochitto River, MS. Bank erosion and widening follow channel incision on this fine-grained channel.

Stream Simulation

Wetlands have formed upstream of many undersized or perched culverts. Although artificial, these wetlands may perform important functions for the riparian ecosystem. Carefully consider their fate when replacing culverts.

Presence of fish or other organisms

A headcut can pose a short-term risk of loss of organisms in the bed or pools just upstream of a culvert. The bed may scour at a lower flow than normal in a headcutting situation. Eggs and fry in the gravels may be lost.

Habitat impacts to downstream channel from sediment release

The risk to downstream aquatic habitats depends on the volume and rate of sediment released by a headcut, as well as the transport capacity in downstream reaches. Downstream of large headcuts, not only will the total volume of sediment in transport increase, but sediment will move at lower flows until the upstream channel and banks have stabilized. Sediment deposition may occur in streambed areas not normally subject to deposition. Small headcuts may not pose much risk at all to downstream reaches in many steep mountain streams.

Decrease in culvert and channel capacity from initial slug of bed material

Where bed material is mobile, allowing an uncontrolled headcut upstream of a culvert may result in mobilizing a slug of material during a single flow event. As this material moves through the culvert and the downstream channel, it can reduce the capacity of both. A loss of capacity can result in additional deposition and, in extreme cases, can fill the entire channel and plug the culvert.

Allow less headcutting where the culvert and/or channel have even a short-term risk of plugging by sediment and debris. Consider similar limitations where structures further downstream are at risk from a loss of channel capacity or where banks are at risk of erosion.

Proximity of upstream utilities and structures

If a headcut is allowed to continue upstream, it can jeopardize structures in or beneath the channel or on the banks. Asking the utility company to visit the site and locate any lines is common practice. Be aware of the potential effects of increased bank erosion on structures near the channel.

Potential for new fish passage barriers within the degraded channel

Consider the potential for channel incision to create barriers to passage of fish or other aquatic species. Buried logs, nonerodible materials, and infrastructure, such as buried pipelines, are commonly exposed by channel headcuts. As the channel headcuts to such a feature, the feature itself may become a new fish passage barrier. Adding to the difficulty, these problems may occur where they are not visible from the project site, where access is more difficult, or across a property boundary. In addition, upstream culverts could become perched, or, if they are embedded, their beds may wash out.

Readers may also want to consult Castro's 2003 discussion of headcutting considerations for the planning phase of a culvert replacement or removal project.

5.3.4 Debris

To determine whether woody debris poses a potential hazard to the crossing structure, evaluate the stability, size, and accumulation potential of wood in the project reach, especially upstream of the road crossing. Look for debris accumulations, and dead or undermined trees that could fall into the stream. Review the debris risk assessment in section 4.3, the key-feature summary in table 5.6, and include historical information. Ask the following questions:

- Is the crossing in a land type where floods transport large wood?
- Has the existing structure ever had problems with woody debris plugging?
- Are other nearby structures subject to plugging?
- How large is the wood in transport?
- What is the condition of wood in the reach? Is it durable, or fragile enough to break apart in transport?

To project future debris availability and stability, consider the long-term management plan in the watershed upstream of the crossing. Are debris inputs likely to change?

Where wood is an important structural component of the channel, also consider whether downstream channel conditions and stability depend on

Stream Simulation

upstream woody debris inputs. If so, wood transport through the crossing structure may be critical to the long-term stability of the whole reach.

In general, stream-simulation culverts with good alignments tend to be large enough that debris passes freely through. However, difficulties might occur with large wood and rootwads in low-profile structures or where structures are poorly aligned with the stream.

5.3.5 Unstable Channels

If the channel is unstable (rapidly incising, aggrading, shifting laterally, etc. See **channel stability** in glossary), the design will have to deal with changing conditions as the stream evolves toward a new equilibrium. Any work performed in these situations must factor in both reach-scale and watershed-scale processes:

- What is the cause of the channel instability? Is it caused by local land-use activities? Higher peak flows, due to watershed development? Downstream channel incision? Sudden, large lateral movements? Extensive bank failures?
- What is the proximity and extent of channel instability in relation to the crossing?
- Are any restoration activities already planned for improving channel stability?
- What are the anticipated dimensions and configuration of the recovered channel? What is the time frame for recovery?

Where a channel has been recently disturbed by **mass wasting** events or extreme floods, consider leaving the road closed to allow time for the channel to adjust to the new conditions. If the road must be reopened, consider whether a channel restoration project is feasible, given watershed conditions and trends. If restoration is not feasible, the stream-simulation design approach may not work, and you might need to use an alternative design style (see appendix B).

If stream simulation is chosen, then it is important to estimate not only the vertical adjustment potential but also future channel dimensions and pattern. The uncertainty about channel change, as well as the unpredictability of future disturbances, can make this kind of prediction a very uncertain. Only a qualified and experienced team should perform the

site assessment and replacement structure design on an unstable channel—and, even then, the team should plan for maintenance.

5.4 DOCUMENT KEY DESIGN CONSIDERATIONS AND RECOMMENDATIONS

At this point, document the results of the site assessment by summarizing the project site characteristics listed below. See also the assessment checklist in appendix C.

Project reach characteristics and risks:

- Longitudinal profile; what key features control channel slope? How mobile are they?
- Downstream channel incision; is the crossing acting as grade control?
- Vertical adjustment potential.
- Bed material size and mobility.
- Bank materials, height, and stability.
- Variability in channel bankfull width; what controls differences in width?
- Potential for lateral channel shift and bank erosion.
- Estimate of bankfull and 100-year flows.
- Flood-plain conveyance; sites for flood-plain drainage structures.
- Flood-plain constriction potential.
- Geotechnical concerns: soft soils, bedrock, ground water.
- Key grade controls that anchor the longitudinal profile and that should not be disturbed in construction.
- Habitats requiring special protection in design and during construction.
- Site logistical constraints (property boundaries, infrastructure, etc.).
- Construction and maintenance access.
- Sensitive areas (to avoid during construction) in vicinity of crossing.
- Potential locations for construction equipment and materials storage.
- Construction recommendations: topsoil and vegetation salvage needs and opportunities, potential areas for dispersing and filtering sediment-laden water pumped from the excavation, etc.

Stream Simulation

Also, document interpretations of important geomorphic processes that may affect the site, the new structure, and the feasibility of a stream-simulation design. How will the channel respond to the replacement or removal of the crossing? How should the channel and/or road be modified to accommodate a new structure? With this detailed understanding of the site, revisit the project objectives defined earlier, and develop them into specific design objectives. If stream simulation appears to be infeasible, consider other design methods (see appendix B). Site-specific design objectives might deal with some of the following topics:

- Need for alignment control.
- Need for grade controls outside the crossing.
- Need for channel restoration or habitat protection.
- Special sediment control or stabilization measures needed at road crossing or in stream.
- Characteristics needed for aquatic species passage.
- Characteristics needed for passage of semi-aquatic and terrestrial species.

A key task is to agree on the channel characteristics needed to achieve the desired degree of passage. For example, if weak-swimming species, amphibians, and small mammals that depend on channel margins for movement need to pass through the structure, the structure will need to be wide enough to maintain **banklines** or dry margins at low to moderate flows.

5.5 REFERENCE REACH: THE PATTERN FOR STREAM-SIMULATION DESIGN

The reference reach will not be finally selected until the project profile design is complete (see section 6.1). However, geomorphic data on one or more potential reference reaches are generally collected during the site assessment. For that reason, criteria for selecting a reference reach are discussed here, along with the additional data requirements.

The ideal reference reach represents the physical, hydrologic, and hydraulic characteristics of the channel that would be at the culvert site if the road did not exist. This ideal will not always be achieved because the reference reach depends on the project profile—the longitudinal profile of the stream simulation channel to be constructed. The project profile may have to differ from the natural channel slope for a number of reasons (section 6.1). Although the reference reach may not represent historical

or average conditions of the project reach, it must be within the range of variation found in the vicinity. Looking at the range of variability in slope, width, etc. in the project area can provide an idea of how far a stream segment can depart from average and still be stable in the system.

Slope is a primary criterion for selecting a reference reach because it drives sediment erosion, transport, and deposition. These processes, in turn, control sediment characteristics at a given location in the channel. Thus, the reference reach slope must be similar to the design slope through the crossing. However, keep in mind that the reference reach is simulated in its entirety; width, slope, length, channel shape, bed characteristics, and roughness are all included in the simulation. The reference reach also should be similar in cross-section dimensions and entrenchment to the reaches upstream and downstream of the crossing. It represents the channel that will reconnect those reaches without creating flow discontinuities.

The reference reach is a stable reach upstream or downstream from the crossing but always outside the influence of the existing structure. The factors that control channel dimensions (water discharge, sediment supply) in the reference reach must be similar to those that will control the simulation. At most sites, a reference reach can be identified close to the crossing, and the site data collected during the site assessment typically include a reach suitable for use as a reference. Occasionally, the most suitable reference reach may be some distance from the crossing site. There is no problem with this, so long as flow and **sediment regimes** are very similar. The reference reach should not be separated from the crossing by a major tributary junction, sediment source, or sediment sink.

The following considerations go into selecting a reference reach:

- The reference reach should be out of the area of influence of the existing crossing. Generally, it is upstream of the crossing to avoid any downstream channel changes the crossing may have caused. However, it can also be downstream if crossing effects are localized, and channel dimensions and slope are more appropriate to simulate at the crossing.
- The reference reach channel slope should be similar to the project profile slope through the road-stream crossing. Before selecting a final reference reach, determine the alignment and profile for the crossing project (section 6.1).
- Cross-section dimensions in the reference reach should be similar to the reaches near crossing. Entrenchment also should be similar.

Stream Simulation

- Flow and sediment regimes at the reference reach should be similar to those at the crossing. No major tributary junctions or sediment sources should be between the reference reach and the crossing. The reference-reach bed material must be similar in size and mobility to the reach upstream of the crossing that will supply sediment to the stream-simulation channel.
- The length of the reference reach should be at least as long as the road-stream crossing structure.
- Determine the stability of both the reference reach and project reach. The reference-reach approach for channel design applies only to relatively stable channels.
- Where possible, avoid selecting a highly sinuous reference reach. A good method for testing the feasibility of using a particular reach as a reference reach is to visualize it enclosed in a culvert. Consider the characteristics that cannot be simulated, and whether they might compromise the simulation.
- Consider the distribution of channel units upstream and downstream from the road-stream crossing. For example, pool locations and spacing may dictate that the simulated channel include a run or pool. The reference reach should include those channel units.

At new crossings, the undisturbed natural channel at the site is the reference reach. Ideally, you would build the crossing over the stream without disturbing it.

Where the site has a concave- or convex-profile shape, it may be necessary to measure possible reference reaches upstream and downstream of the crossing. Near grade breaks, a common method of reconnecting the two different slope segments is by constructing an intermediate-gradient transition inside the pipe. Elements of both upstream and downstream reaches may be incorporated in the design (see for example figure 6.8). Theoretically, a similar transition reach on another nearby stream could be used as the reference reach, but it is relatively uncommon to find streams and watersheds that are that comparable.

If a long reach outside the new structure will be regraded, conduct the reference-reach survey more carefully than in simpler cases. In this case, the data will have to support design of not only the simulated streambed inside the crossing structure, but also a channel-reconstruction project.

In the reconstructed reach outside of the road-stream crossing, features typically not built inside a structure (such as soil banks, planform characteristics, and large-wood grade controls) will be constructed and stabilized.

If the stream channel in the crossing vicinity has been recently disturbed, it is likely to be in a state of flux, evolving toward an equilibrium shape and grade. If the road can remain closed for an extended period, wait to construct the crossing until the stream reestablishes some measure of stability. Otherwise, you may be able to find a reference reach upstream of the disturbance.

For streams undergoing regional channel incision, if the headcut will be allowed to progress upstream through the crossing site, use downstream reaches that have already stabilized as the reference reach. Accommodate changes expected as the channel evolves (see appendix A, section A.7.2). If the crossing will be retained as a grade control, select a reference reach that has a gradient similar to the simulated-streambed design gradient.

The incised channel is one possible situation where the channel through the crossing may have a steeper grade than the adjacent reaches. Project objectives (e.g., avoid channel incision upstream, preserve wetland habitat above crossing) or constraints (e.g., rights-of-way, property boundaries) may dictate the steeper grade. In cases like these, achieving stream simulation may or may not be possible, depending on whether reference reaches at the necessary grade exist. Until better information becomes available about how much of a difference is sustainable, a reasonable guideline is to keep the simulated channel within 25 percent of the slope of the reference reach.

If the immediate area clearly cannot provide a reference reach, be sure you understand why not. If the reason is that the channel is highly unstable or the reach has characteristics like tortuous meanders that cannot be simulated inside a crossing structure, reconsider whether the crossing location is a good one. If the crossing cannot be moved, stream simulation may not be an appropriate design strategy.

Stream Simulation

Where no appropriate reference reach exists close to the road-stream crossing, it is occasionally possible to find a reach with similar discharge, slope, streambed materials, and channel type elsewhere in the same watershed or a nearby watershed. Use great care here. Species inhabiting the project reach must be able to negotiate the transposed channel. Also, this kind of transfer may not result in a sustainable simulation because of the differences in particle size or amount of sediment input from the upstream reach. In cases when data is transferred from a reach with a different drainage area from the project site, a regional relationship between drainage area and bankfull width and depth may allow you to size the simulated channel correctly. Refer to Rosgen (1994, 1996) for procedures on scaling channel dimensions from regional relationships between channel dimensions and drainage area. However, again, be aware that, in this situation, sediment availability could be quite different, and the reach upstream of the simulated channel may not be able to supply the size and amount of sediment that the steeper reach needs for long-term sustainability. If long-term streambed sustainability appears unlikely, stream simulation may not be feasible, and you may have to settle for a hybrid or other design strategy (see appendix B).

5.5.1 Reference Reach Data Required for Stream Simulation Design

Assuming that the reference reach is included in the longitudinal profile already surveyed, most or all of the data needed for design may already be in hand. Additional data collection and analysis of the longitudinal profile, cross sections, and other survey data may be needed to define the following reference-reach characteristics.

- Residual pool depth (figure 5.19). Average residual pool depth is used in stream simulation design to determine how deeply to embed a full-bottom culvert, and it is considered in decisions about how deep to construct foundations for an open-bottom structure. Pools formed by unusual controls that would not be simulated in a culvert (debris jams, large logs, large boulders) should not be included here.
- Size, spacing, height, and mobility of grade controls and other key features (figure 5.19).
- Bed material size distribution, degree of armoring (see section 5.2.1).
- Bankfull channel dimensions: depth, width, and width variability.
- Bank or channel margin structure and diversity.

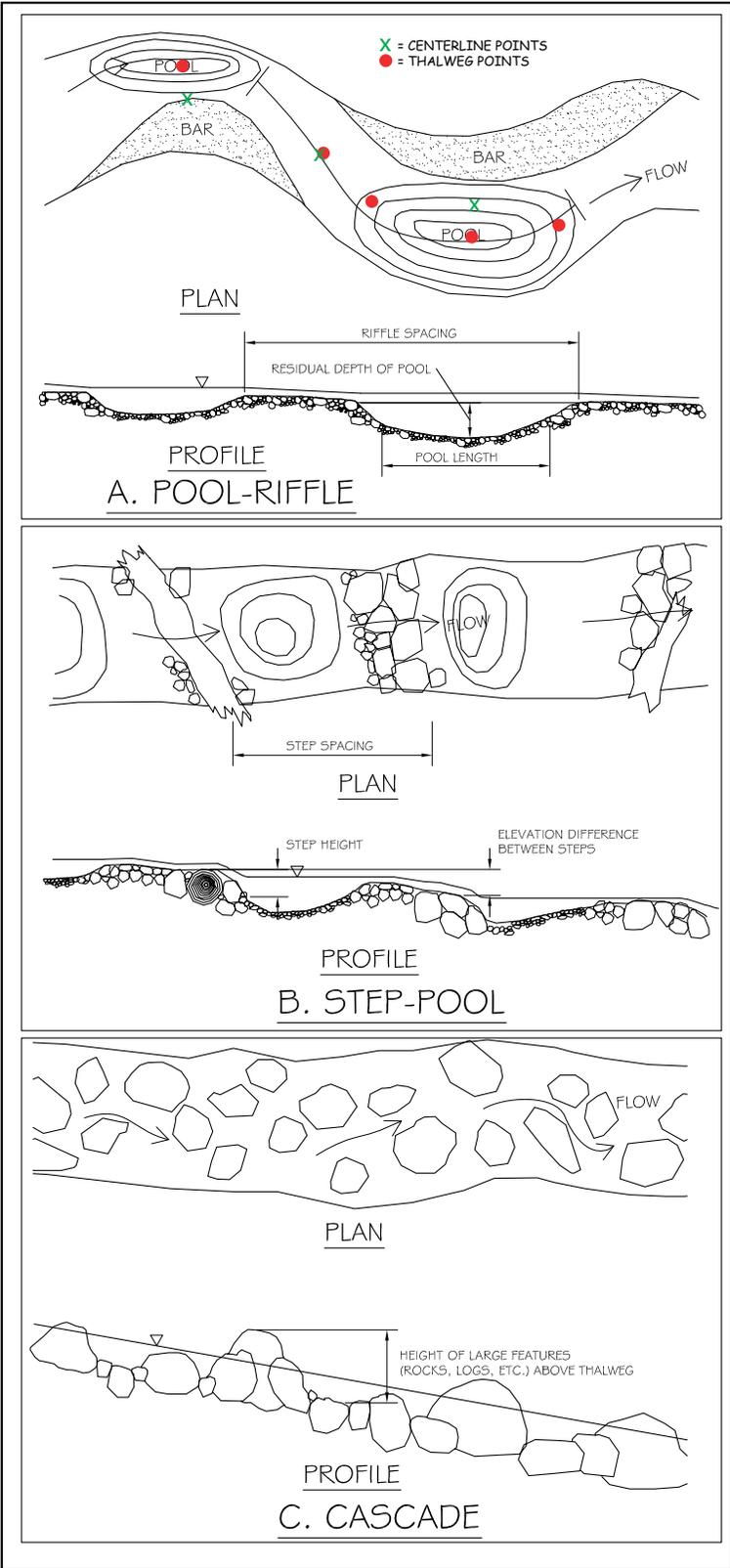


Figure 5.19—Some reference reach longitudinal profile measurements.