Geomorphologic Impacts of Culvert Replacement and Removal: *Avoiding Channel Incision*

Photo Courtesy of Jane Kelly

By Janine Castro, Geomorphologist, USFWS, Portland, OR

These guidelines are used by USFWS when implementing culvert replacement and removal projects, and are recommended practices for entities involved in stream crossing activities. These guidelines should serve to assist with any culvert-related endangered species consultation requirements. Compliance with these guidelines should assist in minimizing or avoiding impacts during project construction activities, and are intended to help culvert projects result in long-term benefits to listed species recovery. However, consistency with these guidelines does not negate the need for Endangered Species Act (ESA) consultation on culvert removal and replacement projects, where listed ESA species may be present. For additional information on ESA compliance requirements for culvert replacement and removal projects, please contact the U.S. Fish and Wildlife Service's Oregon State Office (Rollie White) at (503) 231-6179, or any of the following field offices: LaGrande (541- 962-8509), Bend (541-383-7146), Newport (541-867-4558), or Roseburg (541-957-3474).

OVERVIEW

This technical note describes a specific methodology for determining the vertical stability of stream channels in the vicinity of existing road crossings (primarily culverts), although the methodology is applicable along any reach of a stream. Vertical stability refers to the relative constancy over time of streambed elevation through a given stream reach. A streambed that deepens over time is referred to as "incising," while a rising bed elevation is indicative of an "aggrading" stream channel. Streams that are incising or aggrading on a reach scale are considered to be vertically unstable. However, local variations in bed elevation are inherent in streams because of scour and fill processes, and should not be confused with vertically unstable channels.

Vertical stability is of considerable interest at culverts because these structures often provide elevational control for incising stream channels. Provision of elevational control or "grade control" is important because removal of this control may allow channel incision to migrate upstream, potentially affecting habitat and impeding fish passage. Of primary concern to the US Fish and Wildlife Service (Service), and hence the subject of this paper, are culvert removal or replacement projects in vertically unstable streams. Activities associated with these streams can lead to additional channel incision with a resultant loss of habitat and potential fish passage blockage. Changes to the channel profile post-project are collectively referred to as channel "regrade".

BACKGROUND

Culverts are part of our transportation network and as such, are typically planned, designed, installed, and maintained by various departments of transportation at the local, county, state and federal level. Biologists become involved in culvert replacement and removal projects because the structures interface directly with stream systems and thus floodplain, riparian, and stream habitat. Because of this interface, culvert removal and replacement projects require interdisciplinary participation.

It is deceptively easy to assume that culvert-related problems in a stream system are site-specific and site-limited. This is not always the case, and may in fact be the exception. Streams are linear systems that move mass and energy along the channel primarily in upstream/downstream directions and through the floodplain in all directions. It is critical that these linkages are well understood and analyzed before any instream action is taken. Improperly installed culverts compromise or eliminate fish and other aquatic species passage and can alter the quantity or quality of stream corridor habitat. Even properly designed and installed culverts can become fish passage barriers if channel incision occurs downstream and migrates upstream to an existing culvert, since culverts are static structures in dynamic systems.

Channel incision, the overall lowering of a streambed over time, is one of the most common channel processes encountered when working in streams in the Pacific Northwest (PNW). Understanding the causal factor and related stream adjustments as they pertain to the channel incision and evolution process is essential so that these processes are addressed when designing instream projects. By overlooking the geomorphology of these streams because of lack of time, money, or expertise, otherwise well-intentioned and well-planned projects may be completely ineffective or detrimental to the stream system and related habitat.

Incision Processes

Channel incision may exist at a site prior to project implementation, which requires special design considerations, or it may occur post-project, potentially altering the effectiveness of the project. Channel incision can be initiated in numerous ways (Table 1). One of the most common initiators is a change in peak discharge due to land management activities and infrastructure.

Table 1: Causes of Channel Incision

A. Decreased Erosional Resistance
   a. Decreased or modified riparian vegetation cover or rooting strength due to increased agricultural activity, urbanization, timber harvest, overgrazing, fires and droughts.
   b. Watershed surface disturbance causing decreased permeability (i.e. urbanization).
   c. Removal of instream structural elements such as large wood or beaver dams.

B. Increased Erosional Forces
   a. Constriction of flow by culverts, dikes, bridges, and fill material.
   b. Concentration of flow by roads, trails, and ditches.
   c. Steepening of gradient and energy slope by channelization and meander cutoffs, base-level lowering by decreased lake or reservoir level.

d. Increase in duration, frequency, or intensity of sediment-transporting flows due to more rapid routing of water to the receiving channel, increase in volume of flood peaks, or artificially elevated wet-season base flows.
e. Decrease of sediment load.

Modified from: Schumm, Harvey, & Watson, 1984.

A primary mechanism that changes the volume and timing of peak flows is the road network, which essentially increases the drainage density of channels, intercepts subsurface water, and decreases the time for overland runoff to reach the stream channel. Even though a watershed receives the same amount of precipitation, it is transported through the system much more quickly, thus resulting in higher peak discharges and resultant increases in stream power. This increased stream power can more effectively erode the streambed and banks. Because the total amount of water remains relatively constant, base flows decrease because the rapid runoff reduces the total amount of water that can infiltrate and be stored in the soil.

Lane's (1955) stream balance relationship clarifies this point:

$$Q\,S \propto Q_s\,d_{50}$$

where Q = channel-forming discharge, S = channel gradient, Q_s = bed-material discharge, and d_{50} = median grain size of bed material.

The stream balance equation indicates that if available stream power is augmented by an increase in discharge or the gradient of the stream, there would be an excess amount of stream power relative to the discharge of bed-material sediment whose resistance is a measure of particle diameter. Additional sediment would be eroded from the channel resulting in: (1) an increase in bed-material discharge to an amount commensurate with the heightened stream power, and (2) a decrease in channel gradient and, consequently, stream power as the elevation of the channel bed is lowered.

Assuming, for illustrative purposes, that the streambed and banks are composed of the same material, the streambed will erode first. This is due to the higher shear stresses exerted on the bottom of the stream channel by the flowing water. The streambed will continue to erode until (1) the critical bank height is exceeded resulting in bank failure and channel widening which may restore the sediment/water balance, (2) a control point is encountered such as bedrock, buried wood, pipelines, bridge aprons, fords, or culverts, (3) deposits of coarse sediment armor the channel bed, or (4) there is a significant change in valley type (i.e. alluvial with floodplain to confined with hillslope interaction) and/or gradient (i.e. low gradient to a much steeper gradient). If the channel bed is more resistant to erosion than the banks (i.e. cobble bed with sand banks), then bank erosion will be the likely mode of adjustment.

Since channel incision generally migrates upstream, an existing culvert may be acting as a grade control, halting the upstream progression of the headcut and channel regrade.

Stream Impacts from Undersized Culverts

Culverts in the PNW have always been problematic for migrating anadromous and resident fish species, but have also impacted other aquatic and terrestrial species because they disrupt the longitudinal continuity, or connectedness, of a stream channel. There has been a great amount of interest and subsequent activity to replace culverts in the PNW with larger culverts or bridges which do not constrict flow or disrupt natural stream processes during low to moderate flows in the stream channel. [1] Culverts are often replaced or removed because they are fish passage barriers due to (1) high velocities, (2) shallow flow depths, (3) length of run with no resting areas, or (4) excessive jump height. High quality aquatic habitat or habitat required for a specific species life stage may exist above a culvert providing the impetus for replacement or removal; however, replacing or removing a culvert without a thorough understanding of the stream dynamics may result in the loss of the upstream habitat that was the stimulus for the project.

Culvert design historically focused on passing water, not sediment and large wood, which resulted in small pipes that become pressurized during high flows. This has resulted in significant problems at culverts including (1) plugging due to large wood transport, (2) sediment deposition at the inlet due to the backwater effect, and (3) high velocity flows exiting the culvert resulting in channel scour.

Plugging of a culvert during flood flows can result in overtopping and failure of the road prism. The road fill material is then directly delivered to the stream system, potentially impacting downstream habitat. Bank erosion and plunge pools can develop at the downstream end of a culvert due to flow constriction within the barrel of the culvert and the resultant turbulent jet of water at the outlet. It is the turbulent jet that dislodges particles on the bed and banks of the channel, generally resulting in a deep plunge pool and erosion of the streambanks (Figure 1). A wedge-shaped sediment deposit upstream of a culvert is also expected when a culvert (1) is undersized, (2) is located above the streambed elevation for the provision of stormwater detention, or (3) becomes plugged with debris due to the decreased velocities and backwater effect. The sediment deposit generally occurs directly upstream (mid-channel) of the culvert which can then cause deflection of flow around the deposit and erosion of the streambanks and road fill. This is considered a *localized effect* of an undersized culvert and can be corrected with culvert replacement or removal and sediment excavation. Grade control is generally not necessary. Using the elevation of the culvert and the stream gradient, the upstream extent of incision through the sediment wedge and the total volume of sediment can be calculated.

---

[1] *For specific information on culvert design for fish passage in Oregon refer to the Oregon Department of Fish and Wildlife document "Guidelines and Criteria For Stream-Road Crossings" (1997) and Oregon House Bill 3002. For Washington State, refer to the Revised Code of Washington (RCW), Titles 75 and 77, and the Washington Administrative Code (WAC) Chapters 220-110-010 through 220-110-360.*

Figure 1. Undersized Culvert and Bridge Replacement

Photo Courtesy of Dan Perritt

Stream Impacts from Channel Incision

Culvert replacement or removal may allow channel incision to progress upstream unchecked. Upstream migration of channel incision proceeds in a relatively predictable manner and is *system-wide*. The channel typically deepens due to a change in the proportionality between the amount and size of sediment, the amount of water, and the stream slope. For example, channel incision is very common downstream of dams because the bedload is effectively removed from the stream system, disrupting the balance between sediment input and sediment output from the reach. After channel incision has occurred and the channel bed becomes stable, the "new" channel can contain higher flows before spilling out onto the floodplain. The subsequent pressure of the greater confined flows is then translated to the streambanks where significant erosion can occur. Once the channel has enlarged to such an extent that the near bank shear stress is significantly reduced, the system will start to stabilize. This "Channel Evolution Model" has been well-documented and is discussed later in the Methodology Section of this document (Schumm, Harvey, and Watson, 1984; Simon and Rinaldi, 2000).

If system-wide channel incision has occurred and a culvert is providing grade control, replacement or removal of the culvert may result in the following responses:

1. Headcut migration upstream and subsequent deepening of the stream channel.
2. Relatively higher channel banks that may exceed critical height resulting in mass failure (bank erosion).
3. Addition of sediment to the stream system due to erosion of the channel boundary.
4. Disconnection of floodplains from active stream channels.
5. Prematurely dewatered or disconnected backwater habitat.
6. Locally increased channel slope and loss of pool habitat.
7. Drainage of shallow aquifers which affects riparian vegetation.
8. Meander cut-offs due to knickpoint migration across a meander neck caused by an increased elevation drop between the old floodplain and active channel bed.

9. Deposition of large masses of sediment causing localized channel braiding and instability of the streambanks.

METHODOLOGY FOR DETERMINING VERTICAL CHANNEL STABILITY

The main geomorphic concern with culvert replacement and removal is a rapid, and potentially catastrophic, regrade of the stream channel including channel bed degradation, lateral erosion, and subsequent deposition of eroded sediments. An existing vertically unstable condition indicates that the likelihood for channel regrade following culvert replacement or removal is high. To evaluate the risk for channel regrade, several approaches may be used to determine if a stream is actively incising or has historically incised. Two methodologies (channel evolution and longitudinal profiles) are presented which are widely-used and generally adequate for the purpose of culvert evaluation.

Channel evolution is most obvious in streams with cohesive beds and banks (Figure 2), because headcuts remain fairly vertical as they progress upstream, and are thus readily visible. In gravel-bedded rivers, headcuts may be dispersed out through several thousand feet of channel and may only be detectable with longitudinal surveys. The Channel Evolution Model is a good tool for reconnaissance level work, however, longitudinal profiles are required to quantify the actual extent of incision. While the Channel Evolution Model indicates a trend for channel stability, longitudinal profiles provide some of the data required for the design of grade control structures.

Figure 2. Example of Channel Evolution from South Dakota

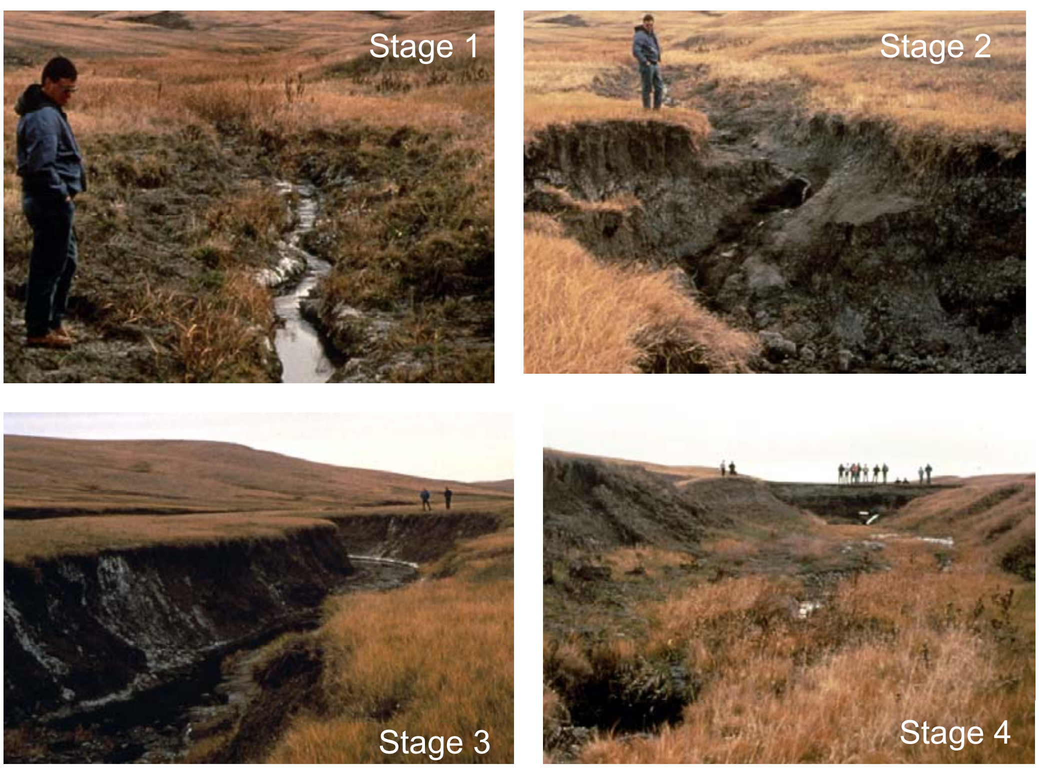


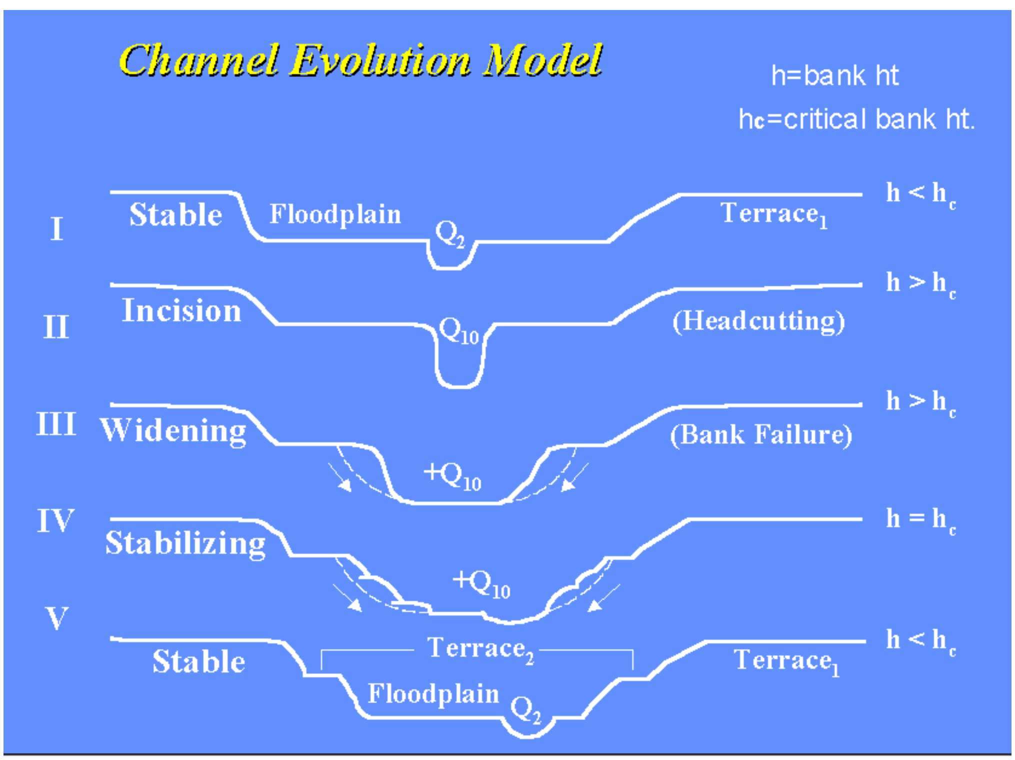
Photo courtesy of Lyle Steffen

Channel Evolution Model

Channel evolution is the progression from a stable channel, to channel incision, to widening, to stabilization (Figure 3). While the rate and timing of the various stages can vary dramatically, the general trend is well documented (Schumm et al., 1984; Simon and Rinaldi, 2000). The use of channel evolution models is appropriate for alluvial streams that can vertically and/or laterally adjust.

Determining what stage of channel evolution exists above and below a culvert is instrumental in determining the vertical stability of a stream channel. Since channel incision is typically followed by channel widening and floodplain development in unconstrained alluvial channels, a difference in the stages of channel evolution above and below a culvert (for example, Stage I upstream of a culvert and Stage III below the culvert) can indicate that the culvert is functioning as grade control structure, essentially preventing a headcut from migrating upstream. In this case, it may be prudent to add grade control in addition to culvert replacement or removal so that additional channel incision does not occur above the structure.

Figure 3: Channel Evolution Model



From Schumm, Harvey, and Watson, 1984.

When determining if channel incision is affecting or has affected a particular stream reach, there are numerous channel degradation indicators that can be used for assessment (Table 2).

Table 2. Channel Degradation Indicators

- ✓ Headcuts – a vertical drop or off-set in the channel bed.
- ✓ No Sediment Deposits – erosion of the channel bed down to bedrock or other resistant soil layer.
- ✓ Toe of Bank is Vertical – lack of a sediment facet at the interface between the streambed and banks.
- ✓ Cultural Features Exposed – exposed bridge footings or aprons, exposed pipelines, or perched culverts.
- ✓ Historical Reference – individual accounts, historical photos, and old maps or surveys.
- ✓ Lack of Pools – long reaches of riffle or run, no pool areas.
- ✓ Dead or Dying Riparian Vegetation – loss of riparian vegetation due to lowering of shallow aquifer.
- ✓ Dewatering of Aquifers – effluent from banks and evidence from wells and piezometers.
- ✓ Upland Species Encroaching into Floodplain – change in moisture conditions resulting in plant community changes.

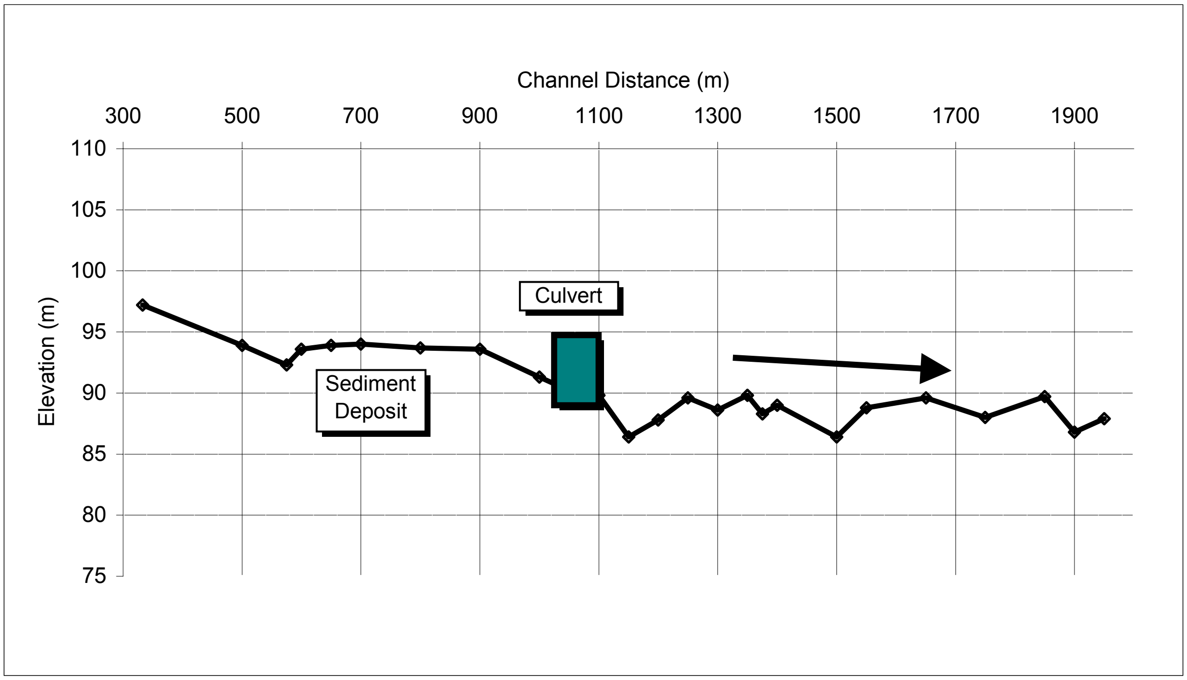
The stage of channel evolution can be determined by investigating the type of erosion that is occurring at a site. If the primary mechanism is erosion of the channel bed, then the channel is at Stage 2. If bank erosion is the primary process, then the channel is at Stage 3. Stage 4 channels exhibit some channel stability and sediment deposition near the banks. It may be difficult to determine whether a stream is at a Stage 1 or 5 if the degree of incision is minimal. It is not uncommon to have a Stage 1 channel above a culvert and a Stage 5 channel below. If the degree of incision is only a few feet, it may be hard to detect, although the impacts of removing the culvert may still occur (see Stream Impacts from Channel Incision, page 5). This situation requires a longitudinal profile to determine the actual degree of channel bed off-set and the stages of channel evolution.

Note: erosion of the outside of meander bends is a natural process and does not necessarily indicate channel incision.

Longitudinal Profile

Longitudinal profiles provide information about overall stream gradient, habitat unit gradient (pool, riffle, run), habitat unit length and spacing, profile breaks or headcuts, residual pools, and bed roughness and variation. A surveyed longitudinal profile for at least 20 channel widths (centered on the road crossing) will be necessary when determining the existence and magnitude of a potential headcut. In addition, it is important to survey beyond the area that is directly influenced by the culvert (i.e. the sediment deposit upstream and area of expansion scour downstream, or beyond areas influenced by other structures such as revetments)(Figure 4).

Figure 4. Culvert with Upstream Sediment Deposit



A longitudinal profile (Figure 5) is a plot of the thalweg elevation of the stream channel which includes all major bed features. A longitudinal profile can also capture the (1) current water elevation, (2) channel forming discharge (bankfull) indicators, (3) floodplain elevations, and (4) terrace elevations. Average channel slope can be calculated from a longitudinal profile if the survey is extensive enough.[2]

Once the profile is surveyed and plotted, it is necessary to determine if there is an off-set of the channel bed at the stream culvert. Examples of longitudinal profiles with and without a bed elevation off-set are provided below (Figures 5 and 6).

[2] *Refer to "Stream Channel Reference Sites: An Illustrated Guide to Field Techniques" (Harrelson et al. 1994) for specific guidance on surveying a longitudinal profile.*

Figure 5: Longitudinal Profile – No Channel Bed Off-Set

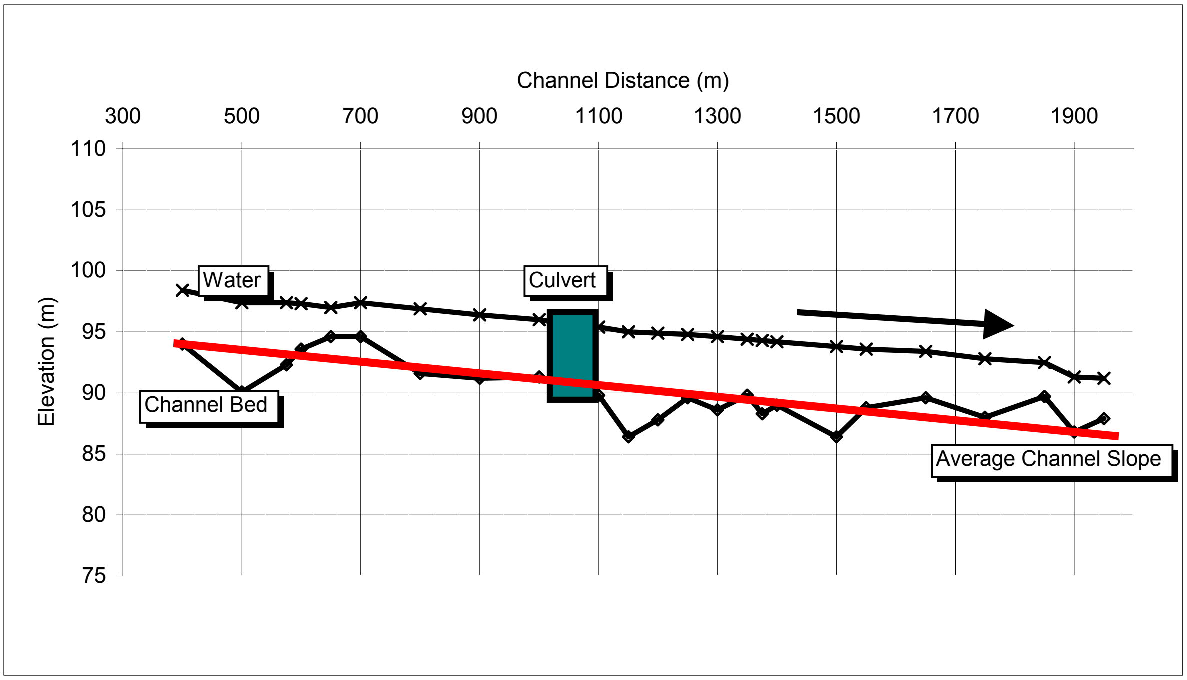
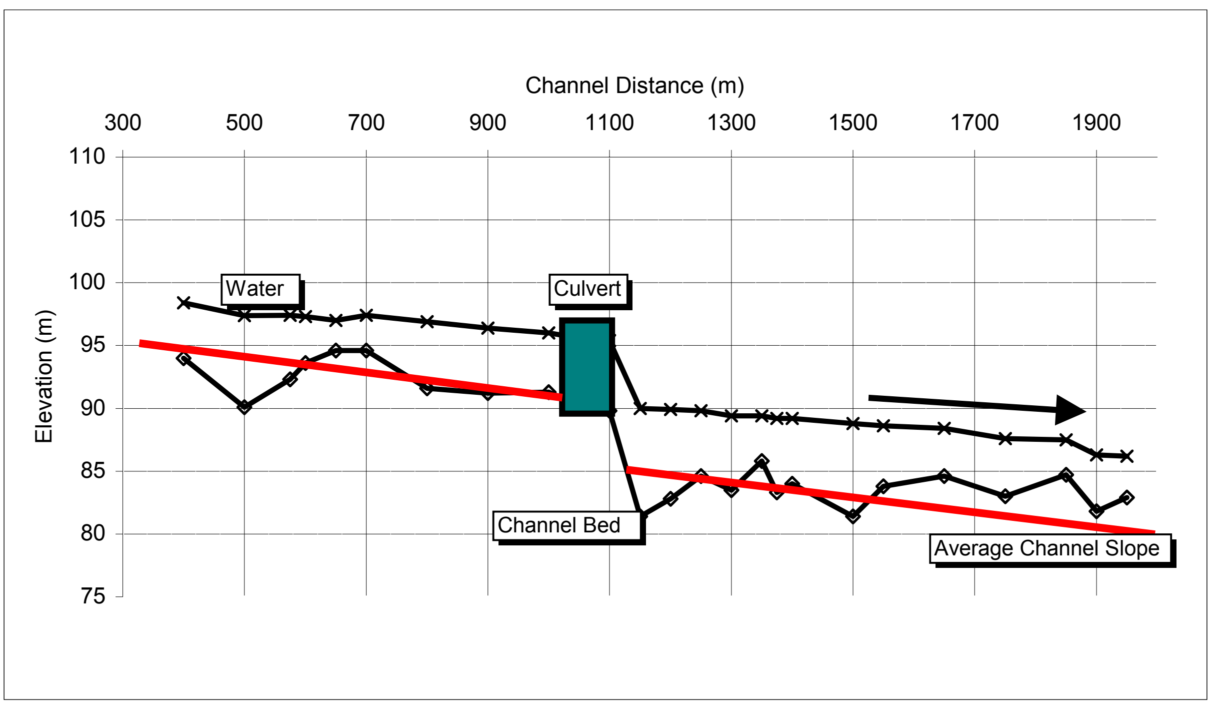


Figure 6: Longitudinal Profile – With Channel Bed Off-Set



Post-Project Monitoring

To evaluate the success and/or failure of culvert replacement and removal, documentation of the design process, changes to the design during construction, and follow-up monitoring is required. In general, photo points are useful for documenting significant changes to the stream, and should be taken from the road surface looking both upstream and downstream. For monitoring, benchmarks and monumented cross-sections should be used for the longitudinal survey. Benchmarks should be located well outside the area of potential stream influence. The survey should include floodplain and terrace elevations to determine if additional channel incision has occurred.

Refer to published monitoring guidelines for specific information regarding monitoring protocols.

RISK ASSESSMENT

Once field reconnaissance and surveys are complete, a determination regarding vertical channel stability is required. If a channel is vertically unstable, then a risk assessment should be performed to determine the potential for additional channel erosion and habitat degradation.

Determining whether the degree of channel incision is significant requires an integration of field indicators and professional judgment. For example, a one-foot headcut may be inconsequential for a stream that is 100-feet wide with a large floodplain, especially if the bed material is large (gravel to cobble). If the stream is only 10-feet wide and is sand-bedded, a one-foot headcut may pose a significant threat to habitat.

Referring back to the potential stream system response to channel incision (page 5), consider the following:

1. <u>Headcut migration upstream and subsequent deepening of the stream channel.</u>
    - *Will the headcut cause a fish passage barrier in the channel or at an upstream structure?*
        - *i. Determine if barrier will be short-term or long-term.*
        - *ii. Develop a monitoring and contingency plan.*
    - *What is the likelihood that grade control will be encountered and how far is it from the site?*
        - *i. Look for evidence of bedrock, boulders or buried wood.*
        - *ii. Determine distance to grade control and calculate volume of sediment that will be excavated by the stream between the project site and the upstream grade control.*
    - *Is there other infrastructure that will be affected?*
        - *i. Determine if there are any upstream road crossings, pipeline crossings, irrigation diversions, or electric or fiber optic cables.*

2. Relatively high channel banks that may exceed critical height resulting in mass failure (bank erosion).
   - *How much bank erosion will occur?*
      i. *Determine average bank heights and potential rates of erosion.*
      ii. *Evaluate land use and structures in the area.*
      iii. *Consider easements.*
   - *Is bank stabilization necessary?*
      i. *Determine if there are existing bank stabilization structures.*
      ii. *Consider alternatives for non-structural bank protection.*
3. Addition of fine sediment to the stream system due to erosion of the channel boundary.
   - *Is the stream water quality limited?*
      i. *Calculate the volume of fine sediment that will be added to the channel from both the bed and banks due to erosion.*
      ii. *Calculate the volume of sediment stored upstream of the existing culvert.*
   - *What is the caliber of sediment (clay, silt, sand)?*
      i. *Determine how will this affect downstream habitat (redds, macroinvertebrates).*
      ii. *Evaluate increases in turbidity.*
4. Disconnection of floodplains from active stream channels.
   - *How often will the old floodplain be inundated -- once every 2, 5, 10, 100-years?*
      i. *Determine channel cross-sectional area and estimate frequency of floodplain inundation. Inundation less frequent than the 5-year flow indicates a channel that is highly incised and probably unstable.*
   - *Will this significantly increase stream power within the main channel (more concentrated flow)?*
      i. *Calculate stream power and determine if this will cause an increase in sediment transport. If the stream transports more sediment, additional incision is likely.*
5. Prematurely dewatered or disconnected backwater habitat.
   - *Will backwater habitat be completely disconnected or will it be functional for much shorter periods during the year?*
      i. *Survey available backwater habitat and determine how frequently it can be accessed by species of interest.*
      ii. *Improve connectivity if possible.*
6. Locally increased channel slope and loss of pool habitat.
   - *Are lack of pools a limiting factor in the stream?*
      i. *From the longitudinal survey, determine the pool/riffle ratio.*
      ii. *If pool/pool spacing is greater than 20 channel widths for stream gradients less than 1%, pool habitat is probably lacking.*
   - *Is pool quality a limiting factor in the stream?*

    i. *From the longitudinal profile, determine the residual pool depths (depth of water in a pool assuming zero discharge). The pool should be longer than the channel is wide.*

7. Drainage of shallow aquifers which affects riparian vegetation.
    - *Can the riparian vegetation survive a drop in the water table commensurate with expected incision?*
        i. *Evaluate the age structure and condition of the riparian plant community.*
        ii. *Determine if there are any impermeable soil layers that will prevent roots from following the water table.*
    - *Many wetland species are very sensitive to changes in moisture regimes. Monitoring of the plant community is recommended.*
8. Meander cut-offs due to knickpoint migration across a meander neck caused by an increased elevation drop between the old floodplain and active channel bed.
    - *What is the potential for channel straightening and simplification?*
        i. *This process is more common in deeply incised channels with somewhat cohesive banks that flood on a five to ten-year basis.*
        ii. *Determine flood re-entry points that are susceptible to meander cut-offs.*
        iii. *Determine historical channel patterns and compare to current condition.*
9. Deposition of large masses of sediment causing localized channel braiding and instability of the streambanks.
    - *Is deposition of coarse sediment en masse likely for the stream in question?*
        i. *Extensive bar formation is more common in arid streams, streams with high sediment loads, and streams that have "flashy" hydrographs.*
        ii. *Calculate the amount of sediment that will be eroded from the channel boundary, assume it will be deposited locally, and consider the impact of this sediment to channel form.*
        iii. *Mid-channel bars may form, causing concentrated flow near both banks.*
    - *Is local aggradation a concern for fish passage?*
        i. *Wide, shallow channels can be fish passage barriers due to the lack of concentrated flow, or due to all flows going subsurface.*

There are numerous other potential impacts due to headcut migration that are site-specific. It is not necessary to quantify all of these processes, but they should be at least qualitatively evaluated for a risk assessment.

OPTIONS FOR GRADE CONTROL FOR INCISING CHANNELS

It is not possible to describe all of the various scenarios for culvert replacement or removal because each site is unique and requires an individual assessment as discussed above. There are however, general characteristics of each treatment that may be favorable in different stream systems.

Grade control treatment alternatives discussed in this document include, but are not limited to, (1) do nothing, (2) large roughness elements, (3) rock and log weirs, and (4) constructed step-pools and cascades. The choice of treatment may be based on site limitations (i.e. channel slope or bed material type), material availability, economics, land use, design competence or familiarity, and/or regulatory restrictions (i.e. jump heights for fish).

The "Do Nothing" Alternative

If the evaluation of channel evolution and the longitudinal profile indicate a low risk for channel incision (i.e. minimal headcut relative to channel size or evidence of natural grade control such as bedrock, cemented gravel, or buried wood), and downstream riparian and channel conditions are adequate, then a "no-action" alternative is indicated. The culvert would be replaced or removed without the addition of grade control.

Determining the significance of a headcut is site-specific and requires the judgement of a geomorphologist or other trained professional. An evaluation of downstream channel resilience (i.e. the existence of floodplains, stable banks, well vegetated riparian zones, etc.) is essential because this area will be impacted by the additional sediment generated from channel erosion.

Benefits

1. Least expensive in the near-term (economically).
2. No maintenance.
3. No risk of grade control failure.

Limitations (see Risk Assessment, page 11)

1. Large potential for lost instream and terrestrial habitat.
2. Loss of riparian vegetation.
3. Downstream flooding.
4. Channel widening.
5. Increased turbidity and suspended sediments.
6. Mid-channel bar formation due to increased sediment load.
7. Decreased bank stability.
8. Loss of wetlands.

Large Roughness Elements: Wood and Boulders

In many PNW streams, large wood and boulders provide natural grade control in the form of channel spanning log jams or debris flow deposits. It is often feasible to mimic this natural analog to provide grade stabilization in areas where the risk of headcut migration exists. The goal of using large roughness elements is not to completely halt the incision process, but rather to slow it down and spread the elevation change over a greater length of channel.

Since log jams are porous structures, not all of the sediment will be held in place; however, sediment inputs will be spread out over time rather than introduced to the stream as one large pulse. A log jam is also self-maintaining as long as more large wood is available in the stream system.

To hold existing sediment in place above a culvert, large wood should be buried into the stream bottom and should be relatively channel-spanning. Boulders can be used as anchor points or to increase structure mass to reduce buoyancy. As with any structural approach, risk can be dispersed through several smaller structures rather than relying on a single large structure. Log jams placed downstream of a road crossing should have some sort of natural or artificial anchoring, but do not necessarily need to be buried in the channel bed. The downstream large wood will capture some sediment as it moves through the reach.

Benefits

1. Provides some stability for upstream banks while allowing dynamic stream response.
2. Improves habitat diversity.
3. Self-healing and possibly self-maintaining if there is an upstream source of wood.

Limitations

1. Initially requires large wood source for construction.
2. Lack of readily accessible, specific design guidance.
3. Structures change over time – variable factor of safety.
4. Risk of damage to infrastructure due to wood transport.

Rock and Log Weirs

Rock and log weirs (Figures 7 and 8) have been used for many years to stabilize channel beds. Straight weirs disperse flows and can cause channel widening and thus structure flanking (erosion around the ends of the structure). To minimize this effect, 'V' shaped weirs that are oriented with the apex upstream and are lower in the center were developed. Since water crosses perpendicular to the weir face, the 'V' shape redirects flow back to the center of the channel.

Figure 7: Rock Weir

Figure 8: Log Weir

Rock and log weirs may be installed to provide some of the following functions: (1) stabilize stream gradient; (2) create pool habitat; (3) establish and maintain a lower width to depth ratio; (4) provide fish passage by concentrating low flows in flat-bottomed channels into narrower, deeper channels; (5) control flow direction and therefore minimize meandering; (6) raise water surface elevations to provide water to diversions and off-channel habitat; (7) center, and sometimes create, a stream thalweg; (8) provide energy dissipation; (9) protect streambanks by redirecting stream flow; and (10) increase sedimentation along streambanks, and recruit and/or maintain spawning gravel (NRCS, 2000).

Benefits
1. Relatively inexpensive for smaller streams.
2. Easy to design, with available guidance tools (NRCS, 2000).
3. Material is easily obtained.

Limitations
1. Potential for unnatural appearance.
2. Maintenance.
3. Prone to failure by undermining or outflanking.
4. Federal and state requirements for aquatic species passage can result in very low weir heights. This may cause weirs to be impractical in steeper streams or in areas where the right-of-way is limited and there is no access to adjacent property. If weirs must be placed close together, the jet from one weir impinges on the next one, tending to undermine or wash it out, and the weir system becomes a turbulent chute which could become a fish passage barrier.

Constructed Step-Pool and Cascades

One of the newest grade control methods is the construction of artificial cascades or step-pools (Figure 9). Cascades and step-pools are natural stream types which are found in steep channels (greater than 3%). Although these stream types may be out of context for a given project site, they do rely on natural channel processes to pass water, sediment, wood, and aquatic organisms. Step-pools or cascades are most appropriate in stream reaches that are naturally steep or in areas where work area is limited due to rights-of-way or other constraints; they may also be preferable in areas where banks are high and excavation is considerable.

Figure 9: Constructed Step-Pool and Cascade

Photo courtesy of Rob Sampson   Photo courtesy of Dan Perritt

Benefits

1. Minimizes work area.
2. Provides energy dissipation.
3. Minimizes the number of structures for large elevation changes or steep stream slopes.
4. Materials are easy to obtain.

Limitations

1. Lack of specific design guidance.
2. Requires careful design and construction.
3. Stabilization of bed material below the grade control structure can be difficult; potential for undermining of the step-pool structure.
4. Risk of low flows going completely subsurface through the structure.
5. Consecutive jumps for fish may limit aquatic species passage.
6. Maintenance.

A "culvert confined cascade" has been designed and implemented in the PNW, which is a variation of the constructed cascade approach. The culvert is placed at a relatively steep angle, connecting the upstream and downstream stable bed elevations. The headcut is basically incorporated into the length of the culvert. This may work in areas with a minimal perch height on relatively low gradient streams. Rock is required within the culvert to provide bed roughness to allow for fish passage. For steeper slopes and higher perches, a culvert confined cascade will likely be a fish passage barrier, especially for juveniles. Rock within the culvert could trap debris and cause chronic maintenance issues or risk of failure. Available information on design and success of this technique is limited at this time.

SUMMARY

A tremendous amount of time, energy, and money is spent replacing or removing fish-impassable culverts. Because of the magnitude of effects, it is critical that a geomorphological evaluation of the site be completed to determine potential impacts both at the site and along the stream channel. Vertical instability can result in a whole suite of negative impacts that range from loss of backwater habitat to increased levels of turbidity. An evaluation of the risks to channel morphology, habitat, and infrastructure should be performed before any decision is made regarding culvert removal or replacement. By utilizing the Channel Evolution Model and longitudinal profiles, the risk can be quantified, or at least described in terms of potential impacts, which is an important tool for managers that oversee stream related projects. These risks will determine whether grade control structures are necessary.

ACKNOWLEDGEMENTS

This manuscript was greatly improved by the input from many individuals including: Paul Bakke, Jane Kelly, Mark Mouser, Skip Haak, Bianca Streif, Janet Oatney, Chad Moore, Chris Hamilton, Alan Wetzel, Diana Hwang, Brendan White, Jon Mann, Dan Perritt, Timmie Mandish, Doug Young, and Jennifer Cannon. Thank you for your time and effort.

REFERENCES

Fischenich, C. and J.V. Morrow, Jr. 2000. Reconnection of floodplains with incised channels. US Army Corps of Engineers, ERDC TN-EMRRP-SR-09.

Galay, V.J. 1983. Causes of river bed degradation. *Water Resources Research*, 19(5):1057-1090.

Harrelson, C.C., C.L. Rawlins, and J.P. Potyondy. 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. General Technical Report RM-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Harvey, M.D. and C.C. Watson. 1986. Fluvial processes and morphological thresholds in incised channel restoration. *Water Resources Bulletin*, 22(3):359-368.

Lane, E.W. 1955. Design of stable alluvial channels. *Transactions, American Society of Civil Engineers* 120(2776):1234-1260.

NRCS (Natural Resources Conservation Service). 2000. Design of Rock Weirs. Engineering Technical Note Number 24, Portland, Oregon.

Schumm, S.A., M. Harvey, and C. Watson. 1984. Incised Channels: Morphology, Dynamics, and Control. Water Resources Publications, Littleton, CO.

Simon, A. and M. Rinaldi. 2000. Channel instability in the loess area of the Midwestern United States. *Journal of the American Water Resources Association*, 36(1):133-150.