CHANNEL MODIFICATION

1 DESCRIPTION OF TECHNIQUE

As described in Chapter 2, *Stream Processes and Habitat*, of the Stream Habitat Restoration Guidelines (SHRG), the physical structure of alluvial streams is a reflection of interactions among available energy, water, sediment and structural elements (such as large wood). These processes are mediated by the stabilizing influence of vegetation, and, sometimes, the extent of available floodplain. Where inputs of sediment and water have been altered from their natural rates, or where the form or structure of the channel or floodplain have been modified by human activities, channel instability and degraded habitat conditions are likely to exist.

As part of an overall management plan that addresses the underlying causes of degradation on a watershed scale, modification of the channel may be an appropriate technique to accelerate recovery of a stable, sustainable natural channel and floodplain. This can be accomplished through alteration of:

- Channel form, which consists of channel
    - planform (the shape of a channel in map view and is defined by sinuosity and meander characteristics)
    - cross-section (the shape, width and depth of channel from bank to bank and across the floodplain)
    - profile (the slope, and variability of the slope, along the channel bed)
- Location of the channel

Planform, cross-section, and profile are integrated features. Thus, altering one will affect the others, and alteration of any of these typically results in a change in the hydraulic and sediment transport characteristics of the channel. Functional habitat is dependent upon variability in all three of these channel components.

Modifications may include direct restoration (reconstruction of a channel) or incremental process restoration (installation of a structural feature to induce change in a channel). Modifications often employ instream structures that reduce bank erosion and reduce or control channel migration, at least during the period of vegetation recovery.

Because all channel modification techniques result in changes to channel process, a thorough understanding of fluvial geomorphology is essential to developing channel modification projects. Refer to the *Fluvial Geomorphology* appendix and to SHRG Chapter 2, *Stream Processes and Habitat*, for further discussion of channel planform, cross-section, profile, and channel stability and equilibrium.

Dedicating Land and Water to Stream Habitat Restoration, Rehabilitation, and Preservation is a complementary technique that protects the investment and increases the extent of restoration as well as its long-term sustainability. See also the *Riparian Restoration and Management* technique for discussion of related riparian areas, and the Integrated Streambank Protection Guidelines[1] (ISPG) for details on streambank components of channel modification. While streambank stabilization should not be considered a form of restoration, the incorporation of deformable constructed streambanks can be an essential component of restoration. Long term solutions using channel modification as a tool will be sustainable only if natural rates of lateral adjustment and channel migration are accommodated. The ISPG[1] details these considerations and concepts.

2 PHYSICAL AND BIOLOGICAL EFFECTS

When properly applied, channel modification techniques can result in a cost-effective, comprehensive fix, preferable by far to the periodic and chronic-fix approach that treats problems symptom by symptom. However, without a thorough understanding of the complexities of channel modification techniques and of the stream channel in question, problems may arise. Channel modification alters the way energy is dissipated as water flows through the reach, which has effects on:

- Size distribution and volume of sediment transported
- Velocity, shear stress, turbulence, and other hydraulic variables
- Scour and fill processes
- Water surface elevations at all flows, including flood flows
- Recruitment, transport and retention of large wood

Thus, the potential for inadvertent consequences is high. Careful physical analysis and design are required. Furthermore, effects on the attributes listed above can propagate upstream or downstream of the modified channel reach, or into tributaries, affecting channel stability, habitat features, and floodplain interactions there as well as locally.

Channel modification projects often provide immediate benefits by creating improved habitat. However, the purpose of channel modification is to accelerate recovery to a stable, sustainable channel form that is in dynamic balance with its sediment, large-wood and flow regime. Successful modification of a stream channel to a more stable, natural shape should create conditions of flow hydraulics and sediment mobilization, transport and storage that sustain this shape and in doing so, sustain high quality, diverse habitat. The long-term benefits will be dependent on the degree to which the reconstructed or modified channel is able to adjust over time to maintain equilibrium.

Successful channel modification may result in any of the possible benefits normally provided by a natural channel system. Benefits may include the following:

- Improved stability and sorting of gravels for spawning habitat
- Improved water access to floodplain
- Greater diversity in channel bedforms and substrate textures
- Greater diversity in channel hydraulics and velocities
- Improved nutrient cycling and exchange within the channel and between the channel, floodplain, and hyporheic zones
- Greater potential for fish to find refuge during high and low flows
- Moderation of water temperature extremes due to hyporheic exchange, floodplain storage and groundwater connectivity

- Improved riparian zone function (e.g. large wood, shading) and stream-riparian interactions
- Improved habitat quality and diversity for riparian-dependent terrestrial fauna (e.g. migratory birds, amphibians)

Channel modification can be part of a process-based restoration strategy. For example channel modification may be utilized as a tool to assist in reconnection of a channel with its floodplain, reestablishment of natural streambank erosion and channel migration rates, reestablishment of natural sediment storage and mobilization patterns, or natural large wood recruitment and retention patterns. Successful restoration of a stream to a more stable, natural shape can have tremendous benefits for fish and wildlife by providing natural diversity of habitat, and natural in-channel and riparian zone disturbance regimes.

Because of the spatial scale of construction-related disturbance associated with channel modification projects, the risk of unanticipated impacts can be very high. This is particularly true when finished projects do not meet restoration objectives, were not constructed as specified in planning, or were designed with inadequate knowledge of watershed processes, disturbance regimes or altered watershed conditions. Many well-intentioned channel modification projects have resulted in unexpected bank erosion in adjacent reaches, aggradation or degradation of the channel bed, or other impacts to habitat and processes due to changes in channel slope, bed elevation, and sediment transport capacity. Furthermore, the dynamic nature of hydraulic forces, and the uncertainties inherent in design and analysis may result in inadvertent impacts from channel modification, even when properly designed.

Some of the inadvertent consequences of channel modification may include:

- Incision or aggradation of upstream, downstream or local channel reaches and tributaries
- Bank erosion due to changes in hydraulic forces or bank stability
- Mid-channel bar formation and widening
- Channel avulsion (sudden shift in channel location across intervening floodplain)
- Out-flanking of in-stream structures
- Increased sediment delivered to downstream reaches due to post-project channel adjustments
- Decreased sediment delivered to downstream reaches due to reduction of bank erosion rates to below natural levels
- Altered patterns of flooding
- Creation of fish-stranding hazards
- Shifts in composition and distribution of riparian plant, fish, and wildlife species, including establishment of non-native species

In addition, short-term impacts that occur as the system recovers from construction-related disturbance must be considered, especially where at-risk species are present. These short-term impacts, which can be minimized but not eliminated, include:

- Mortality, physiological stress or displacement of aquatic macroinvertebrates, amphibians, and fish due to in-stream activity, increased turbidity, deposition of fine-sediment, and channel abandonment

- Increased sediment input to downstream reaches during construction or during channel re-watering, affecting pools and spawning gravels
- Increased sediment input to downstream reaches during the wet season following construction, affecting spawning gravels
- Disturbance or displacement of wildlife due to construction activity and loss of riparian vegetation
- Temporary loss or imbalance of nutrients and food supply

Short-term impacts associated with construction, and how to reduce those impacts, are discussed in greater detail in the *Construction Considerations* appendix. These impacts must be weighed against long-term benefits in the context of species and habitat resiliency.

3 APPLICATION OF TECHNIQUE

Before selecting channel modification as a technique to address channel instability or degraded habitat, a context for both the symptoms and the technique is needed. Disruptions to channel equilibrium typically fall into two categories:

1. *Reach specific impacts resulting from physical modification of the channel or immediately adjacent areas*. Examples include road crossings, channelization (straightening, dredging, widening, bank or bed armoring, and levee construction), removal of large wood, removal of bank vegetation, or other actions that artificially confine a channel, alter its slope or hydraulic roughness, or the resistance of the bank to erosion.
2. *Reach impacts that result from watershed-scale disturbance*. Habitat degradation often occurs as a result of land use practices on a watershed scale that affect the rate, timing, distribution, and type of sediment, water, and large wood delivered to the stream. Such changes can alter the stability of the channel bed and banks, and can induce sudden or progressive change in the channel type or form. These changes alter the distribution, abundance, quality, and accessibility of habitat within the stream corridor.

If reach-specific impacts are the cause of degradation, simply removing the cause of degradation and allowing natural recovery to take place (passive restoration) may be a cost-effective, low-risk solution, particularly if much of the potential degradation has already occurred. If, however, the rates of channel change are still high or accelerating, channel modification can be an effective tool to boost natural recovery (active restoration).

In the case where watershed-scale disturbance is the root cause of degraded conditions, these causes must be addressed first. Chronic, watershed scale disturbance, such as accelerated sediment input or altered hydrology, are likely to perpetuate the unstable, degraded conditions, hampering natural recovery and putting channel modification projects at risk. If watershed conditions are in flux, channel modification designs are unlikely to be sustainable over the long term. Furthermore, the spatial scale of channel degradation when watershed processes are the cause is sufficiently large that use of channel modification on a significant portion of the affected reaches becomes economically infeasible. Greater benefits for cost may be obtained by addressing land-use-related disturbances and then allowing for natural recovery.

If land use has been corrected, channel modification can be used to accelerate recovery. The effectiveness of channel modification techniques will depend on the degree to which the watershed impacts have been remedied or stabilized. If watershed processes have been permanently changed but are now stable, channel modification may be used to create a new equilibrium condition or to promote more rapid natural adjustment to altered watershed conditions, provided the current hydrologic, sediment, wood recruitment, and disturbance regime can be accurately quantified and accommodated in the design.

By nature, channel modification is an invasive technique, involving substantial on-the-ground and in-channel disturbance. As such, it should not be a first choice in restoration, but should be used only when restoration goals cannot be obtained using less invasive techniques (natural recovery, passive restoration, removal of barriers, etc.).

Generally, the goal of channel modification is to reconstruct a channel form that is self-sustaining. This implies that processes such as channel migration will occur, but at natural, sustainable rates. A stable channel is not an immobile channel, but rather one that maintains its form over time as it moves all of the sediment and water presented to it from upstream (i.e. is in equilibrium). In order to be self-sustaining, processes by which natural structural elements such as large wood are recruited should also be restored. If large wood recruitment and channel migration are not accommodated, what remains is a managed structural approach, which is not self-maintaining over the long term. The managed structural approach may be appropriate in some settings, such as urban areas, but it does not represent long-term restoration.

It is important to note that while an equilibrium channel is pleasant to look at and falls within expected parameters, habitat-forming mechanisms may not be present[2]. Channel modification can provide an equilibrium condition that is conducive to maintaining habitat or promoting the development of habitat, but may be lacking in habitat at the onset. Other habitat enhancement techniques, such as log placements, should be considered in conjunction with channel modifications to provide target habitat and bed and bank stability in the short term. Long-term habitat sustainability can only be addressed by restoring and maintaining habitat-forming processes such as large wood recruitment and channel migration, both of which result in dynamic channel boundaries and “messy” appearance at times.

It is also important to note that not all channels exist naturally in an equilibrium state. As discussed in SHRG Chapter 2, *Stream Processes and Habitat,* alluvial channels are “self-formed,” that is, built from material transported and deposited by river flows, and thus taking on a shape that allows sediment input and sediment output to be in equilibrium. However, if the time between channel-modifying disturbances is shorter than the disturbance recovery time, the type of equilibrium assumed in this paradigm may not apply. For example, morphological recovery from debris flows or large floods may take a long time. Sometimes, analysis of such channels may reveal a consistent size and frequency of disturbance. However, channel modification in such cases is highly risky, due to design uncertainty and the power of large, frequent disturbances to undo human efforts.

Some valley settings are known to be highly dynamic, making them poor or risky choices for channel modification. A partial list would include:

- Transitional areas, such as alluvial fans, where high stream power, decreasing sediment transport capacity, and convex topography drive frequent avulsions and rapid channel migration rates
- Areas with high sediment loads, such as glacial outwash valleys (which tend to be naturally braided channels)
- Confined channels with fine-textured, erodible valley side slopes (which have concentrated flow and high energy during peak runoff)

Channel modification methods can be used at virtually any scale, from site-specific to multiple continuous reaches of a river, and on any size stream. However, the risk of failure increases with increasing stream size and stream power (i.e. discharge and slope). Site-specific channel modifications may include bedform modifications or removal or installation of structures to improve fish passage or increase habitat complexity. Reach-scale modifications may include channel relocation or planform, profile, and cross-section modification. Large-scale modifications may include removal or setback of levees through long reaches of a valley (refer to the *Levee Modification and Removal* technique).

Channel modification projects may include changes to the profile (slope) of a channel and its bedforms, changes to the planform, cross-section, or all of these combined. In some instances, such as when a channel has been straightened, rerouted, or otherwise dislocated, complete relocation of the channel may be appropriate. However, it is important to recognize that changing one component of a channel usually results in changes to, or necessitates changes to other channel components. For example, significant changes to channel planform often result in changes to channel profile. A channel cannot be lengthened without reducing its slope. Modifying the elevation of the channel requires slope alteration at either the upstream or downstream end of the modified reach, or both.

3.1 Channel Profile Change

Channel profile refers to the slope, or gradient, of the channel bed and the variation of that slope through a reach. Channel slope will change as a result of any activity that changes the bed elevation at a point or changes the length of channel between two constant elevation points. Physically, the main objective of altering channel profile is to alter energy dissipation patterns. Specifically, this will alter:

- Total sediment transport energy for the reach, changing both the sizes and amounts of particles moved
- Velocity patterns (maximum velocities and velocity gradients near the bed or banks)
- Near-bank and near-bed erosive force (shear stress)
- Water access to floodplain and side channels at given discharge levels
- Bed sediment texture (particle sizes)
- Volume, extent and pattern of hyporheic flow

These physical objectives are clearly linked to biological objectives as well, through effects on habitat complexity, riparian zone function, habitat connectivity and water quality. Reach-scale channel profile alteration is often proposed specifically to address the degraded habitat which has resulted from past river management, including:

- Straightened, incising (eroding) channels
- Widened, aggrading (depositional) channels
- Man-made fish passage barriers

Specific channel profile changes implemented to improve habitat include:

- Installation of large wood, drop structures or channel fill (i.e., roughened channel bed) to raise the bed
- Reconfiguration of a previously straightened or channelized stream to lengthen the channel, thereby increasing sinuosity and reducing the slope
- Installation of large wood, boulder clusters, or other roughness elements that promote predictable patterns of scour, deposition, and local energy dissipation
- Enhancement of hyporheic flow by steps in water surface elevation, either longitudinally (along the channel) or laterally, such as between a main channel and a side channel

Since channel profile governs the energy dissipation pattern of a stream, knowledge of stream channel response to these altered energy patterns is essential. Physical responses, in turn, have biological implications. Factors to consider include:

- Steeper channels have greater energy and capacity to transport sediment for a given discharge and channel dimension. Conversely, flatter profiles (more sinuous channels) reduce sediment transport capacity
- Steps, which cause abrupt drop in elevation, dissipate energy locally and thus break up the channel profile. This has the effect of:
    - Making less energy available overall to transport sediment through the reach
    - Creating a localized scour and associated deposition area;
    - Reducing the longitudinal extent of high-velocity zones.
- Proper channel profile is needed for equilibrium sediment transport processes
- Channel profile influences the passage of fish and other aquatic organisms through the channel and into adjacent floodplain habitats
- Variations of the profile through a reach, in the form of steps (drops), riffles (steep sections) and pools (deep, flat sections) promote habitat variability and hydraulic complexity
- Raising stream bed elevation can cause water to spill onto the floodplain at relatively lower discharges

3.2 Channel Planform Change

Channel planform refers to the spatial pattern and location of a channel looking down on it from above. One common descriptor of planform is “sinuosity,” which is a ratio of channel length to valley length and describes the degree of meandering. Most channel planform modification efforts are focused on restoring single-thread, straightened channels to a more sinuous pattern. Physically, the main objectives in doing this are:

- To increase the proportion of the stream’s energy which is dissipated by friction (as the water is made to turn around bends) rather than erosion
- To establish a natural pool-riffle pattern and channel migration dynamics

Since planform change is impossible without altering the slope or profile, it is difficult to discuss effects specific to the planform alone. Nevertheless, increasing sinuosity is generally accompanied by:

- Increased diversity of bed sediment texture (sizes), due to variation in deposition patterns (sorting) through the meander sequence (e.g. pool, pool tail-out, riffle, etc.)
- Increased vertical topography
- Bedforms, such as point bars
- Increased volume of hyporheic flow
- Establishment of a channel migration process due to differential erosion at outer bends, which results in:
    - Gravel recruitment
    - Large wood recruitment
- Diversity of edge habitat (undercut banks, etc.)

Planform modification is often proposed to address the same reach-scale habitat degradation syndromes discussed under profile change, including straightened, incising channels and widened, aggrading channels. Disruptions to natural planform can also result from:

- Activities which increase bank erosion rates, such as:
    - Removal of large wood from channels
    - Removal or modification of riparian vegetation
    - Upstream modification of channel banks (including armoring) or upstream constrictions (levees, road grades, landfill, etc.)
    - Aggradation (deposition) and widening caused by downstream flow restrictions (e.g. at road crossings)
- Land use which confines whole reaches of channel, such as:
    - Confinement by levees
    - Impinging floodplain fill or road grades
- Land management which alters sediment loads (e.g. heavy road density, heavy logging, disruption of streambank vegetation), or flow regime (e.g. dams)

Channel planform changes implemented to improve habitat include:

- Reconnection or reconstruction of historic meanders in straightened (channelized) reaches
- Removal or modification of levees, bank armoring, and infrastructure that artificially confine the channel (see *Levee Modification and Removal)*
- Redirection of a channel to improve processes that promote or maintain habitat while accommodating infrastructure constraints
- Redirection of a channel away from a source of contamination or a physical hazard (such as an abandoned floodplain gravel mine)

Relocation of stream channels is particularly effective at restoring channel stability in the case of:

- Aggraded channelized streams if the channel is perched above the surrounding landscape making it susceptible to avulsion, and stranding of fish when flood flows leave the channel and go to the low point in the land, abruptly reducing the sediment carrying

capacity of the remaining flow in the channel;
- Aggraded channelized streams that were lengthened from their historic planform in order to follow human-imposed boundaries, reducing their slope and sediment carrying capacity.

Relocation of stream channels can also be an effective way to restore incised channelized streams, reestablishing bank stability, floodplain connections, and riparian functions. However, establishing a stable transition from the reconstructed reach to the downstream reach is often a weak point in such designs.

Channel planform modification is a major undertaking, involving reconstruction of the channel bed, habitat features, channel banks and floodplain. It requires consideration of sediment transport, sediment mobilization, hydrologic regime, and disturbance patterns. Channel planform modification should be considered only where the existing planform is in disequilibrium and the watershed causes of that disequilibrium have been addressed, or are quantified and can be accounted for in the channel design.

3.3 Channel Cross-Section Change

Changing a channel's cross-section involves altering its width, depth, or shape across the channel, and can include modification of channel banks and bars. Cross-section modifications are most commonly applied to the main channel, but also include modification of floodplain elevation or features such as levees (refer to the *Levee Modification and Removal* technique for discussion of levee modification). The main physical objective of cross-section changes is to alter the channel depth, and thus alter the hydraulic forces acting on the bed and banks. In particular, making the cross-section narrower and deeper has the effect of:
- Increasing the volume and particle sizes of sediment transport for each given discharge
- Increasing average velocity, while
- Maintaining water volume capacity

Other important effects on physical habitat include:
- Increasing the chances that large wood is retained and interacts with the water at all flows
- Reducing surface area for solar heating
- Promoting habitat complexity and hydraulic diversity
- Altering the physical habitat suitability for various species, which is a function of substrate type, velocity, depth, and bank characteristics

Cross-section modifications can be accomplished by:
- Encouraging the channel to narrow itself by restoring vegetation and/or large wood, porous weirs, or other in-stream structures that redirect flow
- Installation of in-channel structures, such as large wood, boulder clusters, drop structures, porous weirs, groins or barbs (refer to ISPG[1]) that obstruct, constrict, or redirect flow.
- Reshaping or relocating the bank.
- Excavating a new floodplain for an incised channel to accelerate the natural recovery process, which typically involves initial incision, channel widening and enlargement, and eventual deposition of floodplain within the incised and enlarged channel[3]

- Excavation of depositional materials from discrete aggraded reaches
- Removal of levees (for further discussion of levee removal, see *Levee Modification and Removal*)

3.3.1 Incised Channels

A special case of channel cross-section modification is restoration of incised channels. The dynamics and causes of channel incision are detailed in the *Fluvial Geomorphology* appendix. There are three general approaches to rehabilitation of incised channels[4,5]:

1. Allow natural process to establish a new equilibrium condition, which typically involves initial incision, channel widening and enlargement, and eventual stabilization of banks and deposition of floodplain within the incised and enlarged channel[6]
2. Excavate and construct a new floodplain at the incised channel elevation or higher (but not at the original level), which is a proactive acceleration of the natural progression of incised channels listed previously. Variations include:
    a. Partial excavation of a new floodplain, such as by excavating material on the inside of meander bends and creating floodplain or bankfull “benches”
    b. Creation of a different, but more stable, stream type within the incised channel, such as a step-pool system
3. Restore the historic channel grade and elevation to reestablish reconnection with the floodplain by raising the channel bed or moving the channel to a new or former location on the old floodplain surface

The first two approaches are appropriate when the cause of incision is systemic and not likely to be restored, such as in developed or developing watersheds that have a permanent change in sediment transport character, or where structures have encroached on and narrowed or eliminated the old floodplain. The third approach is appropriate when reach alterations are the primary cause of incision, and sediment supply and hydrologic regimes are not otherwise significantly altered. A fourth approach, stabilizing the channel in-place using artificial, hardened structures is often considered, but offers little in terms of habitat value or long-term stability. Such an approach does not constitute restoration.

Restoring the historic channel grade (the third approach listed above) involves installation of drop structures, grade control, or channel fill to restore the elevation of the channel bed following incision. An increase in bed elevation can aid in reconnecting the incised channel to its floodplain. Incised channels that are reconnected to an active floodplain become more stable because water depths and velocities in the channel are reduced relative to those in an incised channel. If flood flows spread out over the floodplain during relatively frequent floods (one- to five-year return-interval events), channel erosion may be minimized. Therefore, raising the elevation of an incising channel bed should be considered as an effective means of stabilization. Incised channel restoration involves detailed analysis of sediment transport and consideration of sediment supply. Refer to the *Sediment Transport* appendix for more information on analysis of sediment transport. For further information on problems and solutions specific to incised channels, refer to the Additional Reading.

4 RISK AND UNCERTAINTY

4.1 Risk to Habitat

Channel modification projects should be designed to provide aquatic and terrestrial habitat benefit. However, large-scale channel modification may result in significant short-term adverse impacts to, and loss of, habitat, fish and wildlife due to disturbance. Months to years may be required for full recovery of some habitat components and recolonization. Aquatic species that colonize the bed and banks of newly constructed channels are particularly at risk until vegetation becomes established and bed material is redistributed to a stable configuration during high flow events. There is also a risk that a poorly designed channel modification project may fail in critical areas and have a negative effect on habitat or channel maintaining processes rather than a positive one. A contingency plan should be in place to deal with unexpected consequences. For further discussion of the potential impacts to habitat, refer to the previous section on *Physical and Biological Effects*.

4.2 Risk to Infrastructure and Property

Channel modification may result in risk to infrastructure if inappropriately designed due to the complexity of accurately predicting relationships among various channel attributes in design and implementation (e.g. raising the channel bed elevation can increase the local flood risk). However, the intent is to improve channel stability and, thereby, reduce risk to infrastructure. Some desirable channel characteristics for habitat may be at odds with land use. For instance, flooding is a natural and beneficial feature of healthy channels. In-stream wood increases roughness and flood elevations. Wood, as with any in-stream obstruction, may redirect flow, collect additional wood, and influence scour and deposition, all of which may impact bank erosion or cause channel migration or avulsion.

4.3 Risk to Public Safety

Because channel modifications are typically relatively comprehensive reconfigurations of the channel, public safety should be considered in design, and if adequately addressed, risks can be avoided or minimized. Complementary techniques that may be implemented simultaneously, such as large wood placements, may present additional safety concerns. Refer to discussion of risk for each complementary technique.

4.4 Reliability/Uncertainty in Technique

Because all channel modification techniques will potentially alter hydraulic variables (depth, shear stress, velocity, turbulence) and sediment transport, there is a risk that an inappropriate design or unanticipated conditions will cause a project to fail. It is difficult to predict the response of channel modifications to the hydraulic character of the reconstructed and adjacent reaches as well as the sediment transport through the reach. A thorough understanding of fluvial geomorphology is an essential component of developing channel modification projects. Refer to SHRG Chapter 2, *Stream Processes and Habitat*, and the *Fluvial Geomorphology* appendix for further discussion of channel planform, profile, cross-section, and channel stability and equilibrium.

Channel modification design requires consideration of many design components, including sediment mobilization and transport, habitat, bed substrate, bank material, vegetation, channel hydraulics, and hydrology, and an understanding of many disciplines, including geomorphology, biology, hydrology and engineering to name a few. The risk and uncertainty associated with conducting a channel modification project can be greatly reduced by adequately accounting for many interdependent design components and by involving specialists from all related disciplines.

5 METHODS AND DESIGN

5.1 Data and Assessment Requirements

Channel modification should be integrated with fluvial geomorphic processes. These processes act on the stream channel to determine its form and character, which then influences the processes themselves, creating an evolving system. Watershed inputs to the stream that determine channel form include flow, sediment, and large wood inputs. These inputs, and the character of boundary materials of the channel, including bank vegetation, determine channel form, and available habitat and habitat quality. Stream habitat design will benefit greatly from consideration and evaluation of the geomorphic processes shaping the stream and the resultant form (slope, planform and cross-section characteristics) of the stream. Concepts in fluvial geomorphology that are pertinent to channel design are discussed in SHRG Chapter 2*, Stream Processes and Habitat*, and detailed in the *Fluvial Geomorphology* appendix.

As such, data collection and assessment in support of project design and monitoring should include elements that allow for this geomorphic approach. Data and assessment needs will be highly dependent upon the availability of existing watershed assessment information, the intent of the project, the nature of the channel, and the modifications to be implemented. However, because the character and behavior of the stream is highly influenced by the character and condition of the watershed and because any alteration of channel can have far-reaching impacts, it is essential that data collection and assessment for channel modification be comprehensive and allow for careful consideration and analysis of impacts and effects.

Channel modification design should include reach assessment at a minimum, and watershed assessment in most cases. The scale of the survey should match the scale of problems being addressed, and the root cause of those problems. For instance, assessment required to narrow a short reach of stream that has been over-widened due to grazing of riparian vegetation and uninhibited livestock access to the stream will require assessment of the affected reach and a stable reference reach. In contrast, a watershed scale assessment will likely be necessary to modify an incised reach of stream in order to correctly identify and address the cause of the problem. For further discussion of assessment, refer to SHRG Chapter 3, *Stream Habitat Assessment*.

The following are minimum factors to be considered for modifying stream channels:

- What is the root cause of the problem? Has it already been addressed or will it be fully addressed by this project? If not, the project will likely address only the symptoms of the problem and it may reoccur.
- How has the stream or watershed been altered from historic conditions? How has the

flow regime of the stream, its sediment and wood supply, and its disturbance regime (frequency, magnitude, and extent of flooding, fire, mass wasting, and other events) been affected by these changes? What impacts has this had on riparian vegetation, stream habitat, and channel profile, cross-section, and planform?

- Are in-stream and watershed activities and conditions likely to have additional impacts to the project site? If so, how will they impact the project's success? Where there is a moderate to high risk of detrimental impacts or project failure, consider implementing watershed recovery projects prior to channel modification or wait until the watershed naturally recovers.
- Evaluate whether or not the modified channel will be self-sustaining. Items to consider include:
    - Is the channel in a natural setting or has it been moved to an unnatural location (e.g., it is perched or has it been lengthened or shortened making it susceptible to aggradation or incision)?
    - Is there a source of bed material to replenish that transported out of the reach during high flow events? Consider the site's location relative to any upstream reservoir, pond, wetland, or sediment detention basin.
    - How will the proposed cross-section, configuration, and slope affect the stability of the naturally available bed material?
    - How will the proposed modifications respond to recruitment of large wood? Will instream large wood need to be actively managed?
    - Will channel migration be accommodated by the proposed design? Are there structural elements that will need eventual maintenance and replacement?
- If the proposed design will not create a naturally self-sustaining channel, is there a self-sustaining design alternative? If not, are there staff and funding to support permanent monitoring and maintenance of the project?
- What are the potential impacts to upstream, downstream and adjacent habitat, infrastructure, and public safely if the project succeeds, or if it fails? What is the probability of those impacts occurring? What factors influence that risk (e. g. valley setting, large wood input, or dependence on man-made structural elements such as grade control)? What can be done to minimize the risk?

Elements of a reach-scale analysis generally include:

- Topography of project area and adjacent reaches, including floodplain and terraces
- Survey of planform, profile, and cross-sections of existing reach, upstream and downstream reaches, and reference reach (if available) with permanent benchmarks located outside of the construction area
- Sediment characterization of streambed (surface and subsurface) and bank materials of existing reach, upstream and downstream reaches, and reference reach (if available)
- Evaluation of sediment transport volumes and size distribution (see Section 5.1.3, *Sediment Transport Capacity*). Any channel modifications must be able to accommodate the sediment load without unanticipated adjustments.
- Determination of pertinent aspects of site hydrology (see Section 5.1.1, *Hydrology*). This includes channel forming discharge, low flow and flood discharges.
- Hydraulic conditions (see Section 5.1.2, *Hydraulics*), including velocity and shear stress

of existing channel, flood and overbank flow profiles and floodplain flow patterns (especially channel exit and re-entry areas)
- Documentation of physical, regulatory, social, and economic constraints and project limits
- Documentation of property, infrastructure, and land use activities that may be at risk by implementing or not implementing the project
- Evaluate access and materials availability. What access routes and staging areas are available? Will they limit the type of equipment, and therefore, the type of material that can by utilized?
- Mapping of soil materials and vegetation, paying particular attention to soil water regime (ability to support re-vegetation) and soil stability (resistance to mass failure and erosion)
- Evaluation and documentation of the distribution and condition of existing aquatic and riparian habitat. Describe major plant, fish, and wildlife species and communities that may be positively or negatively affected by the project.
- Evaluate bank erosion rates, streambank stability (resistance to mass failure and erosion) and streambed (vertical) stability. Identify active channel incision or aggradation, and the causes of these conditions.
- Document baseline conditions necessary to support any planned monitoring activities at the site. The scope and nature of an assessment depends upon monitoring objectives. It may include documenting existing pool: riffle ratios, width: depth ratios, permanent cross-sections, photo documentation of site from permanent benchmarks that will not be disturbed by the project, or the frequency, extent, and depth of overbank flows, among other things.

In addition, some projects may require watershed-scale analysis elements, such as:
- Sediment budget for the watershed (identification of sediment sources and routing patterns and quantification on a decadal time scale to assess whether current conditions and proposed design reflect the long-term patterns)
- Large wood recruitment, transport and retention
- Riparian function (shade, temperature)
- Groundwater/surface water/hyporheic interactions in terms of volume and timing
- Disturbance patterns (frequency and recovery rates from large disturbances such as flood or fire)
- Trends in watershed land management and response to past management

In relatively small, stable, low energy streams where there is minimal risk to infrastructure, habitat, and public safety, elements of the design, if not the entire design, may be based on reference site conditions. For instance, if a new channel has a similar size, slope, and degree of entrenchment as a stable reach located immediately upstream, it can be assumed that the gradation of bed material necessary to maintain stability of the new channel is equal to that upstream. Many of the highly technical elements mentioned above would then not need to be quantified.

However, high risk projects, high cost projects, high maintenance projects (those that will not be self-sustaining), those where no reference reach is available and those on vertically or laterally unstable channels will require all or most of the reach assessment elements for proper design and evaluation.

5.1.1 Hydrology

There are three ranges of flows to account for that may influence design of channel modifications. The *Hydrology* appendix includes further details on these flows, and how to determine appropriate values for a given project.

1. *Dominant discharge* is the discharge that over time does the most work in the form of sediment transport, erosion and deposition within the channel. In streams in equilibrium, this discharge is commonly equivalent to bankfull discharge. As such, it is the discharge that should be used to determine the size of the bankfull channel dimensions. Refer to the *Hydrology* appendix for a detailed discussion of dominant discharge and its derivation.
2. *Low flow* is the base level of flow in the channel when the stream is not subjected to runoff from storms or snowmelt. Low flow should be used to design and size many habitat components including refuge, pools, and fish passage.
3. *Flood flow* is any low-probability flow that exceeds the capacity of the channel and inundates the floodplain or other adjacent areas. Flood flows, such as the 100-year flow, may be the basis of design for some channel components that are otherwise unrelated to habitat, but which may be required for regulatory purposes. Certain in-channel structures that artificially limit a stream's range of motion, such as grade control, should have associated design discharges to clearly outline risk to the project, infrastructure and general stream health, and future maintenance commitments if such structural controls are not self-maintaining or eventually superseded by natural processes. In many urban areas, channel modification projects will not be permitted to increase water surface elevations during flood flows. It is common to evaluate the 5-, 10-, 25-, 50-, and 100-year flow events.

In addition to the in-channel flows, hydrologic considerations for habitat design may include hyporheic and groundwater flow and interaction. The hyporheic zone is the transition area between surface flow and groundwater and is important for:

1. Supply and sink of nutrients within the channel
2. Temperature regulation within the channel
3. Moderating variations in stream flow
4. Regulating intra-gravel water quality.

While the importance of this zone is acknowledged, the opportunity to actively account for and manage the influence of this zone in habitat projects is very small due to the limits of understanding and the extreme variability of hyporheic conditions spatially and temporally. Bed substrate composition, particularly fine sediment content and surface embeddedness, has a large influence on hyporheic flow conditions. Channel complexity, including topographic variations in the streambed elevation, large wood and sinuosity also influence (promote) hyporheic flow. Refer to SHRG Chapter 2, *Stream Processes and Habitat,* and the *Hydrology* appendix for further discussion of hyporheic conditions.

5.1.2 Hydraulics

Hydraulics refers to the forces generated by moving water within the channel. Consideration of hydraulics is essential to successful design of stream habitat, as factors such as velocity, shear stress, turbulence, and flow vectors determine sediment transport rates, scour depths, bank erosion, structure stability, depositional areas, gravel sorting, and fish passage. The new channel may also alter the depth and extent of flooding. Such changes will need to be evaluated where there is risk to property, infrastructure, or habitat. The *Hydraulics* appendix provides detailed descriptions of analyses and methods for measuring and determining hydraulic variables in the design process.

Mathematical or numerical hydraulic models also provide a valuable tool for determining channel geometry. These models can be used to determine the dimensions of a channel and to determine inundation periods for floodplain overflow, refuge flooding, and other areas of off-channel inundation. Hydraulic models and their application are discussed in the *Hydraulics* appendix.

5.1.3 Sediment Transport Capacity

Sediment in the context of channel modifications includes everything from boulders and gravel to sand, silt and clay. Channel modifications can include components designed to manipulate existing sediment transport and deposition within a channel reach and through the reach. Sediment within a stream can enhance and provide habitat (e.g. spawning gravels) or degrade habitat (e.g. fine-grained sediment within spawning gravel). Characterization and design of sediment transport is an integral component of channel modification design. The size and shape of the channel will determine to a large extent what size material will be transported and sorted within the channel, and thus will influence the viability and quality of habitat, particularly spawning habitat and aquatic food production.

Channel modifications require consideration of existing bed substrate and sediment supply. In alluvial channels (those built from material moved and deposited by the river), equilibrium conditions depend on both bed substrate size gradations and the size and volume of sediment moving into the reach. Channel modifications must ensure that:

- Appropriate size bed material exists to prevent incision but allow mobility and sorting of gravels, or where supply is limited, that bed material is sufficient in size to withstand mobilization
- The channel is capable of transporting all sizes and volumes of material delivered to the reach, without incising or aggrading
- Appropriate size gradations are available to meet habitat objectives, particularly for spawning

5.2 General Approaches to channel modification design

There are three general approaches to channel modification designs: Analog, Empirical, and Analytical[7]. Skidmore et al.[7] provide a detailed discussion of the applications and limitations of these varying approaches. Channel modification design may use any of the approaches described above, or a combination of the three. Project objectives, site conditions, and availability of an appropriate reference reach or sediment data may dictate what approaches are applied. Using more than one approach to determine the same design parameter helps to verify its validity (where results are similar) and alert the designer to potential errors (where results differ).

1. *Analog design* involves replicating channel characteristics from historical data on the project site or from information gathered from a similar, stable channel and assumes those reference channels are in sediment and hydrologic equilibrium. This is sometimes called the Reference Reach Approach. It is best suited to cases where watershed hydrologic and sediment inputs have not been significantly changed. It is a relatively intuitive and simple approach, but this advantage can lead to its use in inappropriate situations.
2. *Empirical design* uses equations that relate various channel characteristics derived from regionalized or "universal" data sets, and also assumes equilibrium sediment and hydrologic conditions. Regional relationships are seldom relied upon as the sole design tool, but are useful to confirm design elements obtained by other means, or to help in evaluation of channel condition. Like the analog approach, empirical design is a relatively intuitive and simple process, which can lead to its use in inappropriate situations. Careful evaluation of similarity between characteristics of the stream and watershed in question, and those comprising the dataset used in the regional relationships must be exercised.
3. *Analytical design* makes use of the continuity equation, roughness equations, hydraulic models, and a variety of sediment transport functions to derive equilibrium channel conditions, and thus is applicable to situations where historic or current channel conditions are not in equilibrium, or where applicable analogs or empirical equations are unavailable. Application of the analytical approach generally requires access to engineering expertise, which can lead to a bias against its use due to cost or availability. The approach is particularly appropriate for cases where watershed sediment dynamics and hydrology are changing, where no reliable analog reaches exist, and where the assumption of equilibrium conditions cannot be applied.

Careful analysis of the watershed should accompany any channel modification work to determine if there has been significant alteration of the watershed hydrology. If urbanization, timber harvest, grazing, agriculture or other human activities have affected the watershed, the hydrology, sediment, and large wood regimes may be significantly and permanently altered. Natural changes such as fire should also be considered. Selection and design of channel modification treatments based on historic conditions should be considered only where changing watershed conditions can be accounted for, or where the watershed has already been restored to historic conditions. In any case, future anticipated conditions are a critical element of any channel modification design.

5.3 Design Methodology

A detailed discussion of channel modification design methodologies is beyond the scope of this document because of the relative complexity and variability in channel modification projects. A qualified geomorphologist should be consulted to help evaluate the necessity and applicability of major channel modification work and to assist in design. Additionally, qualified professional engineers should be consulted to evaluate the potential risks to safety, property, and infrastructure associated with channel modification projects. Finally, plant biologists are essential to assure that recovery and stabilization of disturbed areas is successful. For further information regarding contemporary approaches and limits of knowledge of channel modification design methods, refer to the documents listed in Section 12, *Additional Reading*.

Although each project requires a unique sequence of design actions and supporting decisions, the following conceptual example is provided to illustrate a channel modification design process that could be applicable to each of the three basic methodologies listed above. The steps listed assume that watershed assessment, physical and geomorphic reach survey and biological resource assessments have already been completed, and that project objectives, site constraints and risk/cost/benefit analysis have defined the need for, and scope of, the channel modification project.

Conceptual Example: Steps in Channel Modification Design

1. Determine design discharge
2. Determine channel cross-sectional area
3. Determine average channel width
4. Determine average channel depth
5. Determine planform geometry
6. Compute reach slope
7. Check water and sediment conveyance
8. Go back to Step 3 if sediment mobility is insufficient
9. Design grade control and/ or hydraulic bank protection
10. Develop bank designs
11. Add habitat features consistent with geomorphic function
12. Develop revegetation and riparian designs

The method followed in this example uses channel width as a starting design parameter. That is, a selected value of width is verified (or not) by computations occurring at a later step. If the width is not verified, it is adjusted and the design steps repeated until concurrence is reached. Using average channel width as a starting parameter has the advantage that regional relationships for width tend to have less scatter than relationships for slope, if an empirical approach is used, and width tends to be easily and consistently measured and adjusted if an analog approach is followed. Slope is computed as a subsequent step in the process, where it is used to check for water and sediment transport capacity.

Note that some practitioners advocate the use of slope, rather than width, as an initial design parameter. Design may start with a narrow range of allowable slopes, which then determine cross-section design, progress to planform characteristics, and ultimately lead to confirmation (or rejection) of design slope. Designing from slope as a first parameter has the advantage of direct ties, through physical models and equations, to water discharge and sediment transport. This is often highly desirable, especially if the analytic approach is used.

Note also that the method described in the example presumes that the size distribution of the sediment in transport, and the streambed surface, are known (from measurement at the project site and at the site analog). If actual sediment size in transport is unknown, or if the project involves gravel supplementation, measures must be taken to design the streambed sediment gradation as part of the process rather than treat it as given (see Bed Material Considerations, below).

Note that the design of channels is necessarily an iterative process, to an even greater degree than suggested by the simplified example given above. Whether width, slope, or other physical variables are selected as initial design parameters, the process always involves iterative adjustment of design until physical (hydraulic and sediment transport) process criteria are met. Furthermore, site constraints, stakeholder interests, and other objectives complicate the design process. For example, site constraints may limit planform options to a narrow range of possible slopes. Cross-section characteristics must be designed to achieve the desired hydraulic conditions within the range of acceptable slopes. However, cross-section character influences planform design, as there is a strong relationship between cross-section character and planform in most equilibrium alluvial channels. Once a preliminary channel design is achieved, it must be checked to evaluate sediment transport and ensure equilibrium, which may invoke further iterations. Small changes to various design components are necessary in a backwards and forwards process to achieve the desired end design product. There is no single linear series of design tasks that can be followed to arrive at a final design.

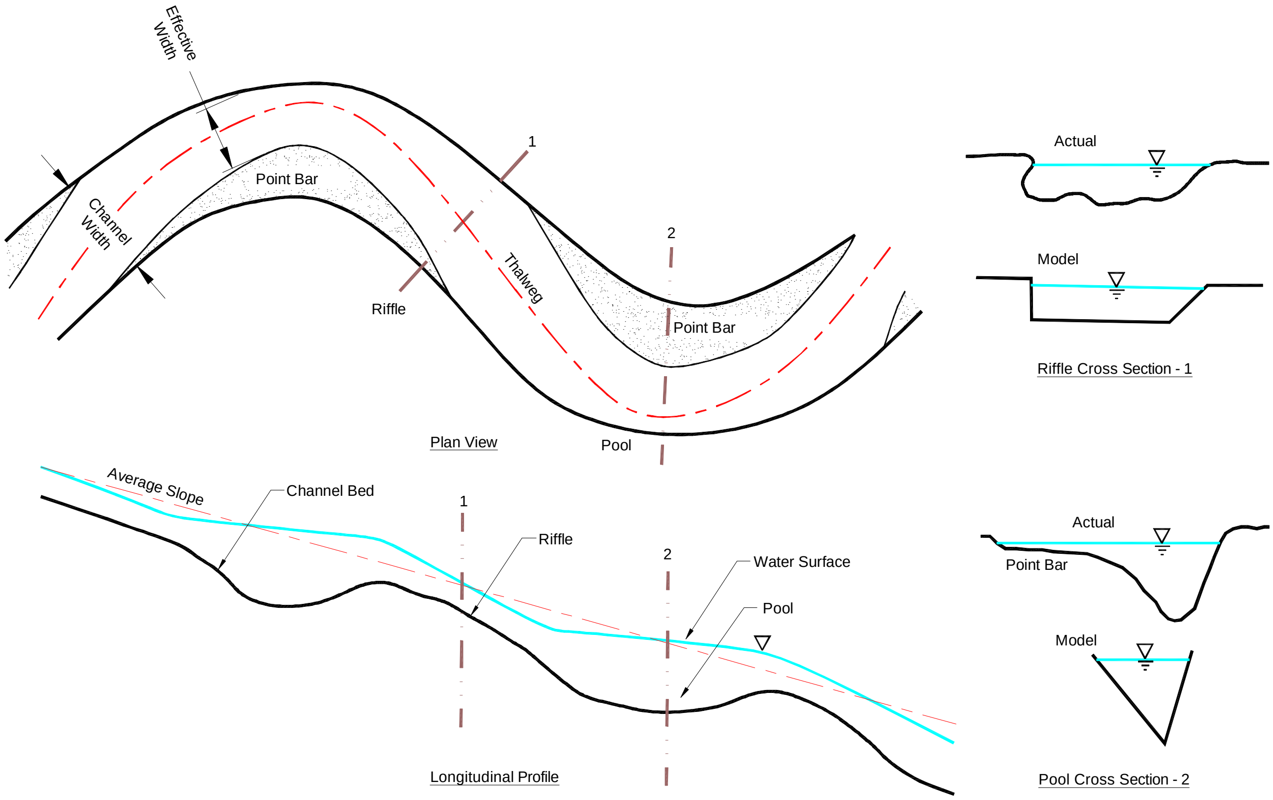
5.3.1 Cross-Section Considerations

The primary design considerations for cross-section modification design are:

- Sizing the cross-section to convey the dominant discharge and sediment supply. If the channel is oversized, deposition will likely occur. If it is undersized, scour will likely occur (possibly causing bank erosion and/or channel incision) unless the bed and bank material are immobile at flows to which they are subjected. Either scenario may impact the profile, sediment supply, and floodplain connectivity of the project, upstream and downstream channel reaches.
- Shaping the cross-section to provide habitat and hydraulic complexity
- Geomorphic stability (self-maintenance of channel shape over time)
- Geotechnical stability (resistance of banks to mass failure).

The size and shape of the cross-section are typically designed simultaneously, as the shape affects the ability of the channel to convey flows and sediment. Cross-section design will also be dependent upon channel slope and roughness as they, along with channel cross-section, are factors in flow conveyance (refer to the Manning's Equation discussion in the *Hydraulics* appendix). Cross-section design is often conducted using hydraulic models (refer to *Hydraulics* appendix), though simpler hydraulic calculations and methods may be appropriate in smaller streams, and field analogs may be appropriate in some cases.

Cross-section design using hydraulic models usually begins with relatively simplistic and angular channel templates for various channel features, including pools, riffles, and runs. Once the template channel dimensions and slope are established to convey the dominant discharge (or other selected design discharge) and to maintain sediment equilibrium, the cross-section can be modified to include a thalweg (point of maximum depth), with asymmetry across the section. Cross-section shape and thalweg position are varied along the channel to create appropriately placed habitat elements (pools, pool tailouts, riffles, chutes, or steps) for the stream type considered. This variation in cross-section generates streambed topography and forces an interaction of cross-section with planform design (i.e. meandering of the thalweg). The thalweg of a meandering channel lies near the center of the channel along relatively straight sections and moves to the outside of the channel bends where a pool typically forms—hence, the cross-section of pools and riffles is different (see **Channel Modification Figure 1**, below). A thalweg is necessary to ensure adequate water depth during low flow. Cross-section asymmetry will affect the roughness of the channel and will have to be accommodated in calculations for channel dimensions. Habitat complexity is improved if cross-sectional dimensions are specified as a range rather than a single value.



Channel Modification Figure 1: Channel cross-section in relation to position on longitudinal pool-riffle sequence. Note how thalweg (deepest point) shifts to outside of bends at pools and remains centered in riffles, and how slope is greater at riffles than at pools. During peak flows, riffle and pool water surface slopes tend to equalize, approaching the average reach slope. Hydraulic and sediment transport models use idealized cross-sections and average slopes, as shown.

The analog and empirical approaches emphasize a cross-section shape appropriate to the stream type being considered. For example, typical width: depth ratios can be obtained through measurements from a reference reach or from regional relationships. These shape parameters will depend on the type of stream being modeled (e.g. gravel-bed pool-riffle system, moderately-confined step-pool system, Rosgen Type C4 versus Type E6, etc.).

Channels come in various shapes. Familiarity with a channel classification system can help in deciding which shapes fit which stream types and which stream types are appropriate for which settings. Self-sustaining channels in nature tend to exhibit consistent relationships between width and depth, cross-sectional area and watershed area, width and pool spacing or meander length, etc. (see discussion of Hydraulic Geometry and Stream Classification in the *Fluvial Geomorphology* appendix). These numbers are not random or based solely on engineering hydraulic models. .

5.3.2 Channel Profile and Bedform Considerations

The primary design considerations when modifying or designing the channel profile are:

- Overall channel slope
- Bed elevation relative to floodplain elevation, existing bed elevation at the upstream or downstream limits of the modified reach, existing water table, or other design parameters
- Bedform characteristics (longitudinal variations in the channel bed) that mimic stable natural channel configurations and provide habitat diversity
- Transitions in slope between reaches upstream and downstream of the project

When selecting a channel slope, the designer should consider the topography, the slope of the upstream and downstream channel, and the effects of channel slope on design discharge and sediment transport. Slope helps determine stream discharge, stream power, shear stress, and sediment transport. If the slope of the modified channel reach is much greater than that of the upstream reach, incoming bed material will be too small to be retained within the modified reach. The modified channel (and upstream channel) will likely incise without stable grade control (e.g., drop structures or immobile bed material). If the slope of the channel is much lower than that of the upstream reach, sediment deposition is likely to occur until a stable transition slope develops. This evolution may be accompanied by rapid channel migration (avulsion) and associated bank erosion and flooding. In severe cases, formation of a depositional landform (such as a channel perched above its former floodplain) may ensue. Deposition can temporarily starve downstream reaches of sediment, inducing bed coarsening or incision.

Profile design is often conducted using hydraulic models (refer to *Hydraulics* appendix), though simpler hydraulic calculations and methods may be appropriate in smaller streams and field analogs or empirical ranges may be appropriate in some cases. For example, where channels are being relocated, the elevation and location of the historic channel may be indicated by the depth of buried alluvial material within the soil profile.

The slope of the bed is typically varied through a reach. It is steepest through riffles or over drops, and shallow or inverse through pools (see **Channel Modification Figure 1**). Bedforms, such as pools, pool tailouts, riffles, chutes and other variations in the bed topography are three-dimensional features, and are therefore incorporated in both profile design and cross-section design.

In streams undergoing restoration or modification, channel profiles typically fall within one of the following types of sequences, which are further discussed in the *Fluvial Geomorphology* appendix:

- Pool-riffle sequences consist of steep armored riffles and deep slow pools, and are most common at slopes of less than 2 percent. Scour patterns form pools on the outside of meander bends and in association with large wood, rock, or other obstructions to flow. Pools typically have tailouts of mobile gravels, which slope up to the head of the next riffle. The riffle gradually deepens and transitions into the next pool. Pool riffle sequences typically occur at an interval of 4 to 10 channel widths[8].

- Step-pool sequences consist of steep drops formed by large wood or boulders, and scour or backwater pools. Step-pool sequences commonly occur at slopes of greater than 2 percent. Step-pool sequences typically occur at an interval of 1 to 4 channel widths.

The channel type found at any location is determined by channel slope, available bed material and large wood, and the surrounding landform. Channel types that occur in Washington State, other than those described above, are described in the *Fluvial Geomorphology* appendix.

5.3.3 Channel Planform Considerations

Channel planform is the shape of the stream in plan view and is described by its sinuosity, wavelength, amplitude, belt width, and radius of curvature.

The primary design considerations when modifying or designing the channel planform are:

- Channel length and channel slope are related. Slope may be constrained by sediment transport characteristics.
- Site constraints on meander amplitude and wavelength may exist due to valley width or placement of infrastructure
- Radius of curvature determines lateral migration tendencies (see below)
- Topography may complicate design options or construction timing. Relocation of the channel away from the valley topographic low point results in a perched condition, which creates instability and fish stranding problems. Designs where a new channel alignment crosses an old channel require careful construction sequencing and use of constructed plugs to prevent avulsion during peak flows.

When using an analog approach, and given an identical valley slope as the reference reach, reference reaches can be used to select both mean and extreme values for various planform parameters, thereby allowing a designer to incorporate variability in design. When using an empirical approach, planform characteristics are typically defined by their relationship to channel width or other cross-section values, and may provide a range of acceptable values for each planform characteristic. Even where an analytical approach is followed, empirical ranges for planform characteristics can be used to confirm reasonableness of designs.

When designing channels in watersheds that have altered hydrologic and sediment regimes, or where lateral constraints preclude other approaches to planform design, the most important characteristics to consider are sinuosity and radius of curvature. Often, sinuosity is already established in the design process as a function of channel slope (note that steeper channels tend to be less sinuous than low-gradient reaches). Site constraints may dictate the limit of wavelength and amplitude. However, radius of curvature (Rc) can be varied considerably in most situations and can provide valuable opportunity for variability in planform. The ratio of Rc:W (radius of curvature to channel width) has been studied extensively and found to correspond to susceptibility to erosion, both in nature and in labs. This ratio, therefore, can be used to define limits for planform characteristics. Meandering alluvial channels tend to have an

Rc:W ratio of between 2 and 3[9]. Channels within this range have been shown to minimize energy losses due to flow curvature. Not surprisingly, this maximizes the energy available for erosion, and thus also corresponds to the greatest lateral migration rates and pool scour depths in otherwise stable channels[10]. Thus, while this ratio is common in equilibrium alluvial channels and mature meander bends, it may not be appropriate for design of a newly constructed channel in large or steep (high energy) streams. In such instances, larger Rc:W ratios (3 to 4) may reduce erosion potential initially. Here, it is worth noting that the design channel type must be appropriate for the slope, substrate and valley setting. Design of meandering, pool-riffle type channels are not appropriate at slopes greater than about 2 percent.

Sine-generated curves may also be used to design planform, but result in a very regular, smooth-curved layout. A sine-generated curve minimizes opportunity for variability. Furthermore, such regular and perfect planform is rare in nature except in extremely homogenous materials with uniform flows

Design of planform requires careful consideration of the location of the new channel relative to the old channel. Construction can be greatly complicated when the new channel alignment crosses the old channel alignment repeatedly, as each crossing will require fairly complicated construction sequencing and careful design of plugs in the old channel. Crossings do, however, provide opportunity to create off channel rearing habitat. Leaving the downstream portion of a previous channel open where it connects with the new channel can provide low velocity off-channel habitat. Channel plugs should consist of compacted earth (not porous rock) and they should be of sufficient length to minimize risk of headcut and avulsion into the old channel during high flow events. A 40-foot minimum plug length is recommended on relatively low gradient small streams (<20’ wide); longer plugs may be necessary for larger or steeper channels. It may be best to break up lengths of old channel into segments, forming a string of ponds, to reduce avulsion risk. It is recommended that plugs be designed by engineers with experience in design and construction of small earthen dams, and should be designed similarly to dam overflow channels. Channel plugs are usually designed to match the floodplain elevation at their crest, and may require armoring on their downstream side to prevent headcutting during overbank flow events. Creating a shallow slope (e.g., 5H:1V) on the downstream end of the plug and heavily mulching and/or vegetating it may also suffice. Likewise, potential headcutting at places where floodplain water enters an old channel from the side must be carefully considered to avoid a channel avulsion.

Finally, subtle valley topography may exclude some proposed channel locations. Channels naturally form in low areas. However, relocated channels are sometimes perched above the surrounding land with levees, making them susceptible to channel aggradation, avulsion, and fish stranding when high flows leave the channel or spill over the levee. Perched stream reaches thus present a high risk of failure, necessitating a long-term monitoring and maintenance commitment to keep them within their constructed channel. Creating or sustaining perched channel conditions should be avoided.

5.3.4 Control of Streambed Elevation

Control of streambed elevation, often called grade control, is often used in order to:

- Provide a gradual transition from a reconstructed reach to a downstream reach

- Prevent incised areas downstream from inducing headcutting upstream through the reconstructed reach
- Prevent channel incision when the size or volume of sediment transported into the reach is too small to provide stability to the new channel (e.g. downstream of a dam or pond that traps sediment)
- Prevent channel incision where the sediment transport capacity is higher than that in the upstream channel (e.g., if the new channel has a greater slope, depth, or degree of confinement than the upstream or existing channel)

Methods commonly used to fix streambed elevation include:

- Drop structures (see the *Drop Structures* technique)
- Buried large wood or large rocks
- Placement of coarse streambed material.

Grade control is often incorporated at the downstream and upstream ends of a newly constructed channel (see **Channel Modification Figure 2**), and in longer reaches at regular intervals along the reconstructed reach. Drop structures should be designed and constructed to be flush with the channel bed elevation, unless there are other habitat objectives incorporated in the control. Drop structures may be rigid or deformable (designed to eventually deform through gradual mobility of materials). The advantages and disadvantages of using drop structures, and design guidelines and considerations necessary for drop structures to control grade are described in the *Drop Structure* technique. In many cases, grade control structures must extend far up into the floodplain to avert potential channel avulsion. Design teams must be forthright about the fact that grade control structures may be necessary to hold some projects together. Thus, long-term project success depends on commitment to monitor and maintain these structures, replacing them in the future as necessary. The best designs will include restoration of processes (such as large wood recruitment and retention) that ultimately eliminate dependence on structures. Refer to the *Porous Weirs* and *Drop Structures* techniques for further information on habitat value associated with these structures, and for design guidelines.

Channel Modification Figure 2: Step-pool drop structures are often employed as streambed elevation (grade) control in transitional zones at the ends of newly constructed reaches. This is particularly common at the downstream end of a restored incised channel.

5.3.5 Bed Material Considerations

In alluvial channels, modifications can often be implemented within existing substrate and alluvium. Channels are designed to establish equilibrium between the streambed and the sediment in transport. However, there are some cases where artificial placement of gravels or other bed material may be part of the initial design, or even part of the long-term maintenance activity. These cases include:

- Reaches with very low sediment input from upstream, as indicated by:
    - Analysis of existing bed substrate and sediment mobilization and transport both in the project area and upstream
    - The existence of dams, ponds or other sediment traps upstream
    - Artificial stabilization of dominant upstream sediment sources, such as pervasive bank armoring
- Where bed material enhancement is needed to temporarily stabilize the bed and provide spawning gravel until natural recruitment provides the supply, as when relocating a gravel-bed stream onto floodplain deposits (silts and sands)

In circumstances where the natural supply has been eliminated, supplementation may be a part of a regular maintenance program. Supplementation of gravels is discussed in detail in the *Salmonid Spawning Gravel Cleaning and Placement* technique. Regular supplementation is costly, but may be justified where resource values are high. Commitment to gravel supplementation requires careful consideration of geomorphic processes, since not all reaches, even within alluvial settings, are conducive to persistence of stable spawning gravel deposits. Supplementation is most effective in response reaches that are not in the gravel-to-sand transition zone (refer to the *Fluvial Geomorphology* appendix for further discussion).

The science of sediment transport straddles the disciplines of engineering and fluvial geomorphology. Typically, engineers conduct the methods and models used to analyze sediment transport at short time scales. Geomorphologists identify dominant sediment dynamics over long time spans and larger spatial scales. Both long (decadal) and short (storm or annual) time scales may need to be considered. The *Sediment Transport* appendix presents methods for measuring and quantifying sediment transport, and for applying these methods to design of channel modifications.

Overall, consideration of bed material and the potential need to supplement should address the following questions:

- Is there an adequate sediment supply (from upstream and within the banks) to replenish any material that is eroded from the reconstructed channel? If not, grade control may be necessary to prevent channel incision.
- Will the sediment supply from upstream provide the necessary gradation of material to provide desired habitat functions in the project reach? If not, then what does the geomorphic setting suggest is sustainable? For example, a high-energy reach with low sediment supply is expected to form a coarse surface layer, and imported gravel may not persist unless hydraulically shielded or placed in off-channel habitat. Likewise, clean gravel is not expected to persist in a gravel-to-sand transition zone.
- Is the reconstructed reach designed to ultimately accommodate channel migration? What size gradation of sediment is recruited when this happens, and is this different from what it was historically?
- Is there alluvial material in the new channel location that can provide immediate stability to the bed and banks of the new channel after construction? If not, it may be appropriate to install bed substrate within the newly constructed channel and run it part way up the banks.

5.3.5.1 Gradation of material for constructed channel bed

Gradation refers to the range of particle sizes present, and their proportions in the bed material mixture. Bed substrate provides both habitat and channel stability. In natural systems, substrate character (size, gradation, porosity, and depth) can vary substantially through a reach. Design of imported bed substrate materials is one of the most complex and challenging aspects of channel modification design. This is in part due to the high degree of complexity of sediment transport processes in natural systems, the difficulty in measuring and documenting these processes, and the fact that most studies resulting in equations to describe these processes are founded on limited ranges of applicable variables such as channel slope, substrate size and gradation, and other hydraulic variables. Obtaining and properly dispersing the desired sediment mixture is equally challenging. The Fish Passage Design at Road Culverts manual[11] provides further discussion and resources for design of bed substrate gradation.

Habitat value (e.g., for spawning) is dependent primarily on size, depth, and porosity, while streambed stability is dependent primarily on scour depth and material gradation. The degree to which the gradation is designed to be mobile or immobile (forming an armor layer) will depend on site-specific channel character, underlying and adjacent materials, sediment input from upstream and the degree of acceptable risk. In some instances, for example in urban watersheds that have limited or no supply of gravels in historically alluvial systems, the bed substrate may have to be immobile to prevent channel degradation. Protection of the channel will have to be balanced with the need for mobile spawning gravels. Ideally, selection of the gravel size distribution for instream placement should be based upon a particle size distribution from an appropriate reference reach. However, in many instances appropriate analogs are not available, in which case detailed hydraulic and sediment transport analyses are necessary to determine substrate gradations.

Size of substrate. The design criterion for bed mobility for channel restoration is usually related to a dominant discharge (Refer to the *Hydrology* appendix for discussion of dominant discharge). In naturally functioning stream systems, bed substrate designs commonly use a target of the D_{84} particle size mobile during dominant discharge flows[11]. Thus, at bankfull conditions, nominally 84% of the bed substrate material would consist of a size that could mobilize, and 16% would be immobile. The surface particle size distribution will differ for different channel bed features.

Also, in practice, a substrate consisting of a range of size classes will form a coarse but mobile surface layer or “pavement” after exposure to high flows. Refer to the *Sediment Transport* appendix for a more in-depth discussion of surface (pavement) layer dynamics. Riffles will require much coarser substrate than non-riffle portions of the channel, and should be constructed to be largely immobile during most flows. How much material actually mobilizes will be a function of scour depth, bed substrate size, surface (pavement) coarsening and the particular hydraulic conditions at a given site and discharge. This allows for gravel sorting processes that are essential for maintenance of spawning gravels, certain macroinvertebrate habitat, and hyporheic flow.

Substrate gradation. In situations where the upstream or downstream reach is used as an analog for design, the substrate gradation from various components of the analog reach can be used as the basis for design. Other methods for determining substrate mobility are presented in the *Hydraulics* appendix and the *Sediment Transport* appendix, the Fish Passage Design at Road Culverts guidance manual, and the *Salmonid Spawning Gravel Cleaning and Placement* technique. A well-graded mix that includes fines is critical to ensure that porosity is reduced to prevent subsurface flow during low flows. Conversely, too many fines will reduce porosity to a degree that limits incubation value of eggs within gravels. “Spawning” sized material is not appropriate in all situations and shouldn’t be forced into a design. The value of adding it may be short lived if it blows out of the new channel in the first storm. Unless it can remain naturally stable in system, it should only be used to supplement other more stable material.

Depth of substrate. Where imported bed substrate material included in the reconstructed channel is expected to be mobile, it should be installed to a minimum depth related to the estimated depth of scour through the channel. Calculation of depth of scour is discussed in the *Hydraulics* appendix. It can also be estimated by measuring pool depths in a reference reach. But keep in mind that scour depths that occur during high flow events are greater than those observed at lower flows. The depth of scour is dependent upon site-specific hydraulic conditions and the size of bed material and will vary through the reach. Using the maximum depth of scour for the reach is recommended for selecting a substrate depth. For loosely mixed material, the thickness of the installed material should be approximately 10 to 20% greater than designed to account for the early transport of fine material and eventual sorting, which leads to more densely packed bed material.

5.3.6 Bank Reconstruction

A stream channel is defined at its lateral margins by its streambanks. Most channel modification activities will require reconstruction of channel banks on one or both sides. Even modification projects that affect only the channel profile should consider the impacts of the activities on the channel banks. Any change in the physical character of a channel typically results in changes to the hydraulic conditions within the channel, and thereby may affect the stability of existing channel banks. The best conceived channel modifications could fail due to poorly designed or constructed streambanks.

Ultimately, some rate of streambank erosion is part of a naturally functioning system. The challenge to designers is to prevent "excessive" erosion, especially during the vulnerable period following channel modification. Elements of streambank stability and design are described more fully in the ISPG[1], but to briefly summarize, bank stability is a function of:

- Geotechnical factors (soil strength, which is affected by bank height, bank slope and augmentation by roots)
- Surface protection (by vegetation, or by resistant soils or rock)
- Near-bank hydraulic forces (including reentry of floodplain water)

Where streambank stability is dominated by influence of vegetation, as in meadow systems, streambank reestablishment requires re-growth of healthy riparian vegetation. Sometimes, re-introduction of flow to the reconstructed channel is delayed or done in stages, allowing peak flows to be shunted away in order to protect the new vegetation as it is being established. Another alternative is to control initial erosion using biodegradable fabrics. Although a risk of fabric washout or undermining during peak flows exists, this may be preferable to the complexity of staged flow re-introduction in many projects.

Sometimes bioengineered approaches are used to accelerate recovery of vegetative stabilization. This may include design of "deformable" streambanks, which lock the channel in place only for a planned time interval. In other cases, hydraulic structures or even judicious use of bank armoring locks the new channel in place for an indeterminate time period. This may be part of a strategy to regenerate a mature vegetative buffer zone that ultimately serves to accommodate channel migration. Or, it may be that social concerns preclude channel migration and the bank protection may need to be maintained in perpetuity.

The design and reconstruction of streambanks for channel modification often requires an equal effort in design, construction, and expense to the channel modifications themselves. In particular, consideration should be given to:

- Deformable vs. non-deformable banks that will accommodate natural rates of lateral

adjustment and channel migration.
- Use of biodegradable materials in channel bank construction
- Proper planting techniques, maintenance and water availability for successful revegetation
- Risk to adjacent property and infrastructure

5.3.7 Riparian Revegetation

Riparian vegetation provides long-term stability to the lateral channel boundaries, nutrients, and detritus to the stream, shade and acts as a source of wood. Revegetation should be an integral part of most channel modification projects, particularly where bank reconstruction is involved, and is often not given due consideration. The long-term stability of a channel, particularly a modified channel, may be highly dependent upon stabilizing riparian vegetation on the channel banks. Process-based restoration presupposes some width of riparian buffer, in which vegetation-dependent riparian functions are allowed to dominate in management actions. In particular, stable streambanks are not immobile, and where healthy riparian plant communities exist, natural rates of bank erosion serve useful ecological and physical functions.

The use of vegetation in reconstructed channel banks is detailed in the *Riparian Restoration and Management* technique and in the ISPG[1]. Note that irrigation, weed control, and herbivory protection is often necessary for one or more years to establish vegetation, particularly in eastern Washington projects.

5.3.8 Habitat Considerations

Most reconstructed or modified channels should incorporate habitat elements. Although proper channel design fundamentally hinges on physical and geomorphic processes, every opportunity should be taken to enhance habitat complexity. Valuable habitat is best achieved in new channels by incorporating large roughness elements, such as boulders or wood. Large wood tends to be a natural magnet for fish, and tends to promote physical processes such as hyporheic flow, gravel sorting and floodplain connectivity.

Creation of habitat in channels is discussed at length in other techniques within this document, and any of them can be incorporated in channel modifications. Large roughness elements and habitat features can substantially affect the hydraulics of the stream by reducing velocity, shear, and sediment transport and by increasing water surface elevations at all flows. The design process should consider the degree of habitat and roughness that is appropriate and intended such that these elements don’t affect the performance of the channel in detrimental ways.

6 PERMITTING

Permitting channel modification projects will be very site-and project-specific. Channel modification invariably involves physical disturbance of the channel, which disrupts habitat and water quality at the site and downstream at least in the short term. A comprehensive discussion of permitting requirements is included in *Typical Permits Required for Work In and Around Water* appendix. Because most channel modification projects involve the movement, redistribution, or installation of material within the channel, permitting for these projects is typically comprehensive and the permitting process rigorous, particularly if conducted in streams affected by the Endangered Species Act.

Many channel modification projects may qualify for a streamlined process for fish habitat enhancement. Smaller projects conducted as part of grander coordinated watershed restoration efforts may be facilitated by an expedited permit application. Both of these alternatives are part of the general Joint Aquatic Resources Permits Application (JARPA) permit process. Refer to the *Typical Permits Required for Work In and Around Water* appendix for details about this streamlined permit process. Note that the availability of streamlined permitting processes should not be taken as an excuse to avoid full involvement of all the necessary disciplines (biology, geomorphology, hydrology, engineering, riparian ecology, etc.) in the design process, or the necessity for careful peer review.

7 CONSTRUCTION CONSIDERATIONS

Construction of channel modification projects requires careful sequencing of work phases. Construction steps may include (not necessarily in this order):

- Installing erosion and sediment control;
- Providing access for and stockpiling imported materials, waste materials and transitional redistributed materials;
- Constructing a diversion channel;
- Diverting stream flow;
- Rescuing fishes from areas to be dewatered;
- Dewatering;
- Constructing the channel bed, streambanks and installing habitat features; and
- Redirecting flow into the modified channel.

Further discussion of these components can be found in the *Construction Considerations* appendix.

Construction of channel modification projects will generally require dewatering of the channel either by diverting all flow or by isolating parts of the channel during construction. Dewatering is essential to facilitate construction and to control sediment inputs to the stream. Fish and amphibian trapping and relocation may be required to remove them from the project construction area. The lower end of an existing channel might be left open and connected so there is in-stream habitat until the new channel is established with vegetation.

Construction contracting for channel modifications requires careful attention to the specialty nature of the work at hand, and is discussed in detail in the *Construction Considerations* appendix. Most channel modification projects are very specialized projects that may require specific equipment and innovative approaches. Selection of a contractor should include consideration of previous experience in stream restoration work, as well as availability of specialized equipment.

Because channel modification and habitat work often requires the direct supervision by experienced habitat construction specialists, a contractor may be unable or unwilling to provide lump sum bids on many project elements. Contracts should, therefore, make allowance for time and materials delivery on certain project elements, such as installation of boulders or wood, creation of bedforms, or other intricate project components. This also allows for small design changes without requiring a work change order.

With channel modification, perhaps more so than with other types of restoration work, the risk to natural resources, aquatic populations and infrastructure necessitates diligent construction inspection and quality control by project designers. Unforeseen circumstances in the field are common, and require prompt, knowledgeable design and implementation decisions. Waiting until late in the project before initiating inspections for design compliance, BMP implementation or fulfillment of material specifications is not an option with channel modification projects.

Channel modification often requires complete dewatering. Consequently, the work should be timed to occur during low-water periods. Critical periods in salmonid life cycles, such as spawning or migration, should also be avoided. Additionally, critical periods for other species dependent upon the channel system, including amphibians and birds should be avoided. In-stream work windows vary among fish species and streams. Contact The Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows. Further discussion of construction timing and dewatering can also be found in the *Construction Considerations* appendix.

8 COST ESTIMATION

Channel modification project costs are site and design specific and vary according to the size of the channel. Reconstruction and relocation projects may range from as little as $20 to well over $1000 per foot of channel (including reconstructed banks and dewatering), depending on the size of the channel, complexity of modification techniques and site constraints. Design costs for channel modification are commonly 10 to 20% of construction costs. Key cost items will include dewatering systems, acquisition of imported materials, location of spoils sites, heavy equipment operation and rental, construction supervision and revegetation. Dewatering may be a significant cost for many channel modification projects because it requires, in most cases, complete dewatering of the entire channel or at least half of the channel. The need to import materials for any component of the modification will greatly increase implementation costs. If an entirely new channel is being constructed, or an historic channel is being reconstructed, all of the work can be done in the dry, thus dewatering is not necessary until the water is turned out of the old channel reach and into the new one. However, high groundwater levels may sometimes necessitate dewatering even in such cases.

Many channel modification projects will require reconstruction of channel banks. Costs associated with bank reconstruction can be significant and will also need to be taken into account. Bank reconstruction may represent 50% or more of construction costs for a reconstructed channel. Refer to the ISPG[1] for further discussion of bank protection construction costs.

9 MONITORING

Because channel modification projects generally involve impacts to the channel and banks, they will require comprehensive monitoring of both channel and bank features, in addition to particular attention to habitat monitoring. For a comprehensive review of habitat-monitoring protocols, refer to Johnson et al., 2001[12].

Monitoring of channel modification projects should be initiated prior to construction, with baseline-conditions surveys of the physical channel, its banks, and its habitat value. This will allow comparison of modified conditions to pre-project conditions. Additionally, monitoring should include detailed as-built surveying and photo documentation of the project area and upstream and downstream reaches to allow for evaluation of performance relative to design. Refer to the *Monitoring Considerations* appendix for further discussion of monitoring considerations and practices.

Monitoring is a topic that often receives insufficient emphasis in watershed restoration. As the restoration field evolves, careful, well-planned monitoring is the only way that practitioners will learn what works, what doesn't work, and what are the benefits and impacts of various procedures. Although a diversity of professional opinion may always exist, reported monitoring results (preferably quantitative) from actual projects will help inform the scientific facets of these opinions. To be of value, monitoring should occur on time and spatial scales appropriate to riverine evolutionary processes. Tracking projects for only a few years will ultimately not settle questions about long-term benefits, recovery from disturbance, or process sustainability. Finally, the importance of reporting project monitoring results, both negative and positive, so that others may benefit from the experience, cannot be overstated.

9.1 Geomorphic monitoring

Geomorphic monitoring should include the following at a minimum:

- As-built construction drawings
- Survey of planform, cross-sections, thalweg and bank profiles, with permanent benchmarks
- Bed substrate sampling
- Vegetation survey for type, abundance, and distribution
- Large wood survey (if appropriate)
- Monumented photo points

Aerial photos are an excellent way to monitor large restoration projects. Changes in planform, vegetation, channel complexity, and the spatial extent of sediment deposits can be easily identified. A good review of geomorphic monitoring planning and implementation is provided in Montgomery and MacDonald, 2002[13].

9.2 Habitat/Fish/Wildlife monitoring

Fish and wildlife populations are determined by numerous biological and abiotic factors besides physical habitat[14]. An increase or decrease in fish and wildlife populations following a stream channel restoration project therefore may be completely unrelated to geomorphic changes effected by restoration. This is especially true of anadromous fish populations, which may be controlled in part by fishing pressure, passage barriers, rearing habitat, or ocean conditions[15]. Fish populations may be subject to natural fluctuations, and an increase in a fish population may lag years behind improvements in habitat as the aquatic invertebrates and terrestrial food sources develop in response to improvements in bank and channel structure[14]. However, habitat and fish monitoring may include the following:

- Snorkel surveys of fish population and use of habitat
- Habitat assessments for fish and wildlife
- Spawning surveys and redd counts
- Juvenile screw traps
- Migratory box traps
- Macroinvertebrate surveys
- Riparian vegetation surveys
- Bird surveys (point counts, nest counts, etc.)

10 MAINTENANCE

Operations and maintenance requirements will be determined largely by project objectives, and by regulatory agency requirements. These requirements should be carefully integrated with a monitoring plan, such that monitoring results will determine the need for various operations and maintenance. In theory, channel modification projects should not require any maintenance, as the objectives should be to create self-sustaining channel systems.

Various project elements associated with channel modification projects, such as bank reconstruction and habitat features, may require periodic inspection and maintenance or repair. For example, a reconstructed channel may rely on vegetation to stabilize soils on the streambanks and irrigation may be necessary to establish plants rapidly. Modified channels may be especially vulnerable to damage during the first years of operation, particularly if they are subjected to high flows before vegetative components are able to provide support. While the intent of channel modification is to create a stable channel, the design must allow some deformity to occur in order to create and sustain adequate fish habitat. For this reason, moderate erosion along banks should be expected, and some degree of maintenance and repair should be anticipated especially during the first three years of the new project.

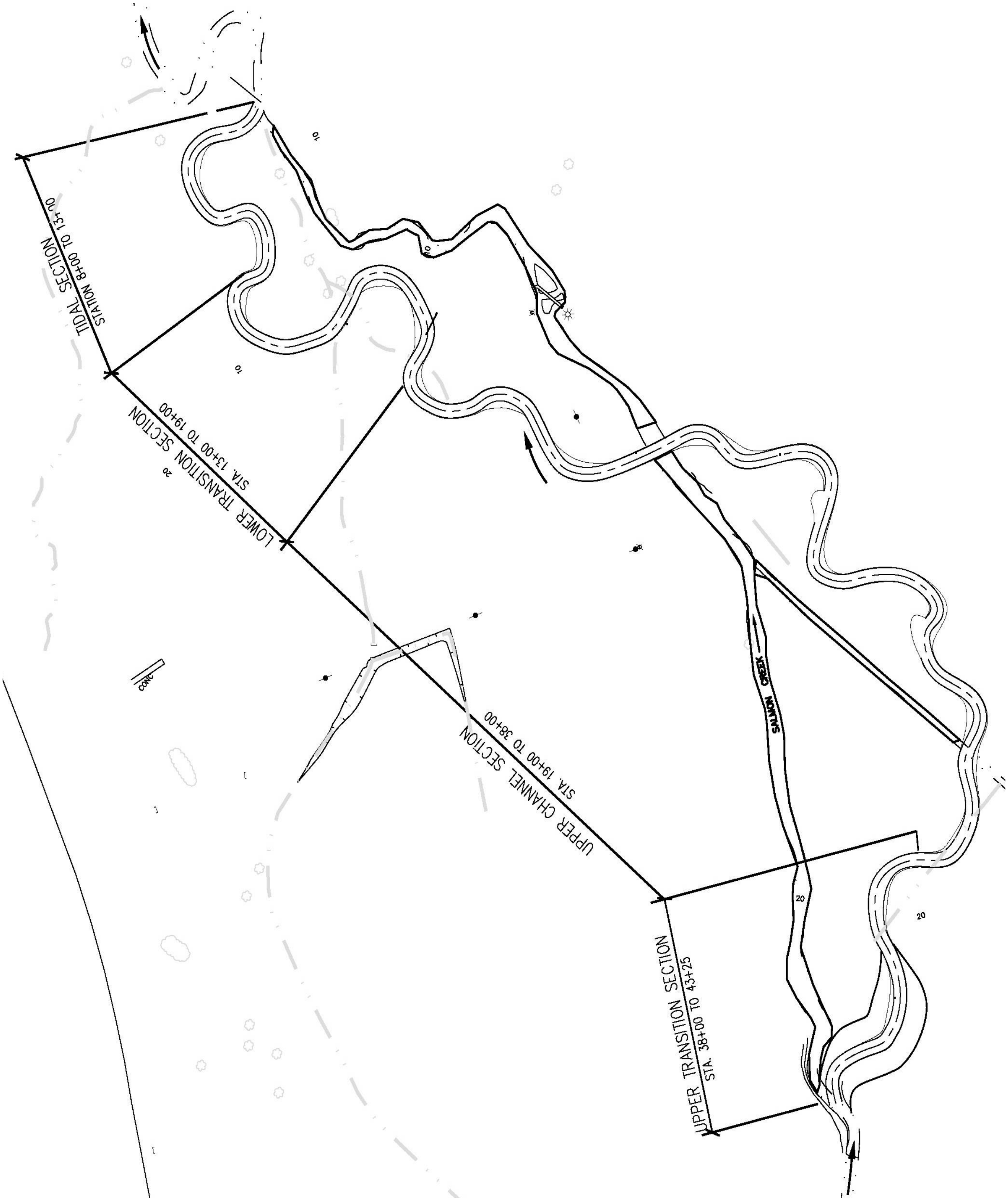
11 EXAMPLE

Salmon Creek Restoration Project

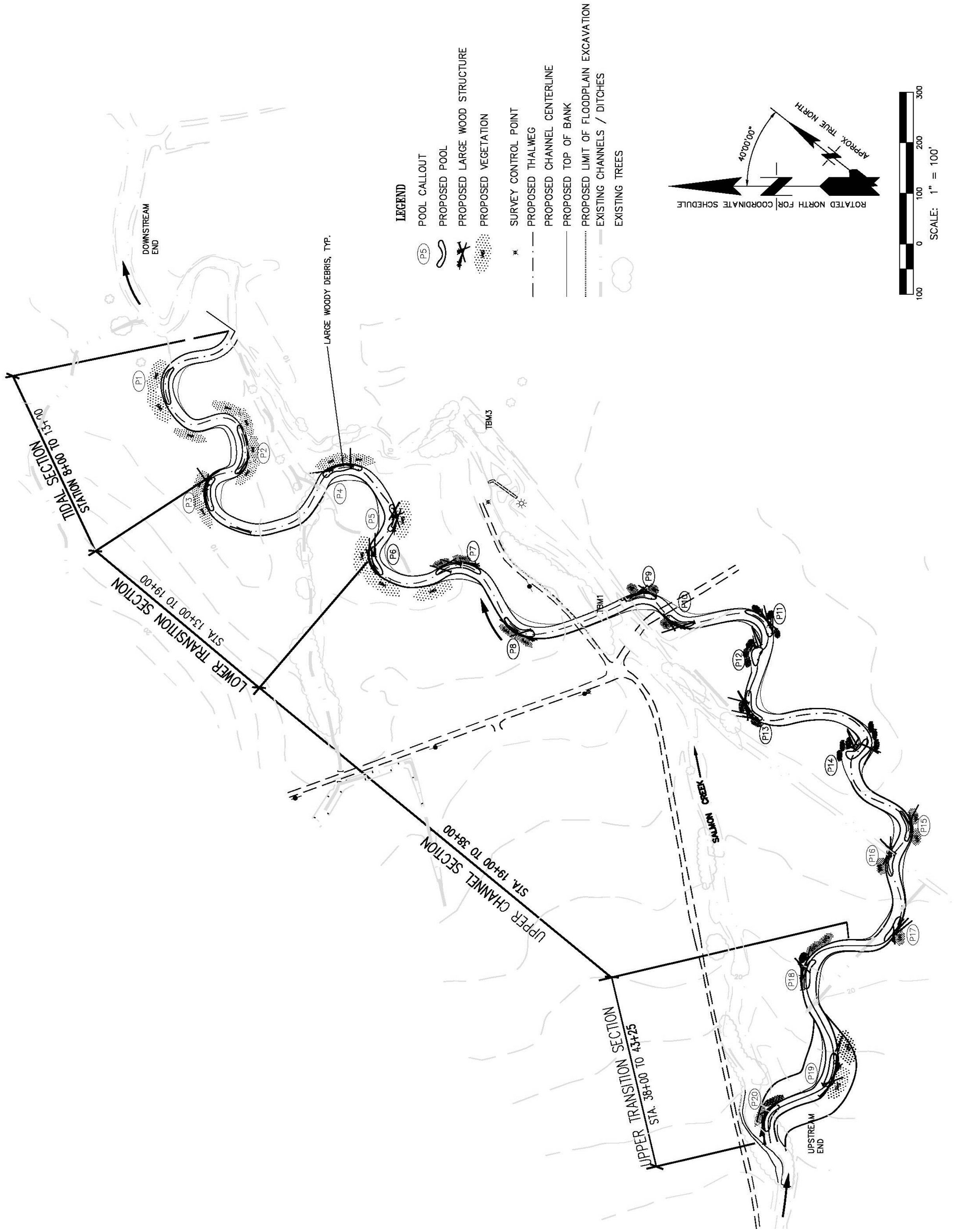
The objectives of the project were 1) to restore an approximately ½ mile reach of Salmon Creek (from river mile 0.25 to river mile 0.75) to a self-sustaining configuration to prevent the need for periodic dredging, and 2) to enhance fish habitat throughout the reach, with a particular focus on endangered summer chum salmon. Salmon Creek is located in Jefferson County and is a tributary of Discovery Bay. The lower reach of Salmon Creek was channelized for agriculture in the late 1880s/ early 1900s and the adjacent property was used as pasture for cattle. Stream habitat throughout the site was degraded. Levees isolated the stream from its floodplain. Riparian vegetation along the channel was sparse. In addition, the channelized reach was subject to aggradation, high water temperatures, lack of channel complexity and in-stream cover, and excessive levels of fines in the gravel.

Aggradation occurred as a result of several factors. The reach lies in the valley bottom; sediment transported from the hill slopes tends to deposit in the break in slope. Sediment supply upstream is elevated above historic levels as a result of extensive timber harvest as well as a pulse of sediment from a large landslide associated with an upstream tributary which was rerouted in the past and now falls over an approximately 25 foot high bluff. A third contributor to channel aggradation is that the stream was relocated such that portion of it are now perched above the surrounding ground. Relatively frequent high flow events jump the right bank levee and leave the channel. The competence of the remaining flow to carry sediment substantially decreases, and the sediment drops out. Lastly, a fish weir is located at approximately river mile 0.3. The fish weir severely constricts the channel and backwaters the upstream reach, encouraging upstream sediment deposition. The reach was maintained in its current configuration by levees and periodic dredging. The reach is an important spawning ground for endangered summer chum salmon. It also provides spawning and rearing habitat for non-listed runs of winter steelhead, coho salmon, sea-run and resident cutthroat trout, sculpin, lamprey, and other fish species.

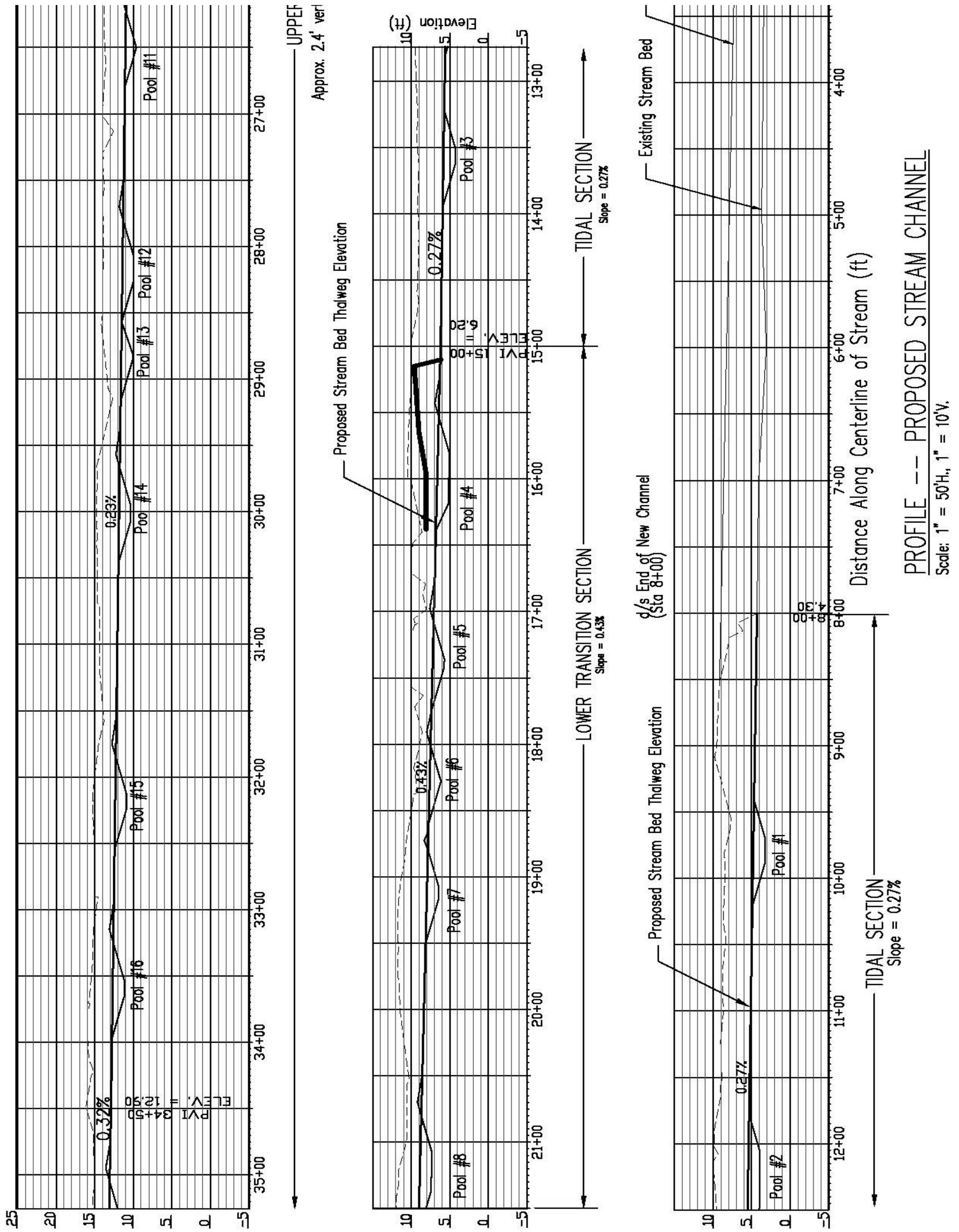
The project entailed constructing an approximately 3,500 foot long new channel with a more natural configuration. **Channel Modification Figures 3 and 4** show the existing channel and the channel modification design in plan view. The designed channel lies closer to the topographic low point in the valley, and achieves better connection with its floodplain. The new channel crosses the old channel once. A floodplain had to be excavated along the upper 300 feet of new channel where it transitions into the existing channel to avoid creating incised conditions. Only the main channel was excavated in the rest of the project site. These features are evident in the longitudinal profile (**Channel Modification Figure 5**). Riffles were constructed with imported bed material wherever gravel was not found during construction, as shown in more detail in **Channel Modification Figure 6**. **Channel Modification Figure 7** is a detailed plan and profile view of a typical mid-reach segment, including cross-section designs and large wood structures. **Channel Modification Figure 8** shows one of these structures under construction. Finally, **Channel Modification Figure 9** is an aerial view of the project under construction. The new channel was excavated and wood and streambed materials were added in the summer of 2003. The project then sat for a year to allow bank and riparian vegetation to somewhat establish and stabilize the soil. Water was diverted into the new channel in June 2004.



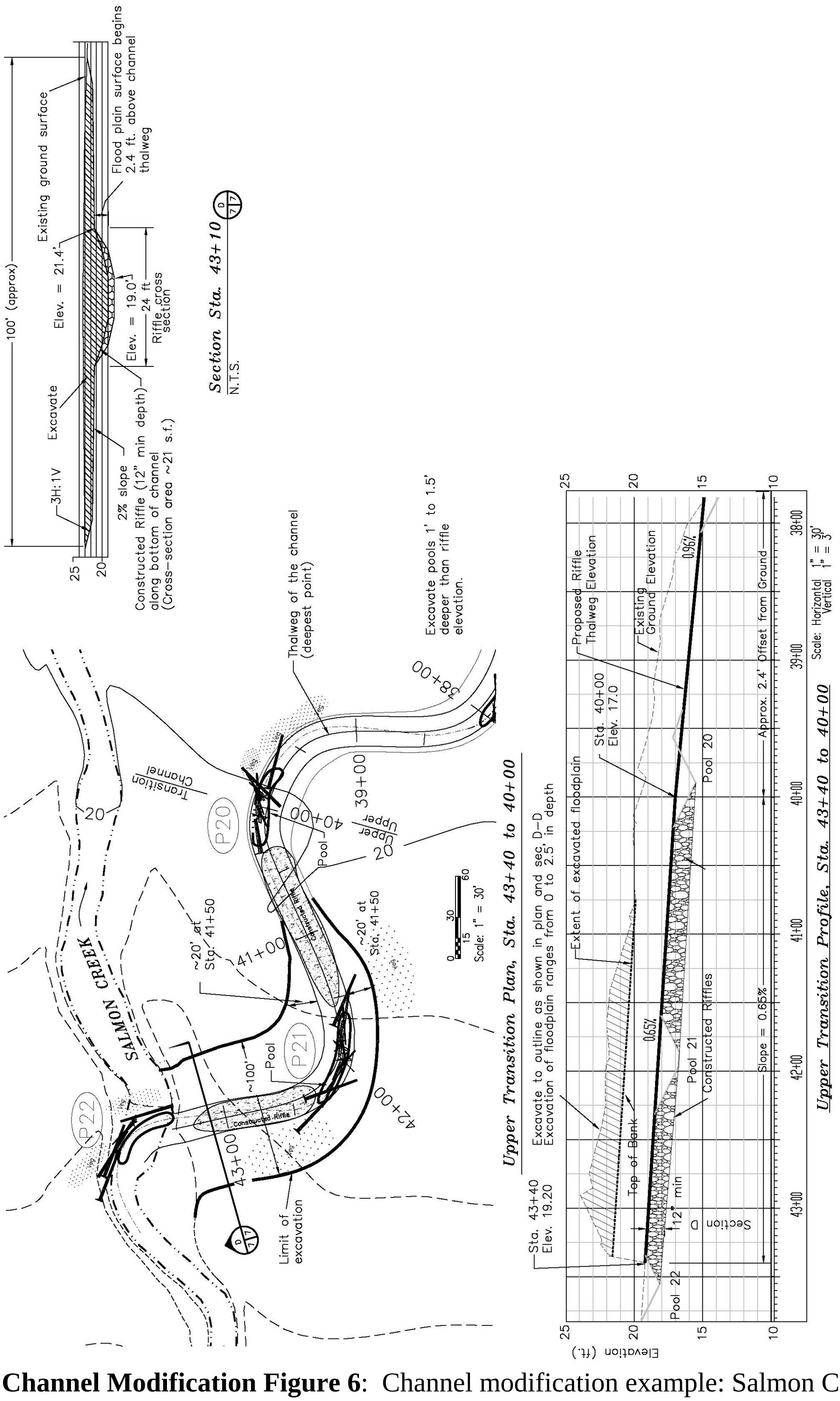
Channel Modification Figure 3: Channel modification example: Salmon Creek, Jefferson County, Washington. Plan view, showing existing channel and new channel design.



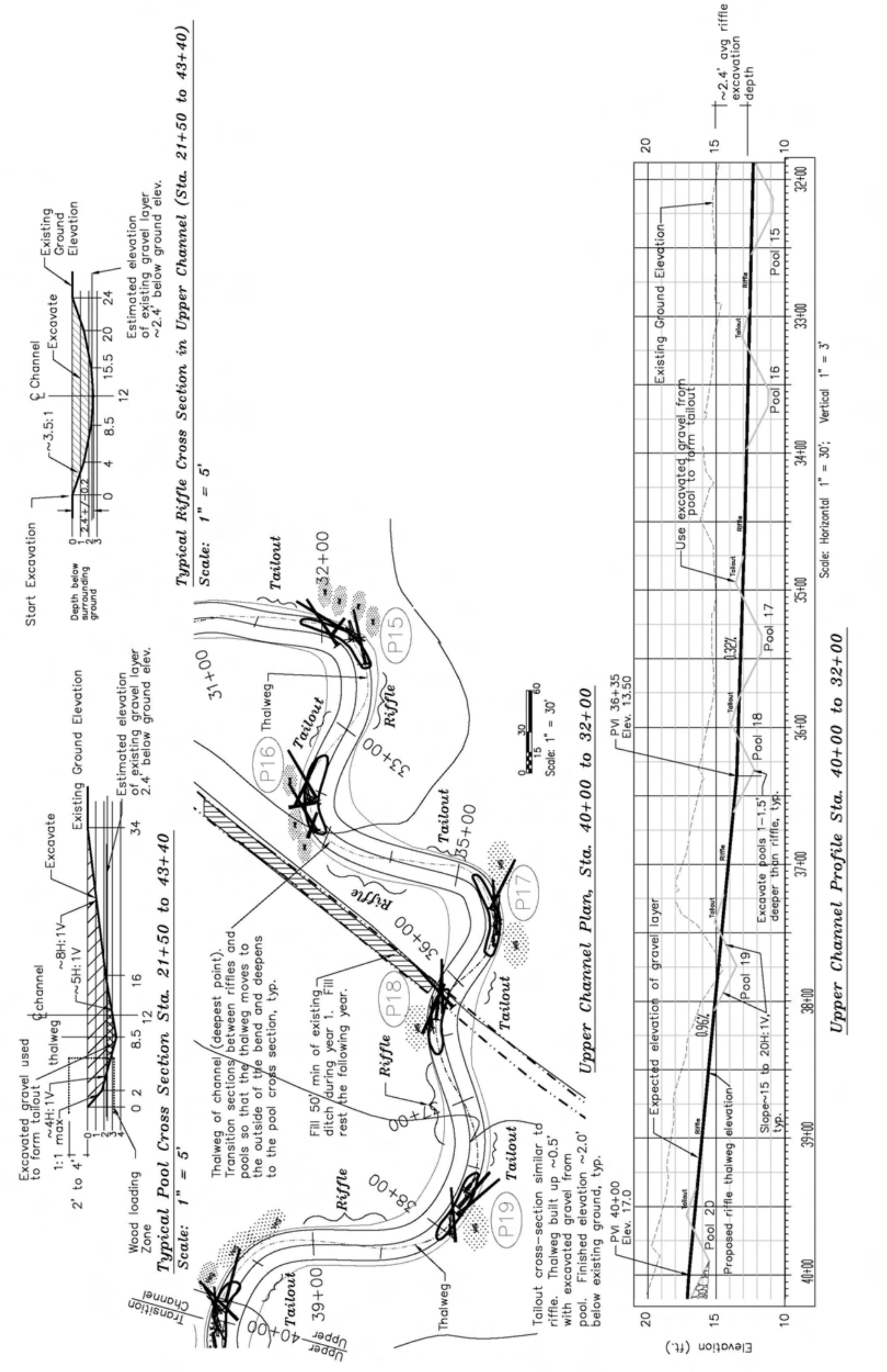
Channel Modification Figure 4: Channel modification example: Salmon Creek, Jefferson County, Washington. Plan view, showing reach delineation, locations of pools and large wood complexes.



Channel Modification Figure 5: Channel modification example: Salmon Creek, Jefferson County, Washington. Longitudinal profile.



Channel Modification Figure 6: Channel modification example: Salmon Creek, Jefferson County, Washington. Plan view and longitudinal profile of transition section at upstream end of project. Connection with existing channel required a short section of constructed floodplain.



Channel Modification Figure 7: Channel modification example: Salmon Creek, Jefferson County, Washington. Close-up details of profile, cross-sections, and large wood complexes.

Channel Modification Figure 8: Construction of a large wood complex.

Channel Modification Figure 9: Aerial view of Salmon Creek project under construction. Photo provided courtesy of the Jefferson County Conservation District.

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