17. Integrating Engineered Log Jam Technology into River Rehabilitation

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Abstract

Reach-scale river rehabilitation projects using Engineered Log Jams (ELJs) were implemented successfully in four demonstration projects in western Washington from 1995 through 1999. ELJ technology is founded on the premise that river management can be improved by understanding, emulating, and accommodating natural processes using sound science and engineering practices. The ELJ demonstration projects were developed as part of river rehabilitation efforts in which reach analyses were crucial for providing information about historical channel dynamics and revealing opportunities and constraints that helped refine project objectives and improve designs. Each ELJ demonstration project constructed to date improved salmonid habitat and addressed traditional problems constraining habitat rehabilitation, such as bank and bridge protection. The projects described here offer examples of instream structures compatible with rehabilitating and maintaining aquatic and riparian habitat in fluvial corridors throughout the Puget Sound.

RESTORATION OF FOREST RIVERS

Rivers of the Puget Sound region, as elsewhere across North America, have been severely impacted by land development. In particular, the role of large woody debris as a principal structural component of forest streams has been almost eliminated during the last century throughout the Pacific Northwest (Chapter 4). In the Puget Sound, as in many other regions, the removal of woody debris has reduced the physical and ecological complexity of streams and rivers (e.g., Marzolf 1978; Shields and Nunnally 1984; Harvey and Biedenharn 1988; Smith and Shields 1990; Hartopo 1991; Maser and Sedell 1994). This is of particular concern today as the physical habitat created by woody debris provides important habitat for salmon and other aquatic species (e.g., Tschaplinski and Hartman 1983; Swales 1988; Pearsons et al. 1992; Lonzarich and Quinn 1995).

Despite the widespread recognition of woody debris as a principal physical and biological component of forest streams, and despite extensive wood reintroduction programs aimed at channel restoration, little has been done to develop engineering guidelines for wood placement. Guidelines that have been developed assume that wood must be artificially anchored to remain stable (D'Aoust and Millar 1999). The engineering analysis of such studies is sound, but the underlying assumptions ignore the mechanics that underpins the stability of natural snags, which, of course, do not benefit from artificial anchoring (e.g., Abbe et al. 1997; Brauderick and Grant 2000). Random placement of woody debris without an understanding of the geomorphology (e.g., mechanics of wood stability, hydraulic conditions, sediment transport, natural woody debris supply, channel dynamics) and social context (e.g., local land use, infrastructure, recreational activity in rivers) can significantly increase the potential for unanticipated consequences, including habitat degradation, property loss, and injury.

Initially, stream channels were cleared of stable wood to improve navigation and later because it was assumed that instream woody debris reduced flow conveyance and increased flood risks. Recent studies, however, have shown that instream woody debris can block up to 10% of a channel's cross-sectional area without significantly reducing conveyance (Gippel 1995; Shields and Gippel 1995). Channel clearing was not the only practice in traditional river engineering that degraded fluvial environments. Traditional river engineering focuses on straightening, impounding, and generally simplifying channel conditions. Common bank protection measures do not emulate natural conditions and processes and dramatically reduce the habitat and hydraulic complexity found in natural forest rivers. Traditional measures such as rock revetments provide little beneficial habitat for most salmonids when compared to unprotected banks with vegetation or woody debris. Incorporation of vegetation into bank protection measures, such as bioengineering, has been widely used to reduce environmental impacts, but many of these measures amount to cosmetic treatments on traditional structures (e.g., Thorne 1990; Shields et al. 1995). Restoration efforts have long attempted to create “natural” structures in streams for habitat and to stabilize channels (Tarzwell 1934) but have not been based on accommodating processes and conditions typical of forested systems, and the resulting structures bear little, if any, resemblance to natural structures that accomplish the same effect.

Forested alluvial river valleys undisturbed by humans have high levels of morphological and biological complexity (e.g., Hawk and Zobel 1974; Sedell and Frogatt 1984). The upper Sauk River north of Darrington, Washington, offers an example of a relatively intact channel migration zone of a large forested alluvial river and exhibits a complex anastomosing channel with numerous log jams (Figure 1A). The White River southeast of Auburn, Washington, and east of Lake Tapps has a significantly simpler channel form with fewer secondary channels and lower sinuosity (Figure 1B). Both the Sauk and White Rivers are low-gradient (<0.01) unconfined gravel bedded rivers. Industrial forestry within the depicted portion of the White River valley has reduced the quantity of functional woody debris (i.e., large trees) capable of forming log jams vital to maintaining an anastomosing system and a complex forest structure. Agricultural development has had even greater impacts, as illustrated by the channelization of the Snoqualmie River north of Duvall, Washington (Figure 1C). This portion of the Snoqualmie is a very low gradient river that once had secondary channels, extensive wetlands, and a diverse riparian forest. All of these have been lost as the river has been channelized into a fraction of its original corridor. Ultimately human development can transform a river valley from a dynamic complex mosaic of forest, wetlands, and channels into a static channel with an impermeable floodplain, such as found in urban areas along the Green River in south Tukwila, Washington (Figure 1D). Here, cultural constraints leave little opportunity for restoration other than improving channel-boundary complexity to improve aquatic refugia for migrating fish.

Current river management often precludes a reach-based, scientific approach because much of the funding to maintain infrastructure along rivers comes from state and federal emergency response programs that require rapid response and often involve replacement of the original structure. Such emergency response actions almost always fail to incorporate environmentally sustainable solutions. The cumulative effect of river management actions arising from emergency response can significantly impact aquatic ecosystems through progressive confinement of a channel by successive rock revetments. Throughout much of the Puget Sound, human activity has transformed complex anas-

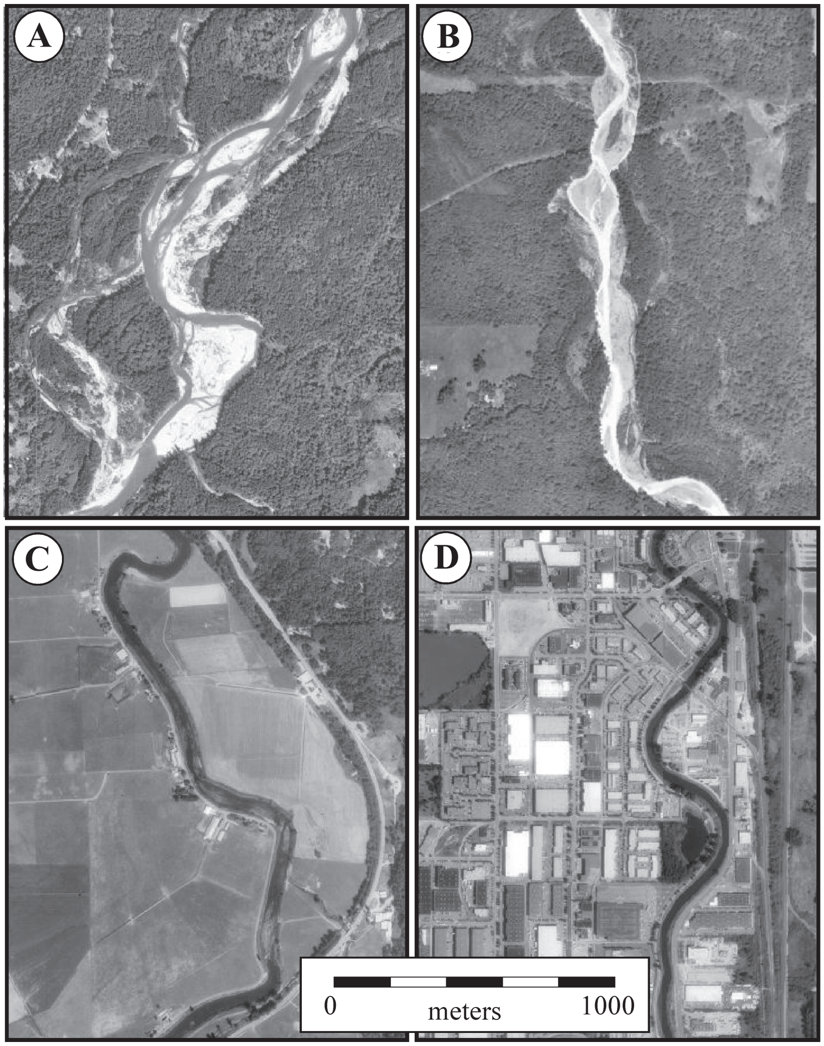


Figure 1. Four Puget Sound river corridors that illustrate reduction of geomorphic complexity and salmonid habitat with loss of woody debris and progressive encroachment on the fluvial corridor. All photos are from the U.S. Geological Survey and are identical in scale. (A) The upper Sauk River north of Darrington (09-07-89). (B) The White River southeast of Auburn and east of Lake Tapps (07-20-98). (C) The Snoqualmie River north of Duvall (08-04-90). (D) The Green River in south Tukwila (07-10-90).

tomosing forest channel systems with abundant woody debris and diverse habitat into simple single-thread channels with little complexity and cover (Figure 2).

Engineered Log Jam (ELJ) Technology

ELJ technology is based on the premise that the manipulation of fluvial environments, whether for traditional problems in river engineering (e.g., flood control, bank protection) or for habitat restoration, is more likely to be sustainable if it is done in a way that emulates natural landscape processes. The concept of ELJs began with the observation that natural log jams can form "hard points" that provide long-term forest refugia (Abbe and Montgomery 1996). Such natural hard points create stable foundations for forest growth within a dynamic alluvial environment subject to frequent disturbance. Log

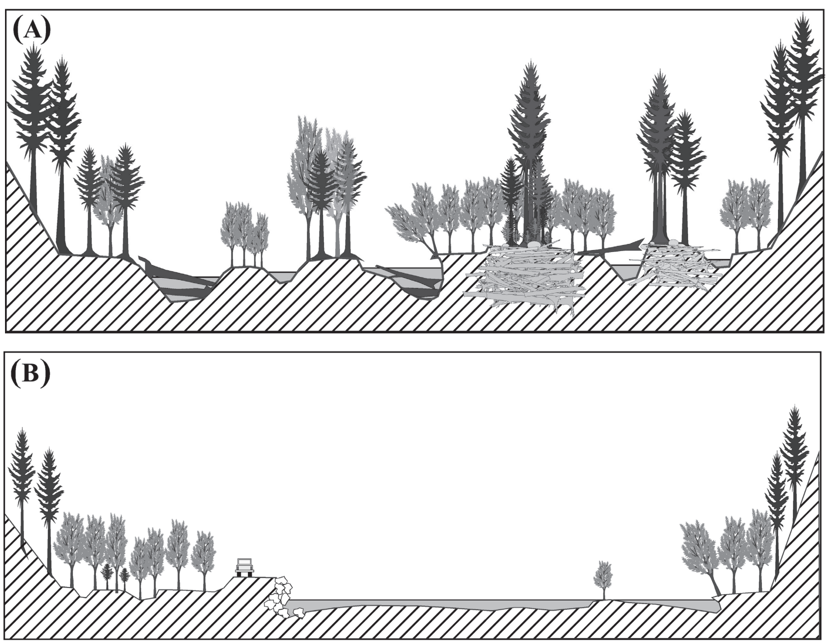


Figure 2. (A) Natural anastomosing forest river valley with abundant instream woody debris, complex mosaic of channels, and forest structure associated with regions such as found in the upper Sauk River (Figure 1A). (B) Degradation of forest rivers due to direct (e.g., channel clearing and confinement) and indirect (e.g., removal of riparian trees, increase in sediment supply or discharge associated with upland disturbance) human disturbance, such as the White River (Figure 1B).

jams thereby enable the development of trees large enough to continue forming stable log jams. Scientific and engineering studies of both woody debris and other types of flow obstructions contributed to the development of ELJ technology, such as the effect of boundary roughness on flow conditions, channel migration, and bed surface grain size (e.g., Raudkivi 1990; Pitlick 1992; Buffington and Montgomery 1999a), the effect of bluff body obstructions on flow deflection and scour (e.g., Garde et al. 1961; Raudkivi and Ettema 1977; Miller et al. 1984; Hoffmans and Verheji 1997), the impacts of debris accumulation at bridge piers (e.g., Melville and Sutherland 1988; Melville and Dongol 1992; Richardson and Lagasse 1999), and the hydraulic and geomorphic effects of natural snags (e.g., Shields and Gippel 1995; Abbe and Montgomery 1996; Gippel et al. 1996; Wallerstein et al. 1997).

Distinct types of log jams, or instream woody debris accumulations, are found in different parts of a channel network (Abbe et al. 1993; Wallerstein et al. 1997). Using observations from the Queets River basin on the Olympic Peninsula in Washington, distinct types of log jams have been classified based on the presence or absence of key members, source and recruitment mechanism of the key members, jam architecture (i.e., log arrangement), a jam's geomorphic effects, and patterns of vegetation on or adjacent to the jam (Abbe et al. 1993). Six jam types (Figure 3) provide naturally occurring templates for ELJs intended for grade control and flow manipulation (Figures 4-9). Jam types primarily applicable to grade control include log steps and valley jams; those types more applicable to flow manipulation include flow deflection, bankfull bench, bar apex, and meander jams.

Channel planform and flow obstructions can result in significant changes in water surface topography, locally raising water elevations enough to inundate secondary channels and portions of the floodplain during flows that otherwise would not engage the floodplain (Miller 1995). ELJs can create the same effect as they obstruct flow and control channel planform, thus serving as one of the principal mechanisms of connecting secondary channels and wetlands within floodplains to the mainstem channel.

The design process recommended for ELJs (Figure 10) begins with analysis of the watershed context within which the project is set, then follows with reach analysis and assessment. If opportunities are identified for potential ELJ applications, then appropriate types of natural log jams are selected based on the project objectives and constraints. After the general reach-scale strategy and ELJ layout are refined, individual structures are designed and specifications for logs and jams are prepared. Finally, the structures are constructed and evaluated over time.

Logs used to construct individual ELJs fall into three basic structural categories. *Key members* are individual logs with rootwads, which are unlikely to

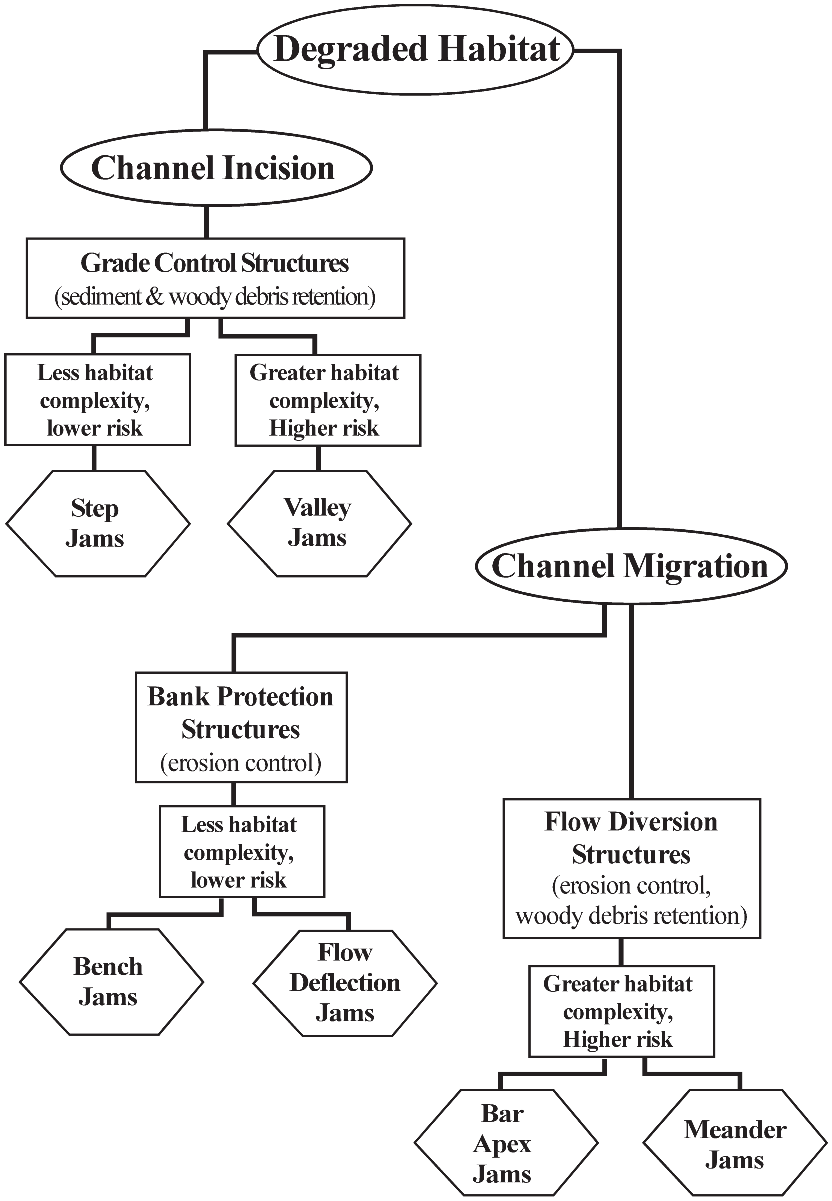


Figure 3. Classification of engineered log jam structures appropriate for treating different problems associated with habitat degradation. Two basic categories of habitat degradation involve vertical (incision) and lateral (migration) changes in channel position.

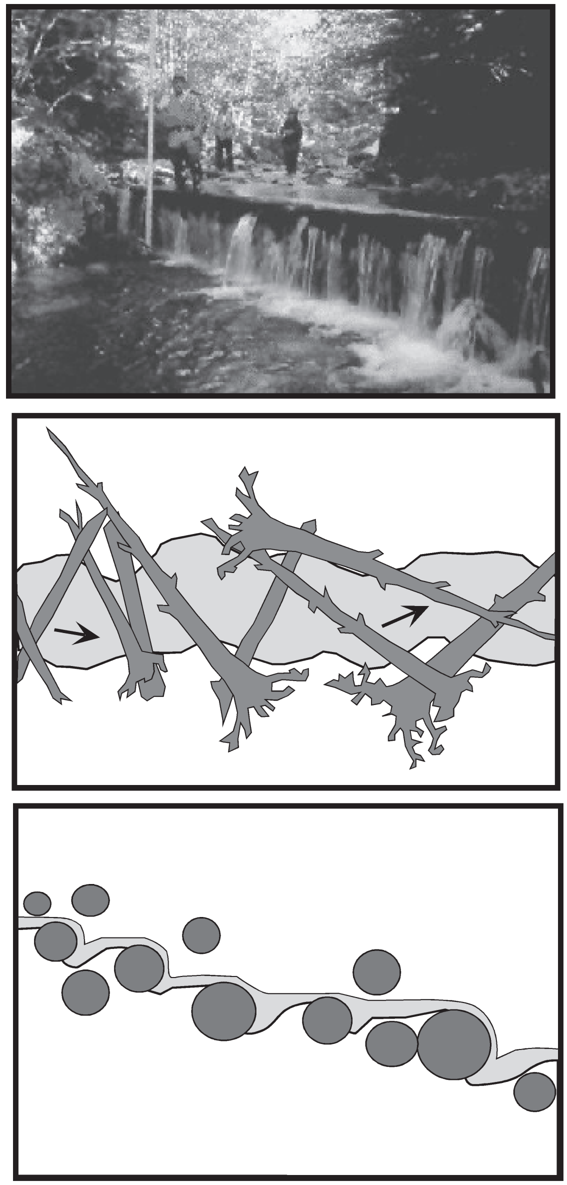


Figure 4. Step jams or multi-log log weirs are found in relatively small channels with a wide range of gradients. These structures can account for more than 80% of the head loss in a channel (Abbe 2000) and almost all of the hydraulic and habitat diversity within the channels where they occur.

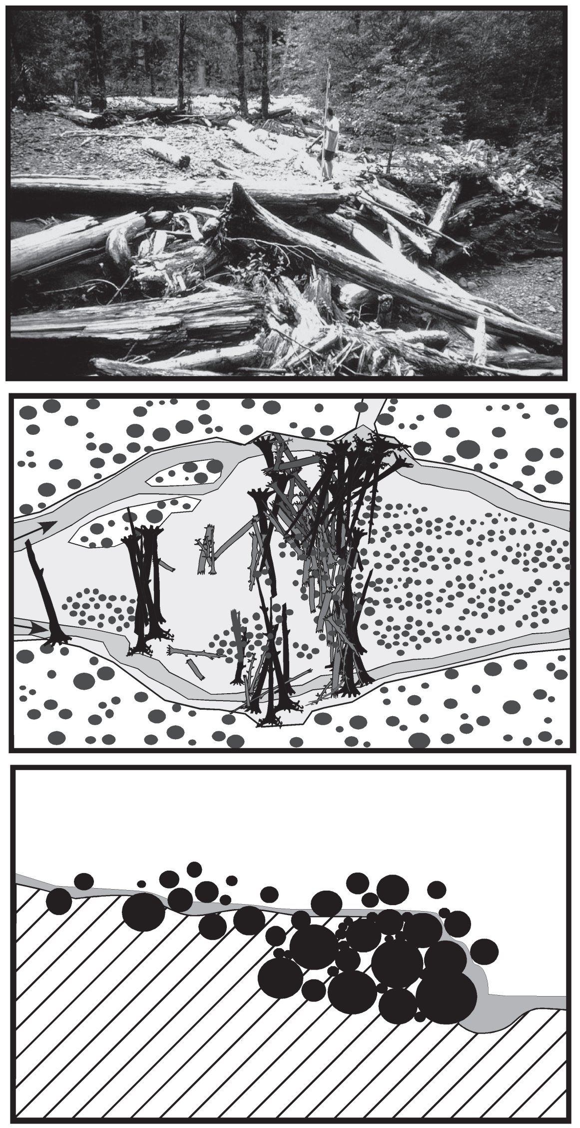


Figure 5. Valley jams are large, complex grade control structures found in channels with gradients ranging from 2 to over 20%. These structures are typically composed of tens or hundreds of trees, can raise the channel bed over 5 m, and transform plane-bed and step-pool channels into pool-riffle channels (Abbe 2000). These structures are also responsible for creating a complex channel network across the valley bottoms in which they occur.

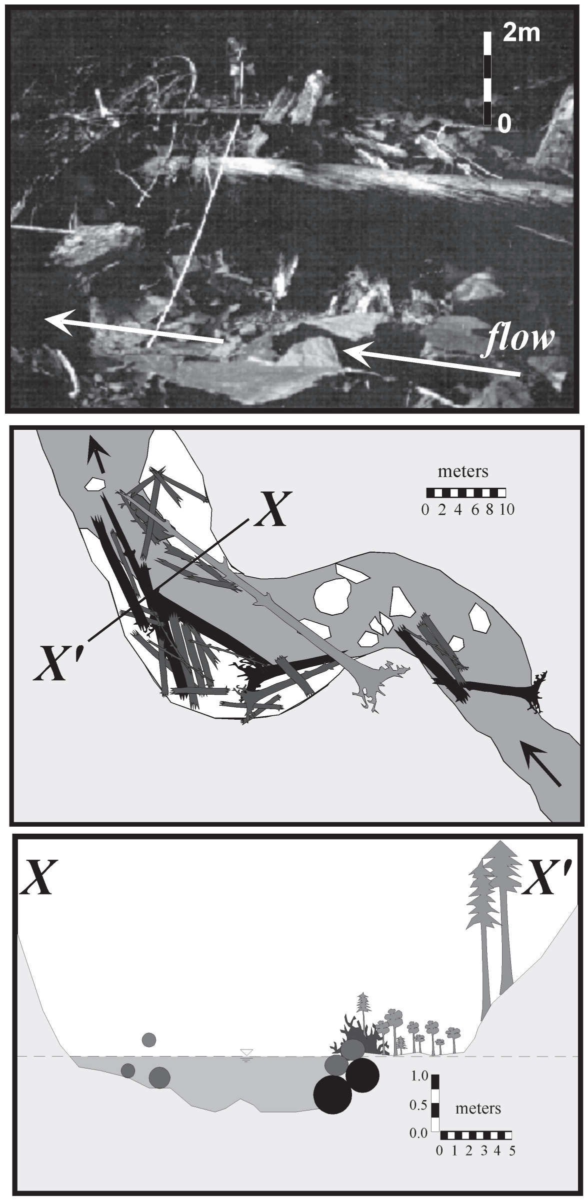


Figure 6. Bench jams are typically found in relatively small, steep channels (slopes >2%) where large logs become wedged into the margins of a channel and create local revetments protecting floodplain deposits and vegetation. Where these structures occur, wood forms the stream bank and prevents erosion of alluvium stored behind them.

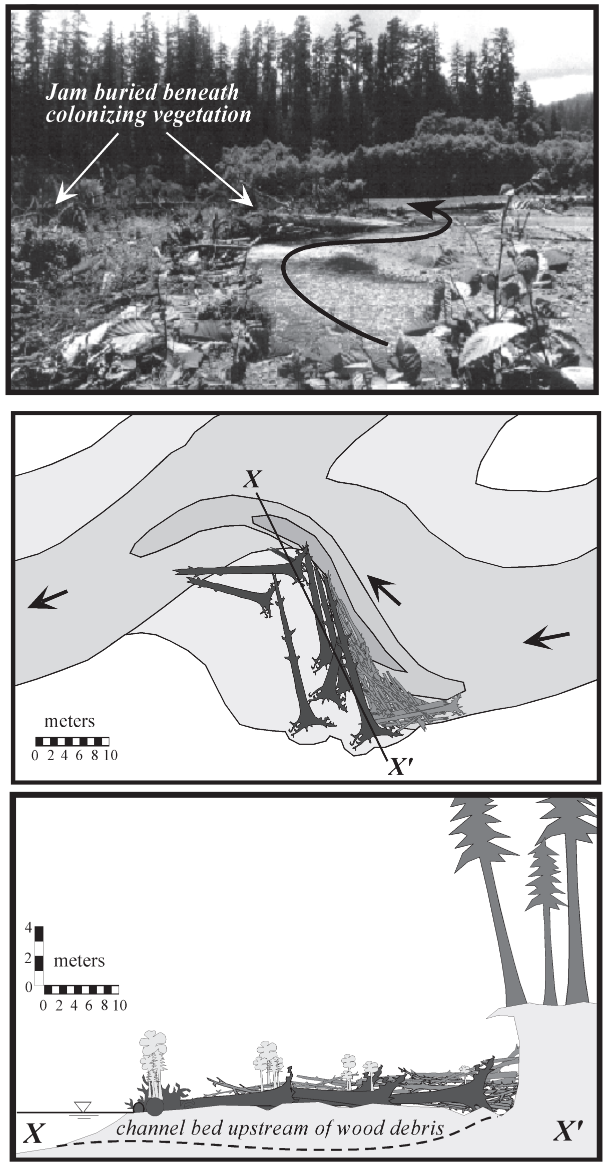


Figure 7. Flow deflection jams are found in relatively large channels with moderate gradients. These structures form initially when large trees (key members) fall into the river and deflect flow. But with time these structures become integrated into a new river bank and are thus classified as bank protection or revetment type structures as opposed to flow diversion structures.

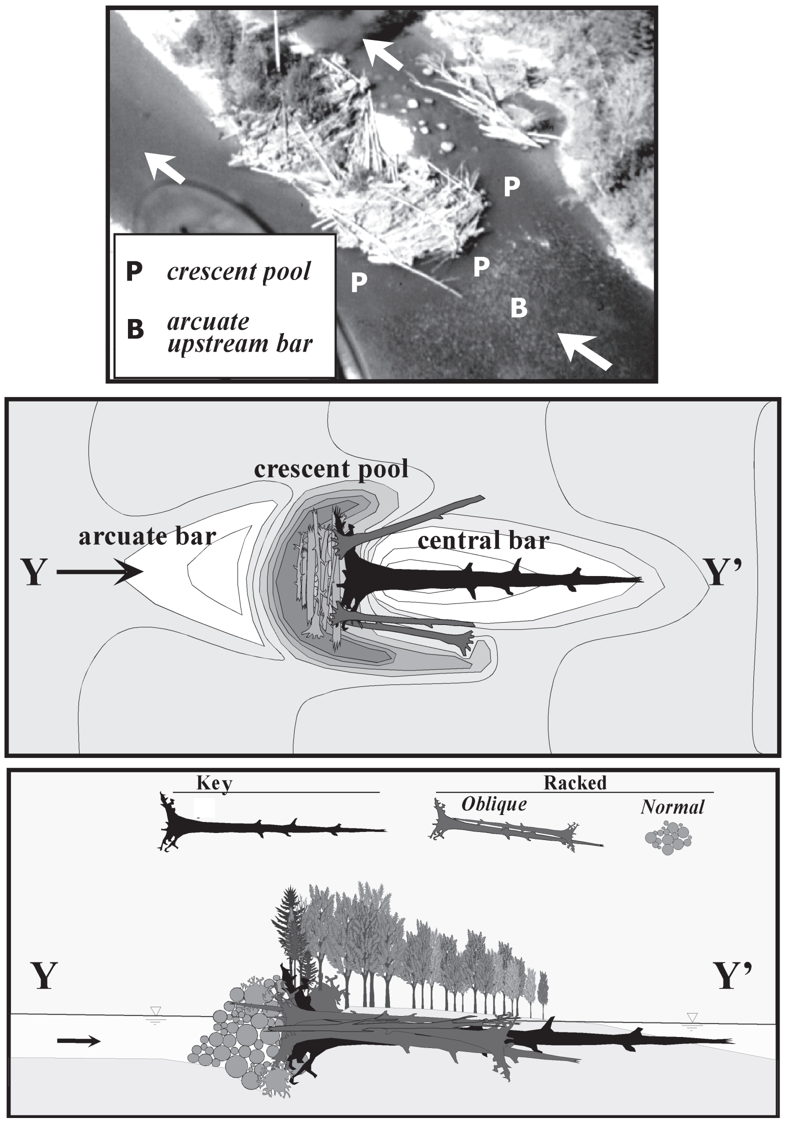


Figure 8. Bar apex jams are bi-directional flow diversion structures found in large channels with low to moderate gradients. These structures create forest refugia in dynamic channel migration zones and are responsible for much of the channel complexity and pool formation in these systems. Bar apex jams are a principal mechanism contributing to the formation of anastomosing channel systems in the Pacific Northwest.

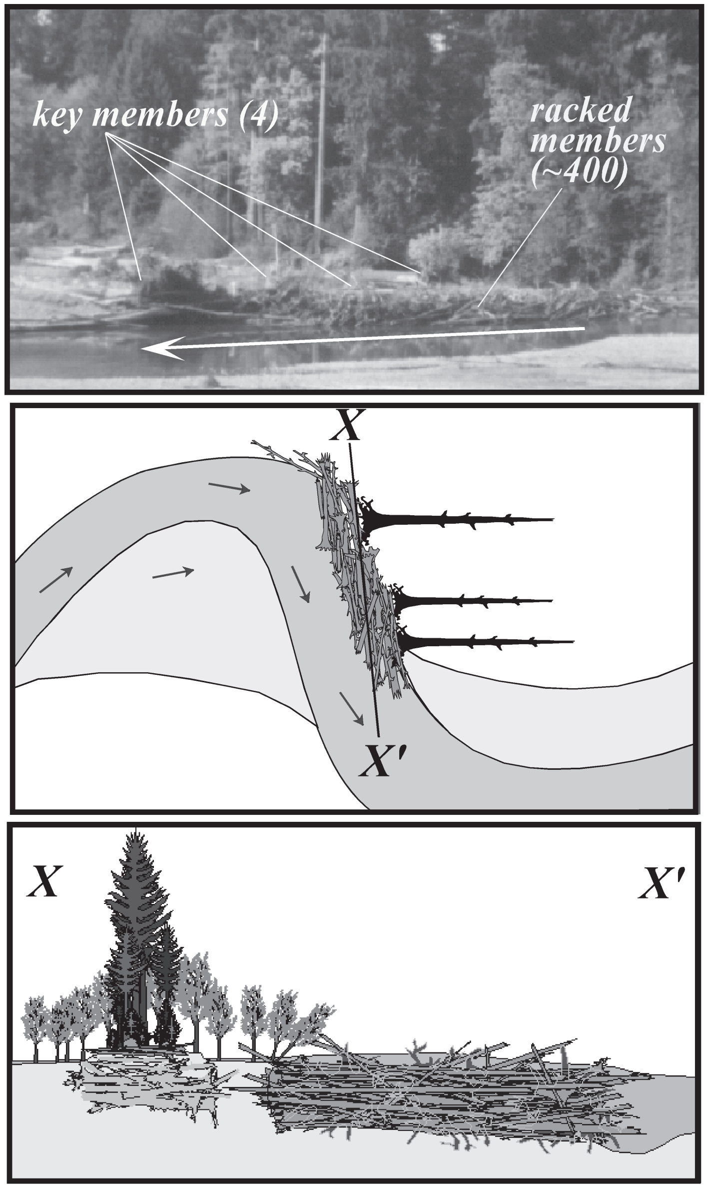


Figure 9. Meander jams are large flow diversion channels found in large alluvial rivers. These structures offer a model that has been successfully emulated to limit channel migration, protect banks, and restore aquatic habitat and riparian forests. Natural meander jams are a principal cause of channel avulsions in Pacific Northwest rivers.

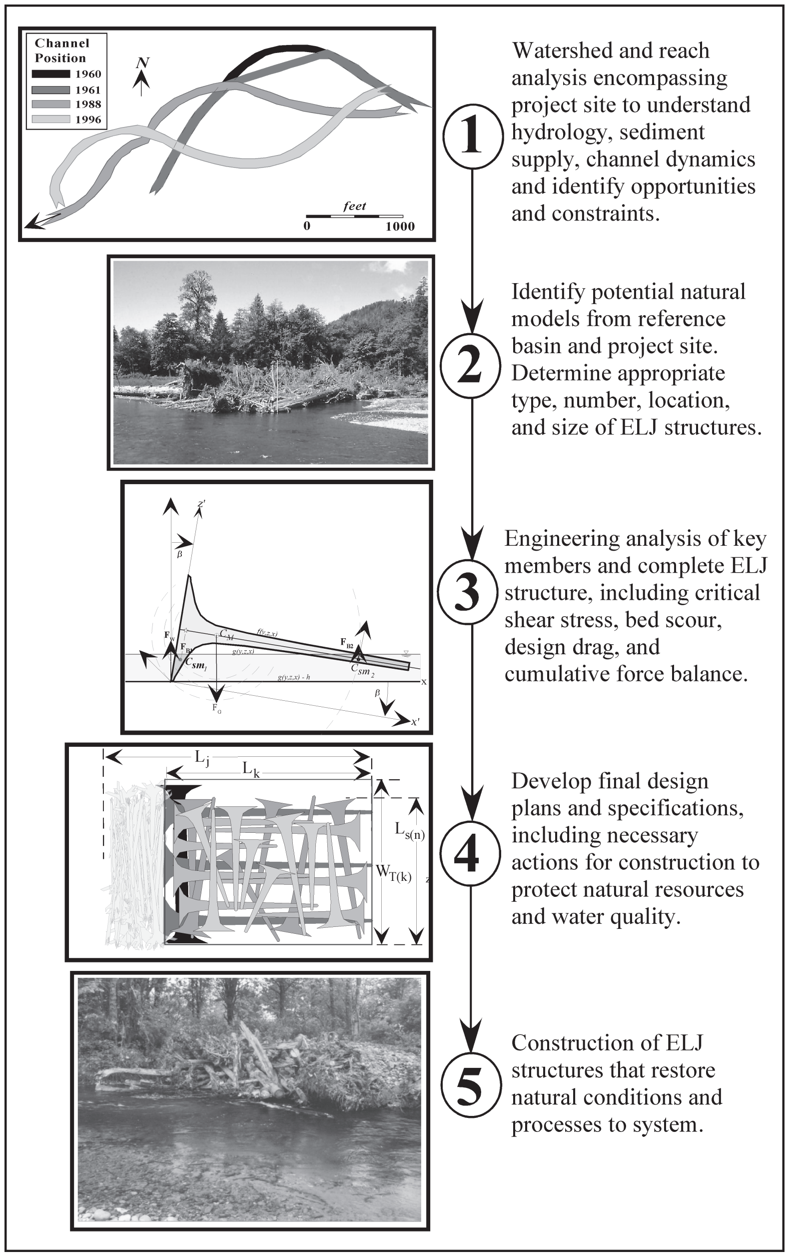


Figure 10. Five basic steps recommended for designing and implementing an ELJ project.

move during a bankfull flow, and are used as the foundation of all ELJs. In alluvial channels, key members are usually set deep into the channel substrate. In bedrock channels, key members are situated on the channel bed between pre-existing roughness elements or opposing banks. Properly situated, key members can transform a bedrock channel into an alluvial channel (Montgomery et al. 1996). *Stacked members* are slightly smaller than key members and are used in some ELJs to supplement key members. Stacked members are laid down in two or more layers that link individual members together and increase the integrity of the structure. Most stacked member logs should retain a substantial rootwad. *Racked members* include the smallest logs, with the largest range in sizes, and are often the only logs visible after construction is completed, depending on the type of ELJ. Racked members form a dense, chaotic pile of debris extending from well below the channel thalweg to above the bankfull elevation. Racked members act to decrease the permeability of and deflect flow around the structure.

No artificial materials are necessary to construct an ELJ. Native trees and alluvium at the site are all that is needed if the trees meet the design specifications for size and shape. Most projects will import trees to the site because it is usually preferable to preserve existing riparian trees, and an adequate local supply of large trees is rare. Trees large enough to act as key members may need to be cut for transport and then glued and bolted together at the site before placement. The stability of ELJs is founded on how snags interact with alluvium and instream flows. The shape and size of individual logs is critical, as are the architecture of the ELJ and its size and position within the river system. Long-term contributions to stability come from trees growing on top of ELJs, due to both root cohesion in alluvium under which the structure is buried and from the weight of the trees themselves.

Most ELJ projects involve a series or array of structures within the channel or extending across the channel migration zone (CMZ). The appropriate type, size, and position of ELJs will depend on a thorough geomorphic, hydrologic, and hydraulic analysis of the project site sufficient to characterize the river's dynamics and predict the likely range of future conditions. Such studies should include historical analysis of the changes the river has undergone and, if possible, what conditions were like prior to human development. These site assessments are referred to as reach studies and are recommended for any project that will manipulate the boundary conditions in and along a river.

Between 1995 and 1999, thirty ELJ structures were constructed in four demonstration projects in western Washington (Figure 11). The objectives of these projects ranged from bank protection to habitat restoration and illustrate a wide range of applications for this technology in Puget Sound rivers and streams.

Reach-Based Design

Before attempting to design ELJs, it is important to understand a river's physical boundary conditions and the relationship of those boundary conditions to fluvial processes and habitat. A reach analysis must be done at spatial and temporal scales adequate for describing these relation ships. With this understanding, ELJs can be designed and placed to achieve the desired goals, accommodate natural processes, and in some cases even diminish risks associated with human infrastructure and property. In a reach analysis, physical and human constraints are identified and demarcated. These areas are then incorporated into design alternatives; for example, differentiating areas within the channel migration zone (CMZ) where the mainstem channel can freely move, areas in the CMZ where only secondary channels are acceptable, areas which can tolerate inundation but no channels, and those areas where no inundation is acceptable.

A reach analysis is linked to changing conditions and disturbance patterns in the watershed. For example, industrial forestry can significantly increase

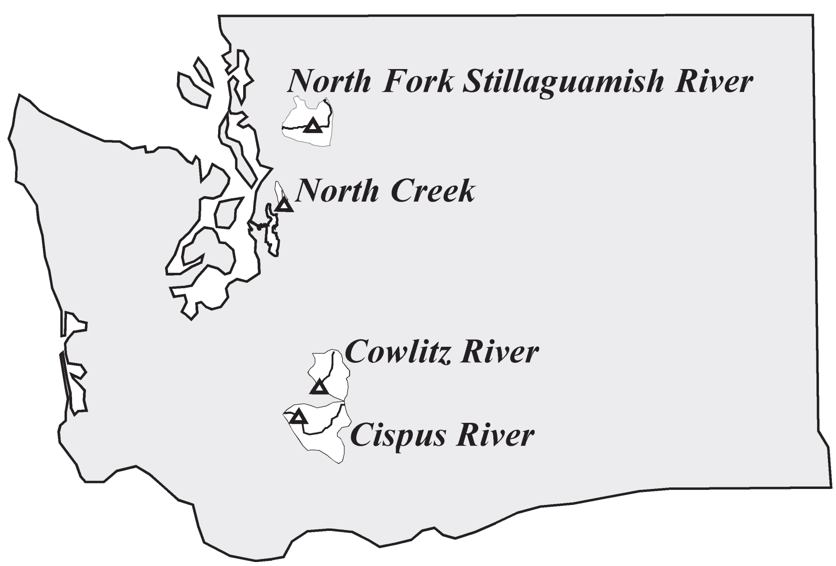


Figure 11. Locations of ELJ demonstration projects constructed in western Washington between 1995 and 1999: North Fork Stillaguamish River (1998), North Creek (1998), Upper Cowlitz River (1995), and Cispus River (1999).

sediment delivery to the river system (e.g., Kelsey 1980), which in turn can result in channel aggradation (Stover and Montgomery 2001) and textural fining (Buffington and Montgomery 1999b). The removal of instream woody debris and riparian forest may also increase the frequency and magnitude of peak flows and lead to significant geomorphic changes such as channel incision (e.g., Brooks and Brierly 1997). The most dramatic increases in the frequency and magnitude of peak flows are associated with rapidly urbanizing watersheds (e.g., Hammer 1972; Graf 1975; Booth and Jackson 1997; Moscrip and Montgomery 1997). Because these types of watershed disturbances will ultimately influence fundamental conditions within a project reach, they should be accounted for in design strategies.

The nature of these reach analyses and subsequent designs are illustrated by four ELJ demonstration projects constructed from 1995 to 1999. The overall goal of each project was to help restore fluvial environments in the contexts of natural processes and existing human constraints. Goals specific to each project are discussed in detail in the following sections.

Case Studies

Upper Cowlitz River

Three unanchored ELJ structures emulating meander jams were installed in December 1995 to halt erosion and reduce property loss from channel migration along 430 m of privately owned land along the upper Cowlitz River, Washington. Cost was a substantial constraint to the landowner, who nonetheless expressed a clear desire to maintain or improve aquatic and riparian habitat. The unvegetated width of the channel at the site is 195 m; the average bank erosion rate from 1990 to 1995 was 15 m/yr. Erosion along the landowner's shoreline from 1992 through 1995 resulted in as much as 50 m of bank retreat and the loss of about one hectare of forest land. After bank erosion associated with a 12-year recurrence interval flow in November 1995, the landowners became concerned they would lose the entire riparian corridor and inquired about erosion control alternatives that could retain as much of the habitat and aesthetic qualities of the site as possible. The high cost of a rock revetment or rock barbs (groins), together with the desire to salvage woody debris along the channel, led the landowners to pursue the experimental use of ELJs.

The floodplain adjacent to the site consists of timberlands that have been selectively harvested since the 1930s. Present forest cover is dominated by a 50–80 year old mixed conifer and deciduous forest with basal stem diameters up to 2.2 m and averaging about 0.4 m. Bank erosion along the Upper Cowlitz is common, and several large, conventional bank revetment projects have been constructed (and reconstructed) since the 1960s. Analysis of historical aerial photographs revealed northward channel migration and progressive widening of the Cowlitz River since 1935.

The three ELJ's built along the Upper Cowlitz River (summer 1996) were based on bar apex and meander jams (Abbe and Montgomery 1996) common in large alluvial channels and naturally occurring in the Cowlitz River. Both jam types consist of large key member logs with rootwads facing upstream and boles aligned with bankfull flow. Bar apex jams are usually relatively narrow structures with 1 or 2 key members that direct flow to either side of the jam. Meander jams usually are considerably wider with 3 to 6 key members, and they are situated such that they force a change in channel direction.

Five weeks after construction, the project experienced a 20-year recurrence interval flow of approximately 850 m^3/s (Abbe et al. 1997). Each ELJ remained intact and transformed an eroding shoreline into a local depositional environment. In addition, approximately 93 tons of woody debris that was in transport during the flood was trapped by the ELJs, which helped to increase the stability of the ELJs and alleviate downstream hazards. Enhancement of physical habitat included creation of deep pools at each ELJ. Because enough trees were found at the site (local landowner) and costs for design and permitting were extremely low, this project cost less than 1% of a traditional rock revetment project along an upstream meander. The cost of the ELJ project for a 430 m long reach was $10,000, or $23 per meter, whereas the cost of rip rap for a 683 m long project was $999,253, or $1464 per meter. This experimental project demonstrates that ELJs can meet local bank erosion control objectives while helping to rehabilitate riverine habitat in a large alluvial river.

Cispus River

In 1998-1999, the United States Forest Service (USFS) and Lower Columbia Fish Recovery Board (LCFRB) collaborated on an ELJ project on two side channels in the Cispus River near Randle, Washington. The project objectives were: (1) to protect a USFS road damaged in 1996, and (2) to create habitat complexity for adult and juvenile anadromous fish in a morphologically simplified stretch of the river. The Cispus River, a tributary to the Cowlitz River, had the potential to support salmonids after a program was begun in 1993 to reintroduce three species of anadromous fish to the upper Cowlitz River Basin and evaluate and improve habitats where possible.

Two sets of ELJ structures (revetments) were constructed along the Cispus River in 1999. Four ELJs were constructed directly adjacent to Forest Road (FR) 23 at Cispus River Mile (RM) 20 (Site B) and another set of three ELJs was constructed upstream at RM 21 (Site C) (Figure 12). All the structures were part of a strategy to protect FR 23 (Figure 13), because the February 9, 1996 flood, reportedly a >100-year recurrence interval event (Brenda Smith, USFS, personal communication), destroyed several hundred feet of the road at Site B and threatened the road at Site C. Pre-existing rock revetments failed at both sites. An emergency rock revetment was constructed along Site B as part of replacing the road washout. Reach analysis commenced in the summer of 1996 and the seven ELJs were constructed in September 1999.

The goal to improve fish habitat focused primarily on the placement of woody debris structures and debris jams into two side channels. Plans for the upstream site (Site C) included the placement of three large structures. The downstream site (Site B) called for the placement of four debris jams (Figure 14). The goal was to place these structures in a manner to protect the road during periods of high runoff while providing habitats for both juvenile and adult anadromous fish. The intent was to provide holding pools for upstream migrating adults and rearing habitats for juveniles during higher flows. It was anticipated that high flows would deposit the scoured materials downstream of the structures, sorting out gravels that may be used for adult spawning. The sites were completed and monitoring began in the fall of 1999.

By the fall of 1999 and the spring of 2000, it was apparent that winter high flows had scoured the base of the structures at Site B but had little effect on Site C. Numerous adult coho salmon were observed holding in the pools at the

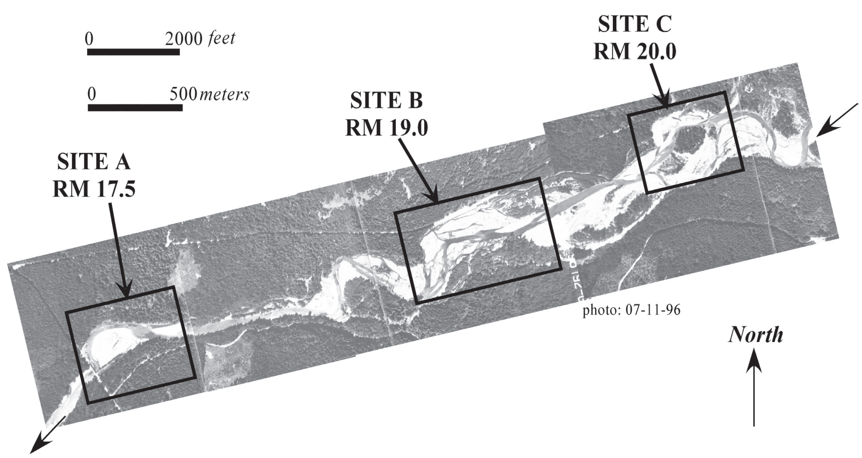


Figure 12. Cispus River sites A, B, and C. River flows from right to left. Forest Road 23 is on the north side of river.

Figure 13. Photographic illustration of the differences between traditional blanket rock revetment (left) and ELJ solution (right) to protecting Forest Road 23 along Cispus River at Site B. A series of 4 ELJs was constructed to protect the road, enhance aquatic habitat, and establish a riparian buffer between the road and river. Each of the structures is approximately 7 m in height with about 4 m exposed above the low water table.

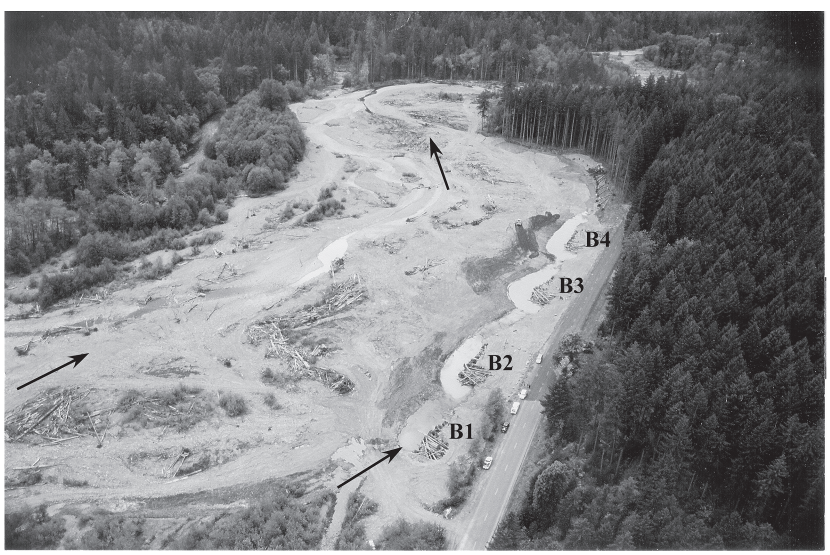


Figure 14. Oblique aerial photograph of the Cispus River ELJ project site B at River Mile 19. Arrows indicate flow direction and B1 through B4 indicate ELJ locations.

structures at both sites. Over 100 redds were counted in the reaches between the jams at Site B. Twelve redds were observed at Site C, but these were located above and below the construction site. One steelhead redd was observed at Site B in 2000. In the spring of 2001 (a period of lower than normal flows), only twelve redds were observed at Site B and none were observed at Site C.

Snorkeling surveys were performed in cooperation with Washington Department of Fish and Wildlife (WDFW) staff in July and August of 2000 to evaluate site utilization by juveniles. Observations indicate extensive use of the structures by young of the year coho. The scouring effects near the structures at Site B provided cover and depth for the juvenile fish. Juvenile coho use was limited in the reach between sites B and C because of local sediment deposition that reduced flow depth. At Site B, 92% of the young of the year coho observed were associated with the structures, and only 8% were found in the area above or below the structures at Site B. Many of the observed fish between the structures were juvenile steelhead. At Site C, 61% of juveniles were located in pools associated with the ELJs, even though these pools account for only a small percentage of the surface area of the stream. The cost of constructing Cispus sites B and C was approximately $300,000.

North Fork Stillaguamish River

The North Fork Stillaguamish River project site is about 8 km east of Oso, north of Washington State Highway 530 and upstream of the C-Post bridge (Figure 15). The project was first conceived in 1996 for enhancement of salmon habitat.

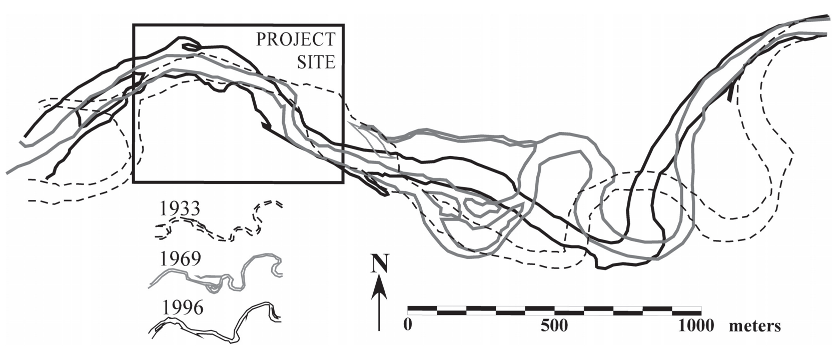


Figure 15. Selected historical planforms of North Fork Stillaguamish River ELJ Project Reach (River Miles 21-23): 1933, 1969, and 1996.

This goal was based on a comprehensive assessment of habitat conditions and historic change that identified a need to develop and maintain pool habitat as a key to recovery efforts for chinook salmon (*Oncorhynchus tshawytscha*) (Pess et al. 1998).

Chinook salmon are large-bodied fish that spend months in deep, cool pools during low flow prior to spawning. A key observation is that chinook spawning location strongly correlates to pool frequency and size; more than 80% of the chinook spawning nests (redds) surveyed in the North Fork Stillaguamish occurred within one channel width of a pool (Pess et al. 1998). Furthermore, twice as many redds were associated with pools formed by log jams versus pools with no wood, which also had three times as much instream cover (Pess et al. 1998). Historically, log jams were abundant and played a significant role in the morphology of the Stillaguamish River (Secretary of War 1931). The combination of these factors led to the proposal to construct engineered log jams in the North Fork Stillaguamish to create and enhance summer chinook holding pools.

The ELJ project reach has a drainage area of approximately 300 km^2 and is a low-gradient (<0.01) meandering gravel-bed channel that has repeatedly migrated across the floodplain during the past century (Figure 15). Natural log jams historically stabilized gravel bars in the North Fork Stillaguamish, allowing vegetation to take hold and create in-channel "islands" that resulted in an anastomosing channel network. Gravel bars and forest encompass most of the floodplain, but some homes and pastures are located along the lower portion of the surveyed reach. Estimates of the one- and five-year recurrence interval peak flows at the USGS gage at Arlington, Washington, are 258 cfs (7.3 cms) and 425 cfs (12 cms), respectively.

The upper North Fork Stillaguamish (above RM 15) has gone through large-scale channel changes over the last 70 years. A four- to five-fold increase in hillslope sediment input (primarily as landslides) between 1978 and 1983 from the upper portion of the North Fork Stillaguamish basin above RM 35 is likely to have contributed to an expansion of the unvegetated channel width and rapid changes in channel position. Many of the landslides were associated with logging and road-building in steep headwaters (Pess et al. 1998). A large increase in the sediment supply of a river can result in channel aggradation and extensive infilling and loss of pools (e.g., Kelsey 1980; Lisle 1995). Channel aggradation and widening, combined with the loss of pool-forming structures such as log jams, is thought to have reduced the quantity and quality of large pool habitat for adult and juvenile salmonids in the North Fork Stillaguamish. The lack of high quality pool habitat has altered migration and spawning timing for steelhead and possibly summer chinook (Curt Kraemer, WDFW, personal communication).

Project Objectives, Constraints, and Opportunities

The primary goal of the project was to increase quality and quantity of holding pool habitat for spawning summer chinook in the project reach. While evaluating the system, a number of additional objectives, constraints, and opportunities were also identified.

Objectives
- Maintain an active channel migration zone
- Increase the quality and diversity of aquatic and riparian habitat
- Increase linkages between channel system and riparian floodplain forest and wetlands by:
    - Maximizing the length of perennial channels
    - Maximizing linkages between channel system and floodplain

Constraints
- Accommodate existing infrastructure encroachment into channel migration zone
- Avoid increasing flood peak water elevations
- Protect property along southern margin of project reach
- Maintain or increase protection to downstream bridge by:
    - Minimizing woody debris accumulation at bridge
    - Minimizing threat of channel avulsion around bridge

Opportunities
- Introduce a multiple channel system for both perennial and ephemeral flow conditions
- Incorporate ELJ structures to:
    - Emulate instream structures representative of a low-gradient Puget Sound river
    - Limit channel migration at sensitive locations
    - Stabilize and help sustain secondary channel system
    - Increase physical and hydraulic complexity within the channel
- Increase bank protection in specific locations using an approach that emulates naturally occurring structures (e.g., log jams) and incorporates natural physical processes (e.g., channel migration, wood accumulation).

Implementation

In the summer of 1998, five ELJs were constructed upstream of the C-Post Bridge (Figure 16). Four of the ELJs were meander type jams designed to deflect flow on only one side. The remaining ELJ was a bar apex type designed to accommodate flow around either side. Each ELJ is completely inundated

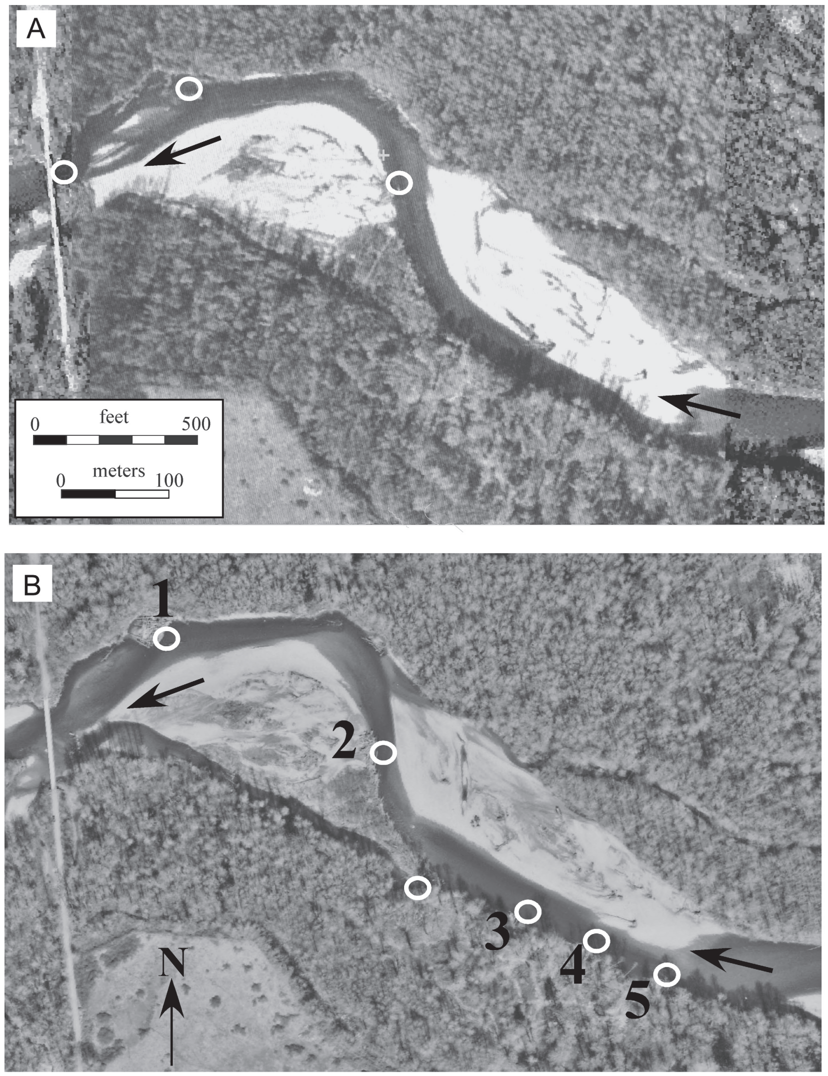


Figure 16. North Fork Stillaguamish River 1998 ELJ project site. March 1998 prior to construction (A) and two years after construction in March 2000 (B). Principal pool locations are noted by circles and ELJ location are numbered. Note the large increase in drift directly upstream of ELJ 2 between 1998 (A) and 2000 (B). ELJs 1, 3, 4, and 5 simulate “meander jams” and ELJ 2 simulates a “bar apex jam.”

during bankfull flow. The North Fork Stillaguamish ELJ project also included the acquisition of 29 hectares of conservation easement within the channel migration zone. This area is set aside to permit natural migration of the channel and migration induced by the installation of the ELJs. The project also included installation of arch culverts at side channels passing beneath the C-Post Bridge road. The total project cost was approximately $400,000.

In 1997 and 1998, we collected information on characteristics of wood naturally occurring within the project reach and of wood for ELJ construction. Post-construction wood surveys conducted in 1999 included a field reconnaissance of approximately 10 km of river downstream of the project site. Natural and imported logs were given identification tags and cataloged with data that included species, location, rootwad dimensions (minimum and maximum diameters), basal trunk diameter (equivalent to diameter at breast height), crown diameter, length, and physical condition (state of decay). Imported logs also included measurements of cut geometry when applicable. These data were used to measure the stability, movement, and recruitment of individual logs, structural integrity of the ELJs, and evaluate ELJ performance relative to the project design and objectives.

Results to Date

Between September 1999 and February 2000, at least fourteen flows equaling or exceeding bankfull stage occurred (Figure 17). All five ELJs remained in place. During the first high flows in November and December of 1998, ELJ 1 was damaged when one of the structure's seven key members was lost. Significant scour occurred beneath the outer upstream corner of the ELJ and undercut the key member in question. With nothing to support the saturated log from beneath, it sank, broke in half, and was carried 10.5 km downstream to where it was found in the summer of 1999. The loss of ELJ 1's outer key member was only confirmed when the structure was inspected from below, since there was almost no change in the structure visible from above (Figure 18). Even with the loss of a key member, ELJ 1 remained in place and continued to perform as predicted. Each of the five ELJs have formed and maintained scour pools ranging from 2–4 m in depth. Sand deposition has occurred downstream of all five ELJs. Designed as a series of flow deflectors, the three upstream ELJs (3, 4, and 5) have prevented further bank erosion along the south bank.

All of the structures except for ELJ 3 experienced a net increase in woody debris or drift, particularly ELJ 2, which collected over 500 pieces of woody debris exceeding 2 m in length. Drift accumulation upstream of ELJ 2 effectively increased the structure's breadth by six-fold and contributed to the development of a perennial secondary channel south of the mainstem channel, thereby

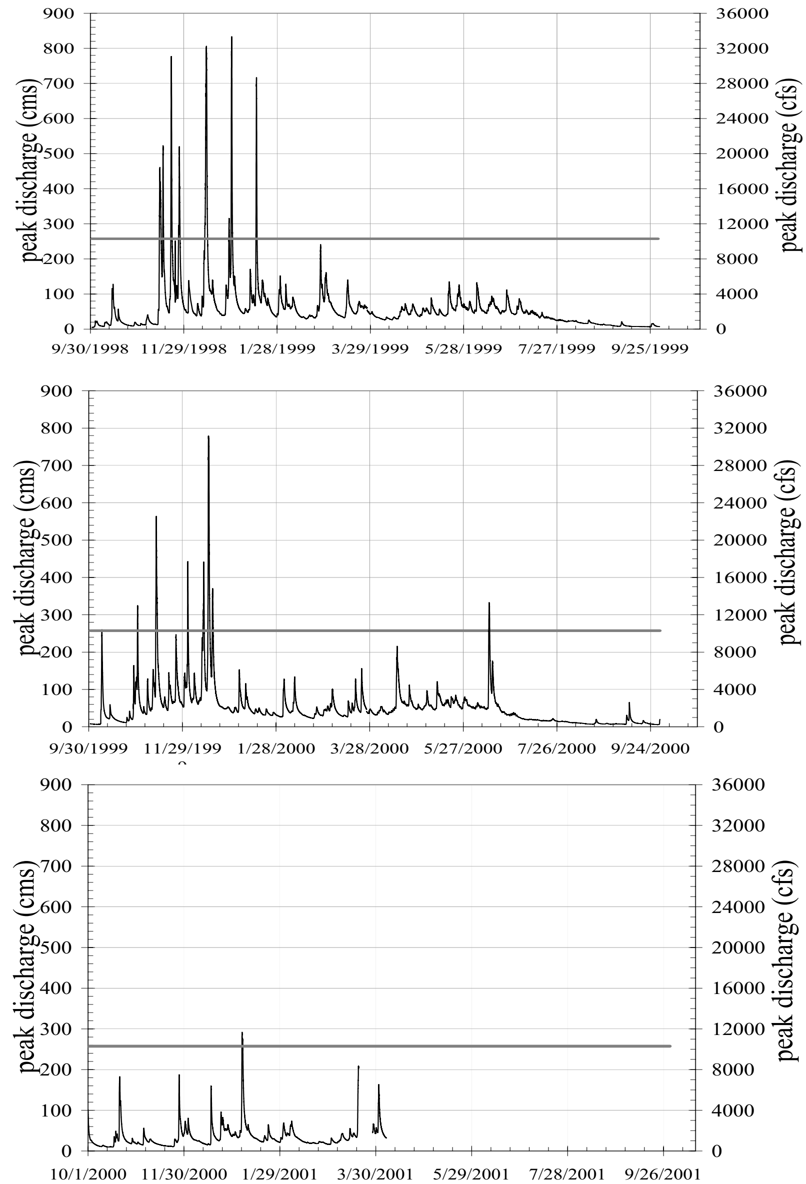


Figure 17. Annual hydrographs for Water Years 1999, 2000, and first half of 2001, North Fork Stillaguamish River, USGS Gage 12157000 near Arlington, Washington. Bankfull stage at the 1998 ELJ site (horizontal line) corresponds to approximately 10,000 cfs at Arlington gage.

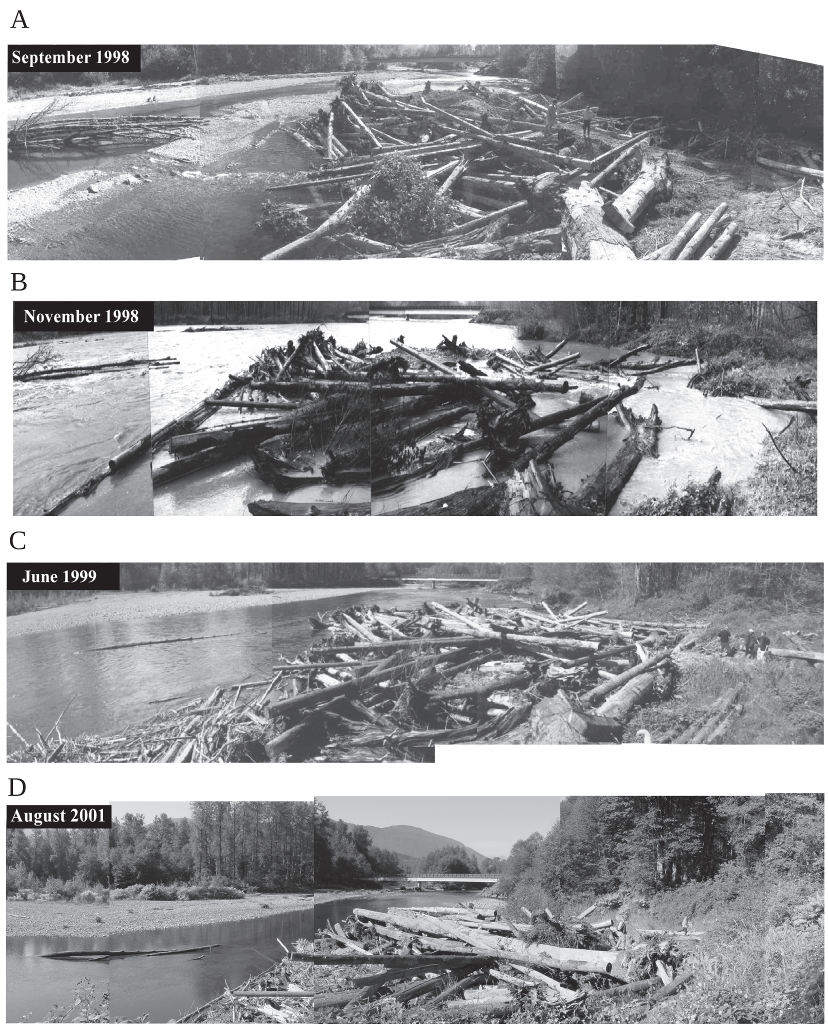


Figure 18. Photographs looking downstream at ELJ 1 (C-Post Bridge is in background). As-built conditions in (A) September 1998; (B) November 1998 during a peak flow cresting bankfull stage and over topping the ELJ; (C) June 1999 after 8 peak flows equal to or exceeding bankfull stage; and (D) in August 2001 after 16 peak flows equal to or exceeding bankfull stage.

creating a forested island. The effectiveness of the North Fork Stillaguamish ELJs in collecting drift is revealed by data collected on log displacement distances during Water Year 1999. Of the logs that moved, those that had to pass at least one ELJ had average displacement distances an order of magnitude less than those logs that passed downstream of the C-Post bridge (Figure 19). The North Fork Stillaguamish downstream of the C-Post bridge is a relatively simple, clear channel lacking stable log jams. From field surveys in September 1999, we estimate that 98% of the approximately 350 logs used in the five ELJs remained in place through eight peak flows equal or exceeding bankfull stage.

Reduction of the drift accumulation at the C-Post bridge was to be accomplished by: (1) trapping drift that might otherwise accumulate at the bridge; and (2) deflecting flow to improve channel alignment nearly orthogonal to the bridge, thereby providing for more efficient conveyance past the bridge. The large drift accumulation formerly lodged on the bridge's center pier was removed during ELJ construction and as of spring of 2001 no drift has yet to lodge on the bridge (Figure 20).

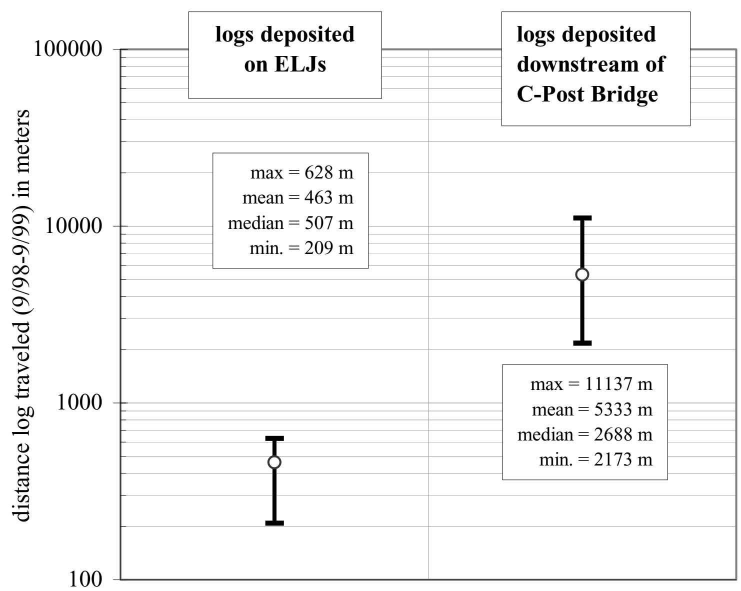


Figure 19. Displacement distances of tagged logs that moved in Water Year 1999: logs which had to travel past at least one ELJ had a significantly lower distance traveled than those logs that moved downstream of the C-Post Bridge, where few major flow obstructions were encountered all the way to Puget Sound.

The biological response to ELJ construction was evaluated by comparing baseline physical habitat and fish population information to post-construction surveys. Baseline data includes adult chinook and other salmonid population estimates through snorkel surveys, quantitative measures of habitat characteristics (e.g., number of pools, residual pool depth), and qualitative measures of habitat quality (e.g., amount of in-channel cover). Preliminary monitoring data suggest that changes in habitat condition have led to redistribution in adult chinook within the treatment reach. ELJs in the North Fork Stillaguamish have increased pool frequency, pool depth, and in-channel wood cover. Pool frequency increased immediately after ELJ construction from 1 pool/km to 5 pools/km and has remained at that level. Residual pool depth in the treatment reach also increased after ELJ construction, increasing from an average of 0.4 m to 1.5 m. The total number of pools in the area shown in Figure 16 increased from 3 to 6 after the project, but residual pool depths increased significantly. Most (80%) of chinook salmon utilization within the project reach was concentrated at the C-Post bridge in the largest, deepest pool within the reach; the remaining 20% was observed in a small pool adjacent to a natural log jam situated where ELJ 2 was constructed (Figure 21). Chinook response was immediate and consistent over the three years following construction. Instead of congregating in one pool (80% found in the C-Post Bridge pool) prior to ELJ construction, chinook redistributed throughout the treatment reach, utilizing the increase in pool availability and quality.

Lower North Creek

North Creek runs through the new University of Washington Bothell-Cascadia Community College (UWB-CCC) Campus in Bothell, Washington. The North Creek catchment is situated at the north end of Lake Washington northeast of Seattle. Restoration of North Creek is the result of a political, environmental, regulatory, and ecological design process that began in 1989 when the Washington State legislature authorized the design and construction of the branch campus. The restoration project was intended to mitigate for impacts to wetlands resulting from construction of the campus buildings and infrastructure. The State of Washington committed to a restoration design of the North Creek channel and floodplain that was significantly greater in scope, complexity, and cost than required by federal regulatory agencies.

The North Creek watershed is approximately 7,300 hectares and extends 20 km north of the Sammamish River. The watershed experienced intensive timber harvest at the turn of the century, which was followed by a long period of agricultural development. Present estimates of percent impervious area within

A

B

C

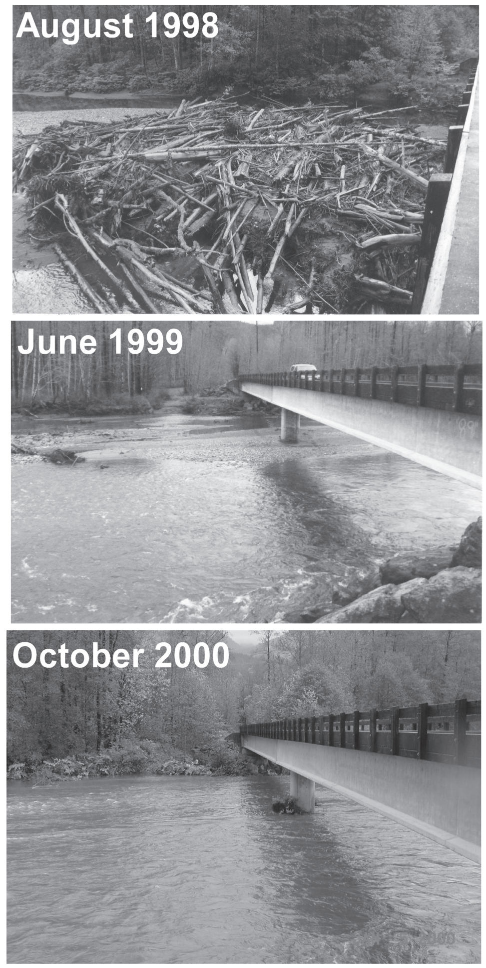


Figure 20. C-Post Bridge directly downstream of the 1998 ELJ project on the North Fork Stillaguamish River. Prior to constructing five ELJs upstream of the bridge, drift (mobile woody debris) accumulation was a chronic problem requiring frequent maintenance (A). Drift was removed in 1998 when the ELJs were built to test the hypothesis that ELJs could reduce drift accumulation by collecting drift upstream and improving channel alignment with the bridge to facilitate drift conveyance beneath the bridge. In the first year, there were eight flow events that equaled or exceeded bankfull stage without any drift accumulation on the bridge (B). The bridge remained clear after two years and 8 more flows equal to or exceeding bankfull stage (C). Only one peak flow equal to or exceeding bankfull stage occurred in the third year (Water Year 2001) and the bridge remains clear of drift.

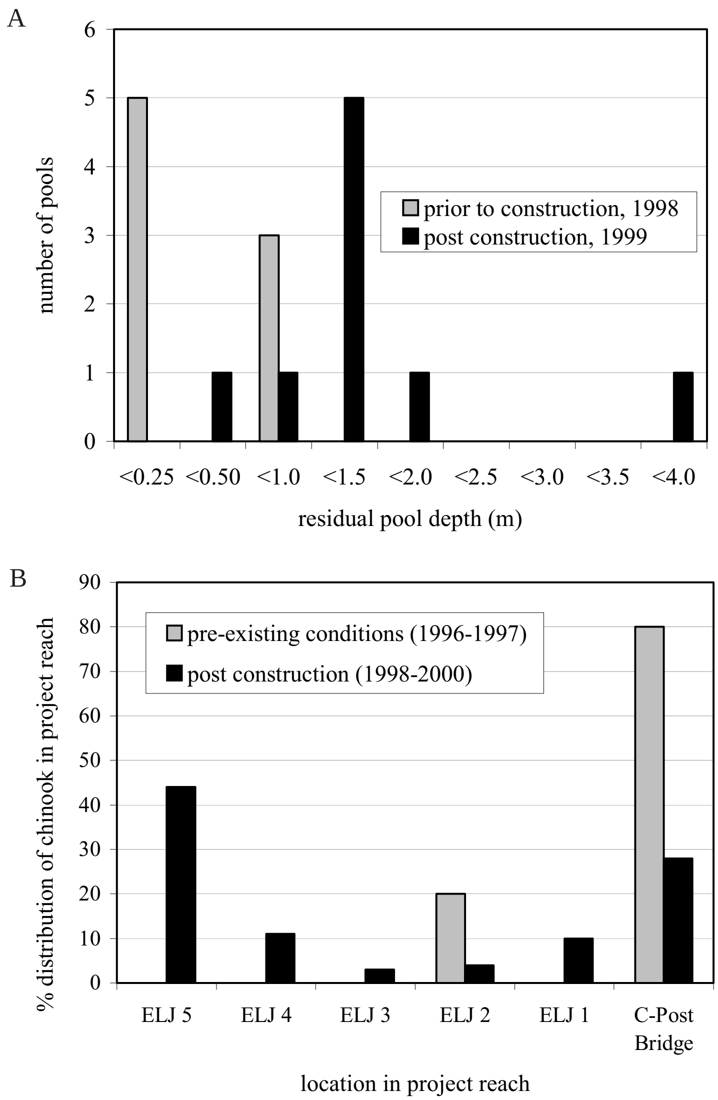


Figure 21. Results of the 1998 ELJ project in the North Fork Stillaguamish River. (A) The total number of pools only increased from 8 to 9 after the project, but residual pool depths increased significantly. (B) 80% of chinook salmon utilization within the project reach was concentrated at the C-Post Bridge in the largest, deepest pool within the reach; the remaining 20% was observed in a small pool adjacent to a natural logjam situated where ELJ 2 was constructed. Chinook distribution dispersed significantly after construction, correlating directly to the presence of ELJs.

the North Creek watershed vary from 14% to 27%. The estimated 100-year flood in lower North Creek is 41 m^3/s based on 16% effective impervious area.

The project site is situated just upstream of North Creek's confluence with the Sammamish River and covers approximately 24 hectares and 1,000 m of the lower creek channel (Figure 22). Historically, the landscape of the North Creek and Sammamish River confluence was a complex mosaic of very low gradient floodplain channels, depressional ponds, and marsh, scrub-shrub, and forested wetlands. The pre-settlement floodplain vegetation reflected the physical diversity of the landscape, with conifer dominated patches, scrub-shrub thickets of small trees and shrubs, and open water ponds fringed by emergent marsh vegetation, all set within a valley bottom deciduous forest matrix comprised of cottonwood and red alder. By the early twentieth century, the site was logged and the North Creek channel was straightened and leveed along the valley margin. An extensive network of ditches was excavated to dewater the forested wetland. These alterations effectively decoupled North Creek from its floodplain, drastically reduced the total channel length, and transformed the native emergent, shrub, and forested wetlands into a pasture. Prior to construction in 1998 the site was covered by Reed Canary Grass (*Phalaris arundinacea*). The net result of this historic land use was to significantly diminish salmonid habitat quality and abundance in North Creek.

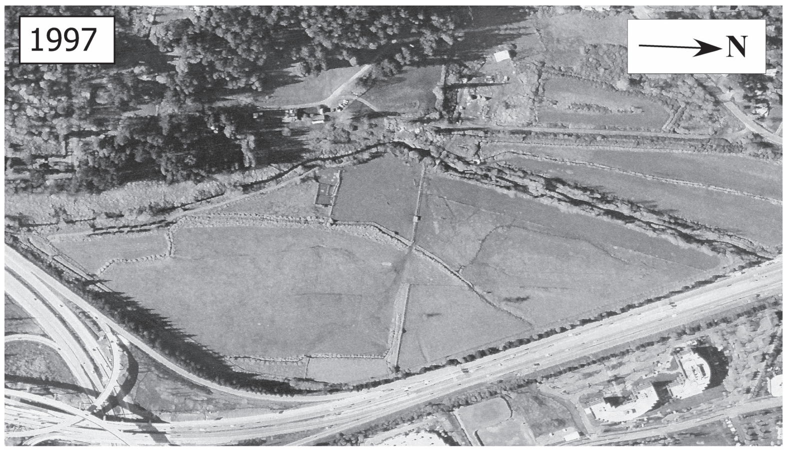
Project Objectives, Constraints, and Opportunities

The UWB-CCC reach of North Creek is typical of many urbanized, low-gradient stream and floodplain environments in the Puget Sound region. The rehabilitation design was constrained by single points of channel entry and exit to the campus property and a floodplain limited in extent by the Highway 405 and 522 road corridors. Given the degraded status and inherent physical constraints of the campus site, the goal of the design was to restore as much as possible the site's hydrologic, biogeochemical, and habitat functions. The restoration design was based upon historic site information, hydrologic modeling, and an extensive sampling effort to characterize ecosystem structural characteristics of similar Puget Sound lowland riverine reference sites.

Objectives

- Hydrologically reconnect North Creek with its floodplain
- Reintroduce both in-channel and floodplain large wood
- Restore native floodplain forest plant community
- Increase the quantity, quality and diversity of aquatic and terrestrial habitat
- Provide visual access from both the campus and highway corridors

A



B

Figure 22. North Creek channel and floodplain restoration site: (A) pre-existing conditions in November 1997 with creek channelized at northern margin of floodplain and (B) after construction of new channel and floodplain system in January 2002. ELJs constructed at the North Creek site include flow deflection jams, a bar apex jam (at inlet to secondary channel) and log crib revetments. Photographs courtesy of Soundview Aerial Photography, Arlington, WA. Flow is from right to left in both images.

- Increase linkages between channel system and riparian floodplain forest and wetlands by:
  - Maximizing length of perennial channel system
  - Maximizing contact time between water and wetlands
  - Maximizing linkages between channel system and floodplain

Constraints

- Limit the area of flood inundation and channel migration on urbanized site
- Accommodate increased peak flows resulting from urbanization of the upstream watershed
- Allow no export of drift downstream of project area
- Protect critical infrastructure beneath and adjacent to the project area (storm sewer pipe and university campus buildings)

Opportunities

- Introduce a multiple channel system for both perennial and ephemeral flow conditions
- Maximize tolerance for channel change (i.e., lateral channel movement)
- Incorporate ELJ structures to:
  - emulate instream structures representative of a low gradient Puget Sound stream
  - limit channel migration at sensitive locations
  - stabilize and help sustain secondary channel system
  - increase physical and hydraulic complexity within the channel

It was decided that a more natural stream channel morphology would be returned to North Creek by constructing a new channel system that provided a greater diversity of habitat such as found in pristine, low-gradient sites in the Puget Lowland. In particular, the new stream channel system was constructed to allow overbank flow to occur on an approximately 1-year return interval. This approach seeks to restore the linkage between channel and floodplain components of the North Creek ecosystem. The new main channel was designed with bed and bank features and a variety of in-channel habitats, including pools, riffles, and large wood. Secondary channels were designed to engage at different flow stages.

Project Design

The North Creek project involved construction of a sinuous new mainstem and a perennial side channel, four types of ELJs incorporating approximately 1200 unanchored logs, and an aggressive revegetation plan. Infrastructure constraints mandated that channel migration be controlled. The overall project goal of improving aquatic habitat with respect to this constraint was achieved by using ELJ structures to limit bank erosion, contain channel migration, and create beneficial instream habitat. Engineered log jams emulating flow deflection jams were used along many of the channel meanders. At the inlet to the secondary channel a bar apex jam was constructed and inside the inlet a set of log steps were placed to prevent incision and dissipate energy. These jams were integrated with flow deflection jams to protect banks of the channel. Toward this end, tree bole revetments and crib structures were used to stabilize the critical banks and meanders; a bar apex type ELJ was built to locally raise water elevations at the secondary channel inlet; and a complex multiple log weir was set beneath the bed of the inlet channel to reduce the probability of the secondary channel becoming the mainstem channel.

The restoration design for the floodplain plant community was based upon quantitative characterization of similar floodplain forests at 58 Puget Sound reference sites. Based on these reference site data, 25 distinct plant communities were designed and planted at North Creek. The goal of the North Creek plant community restoration was to set the stage for the development of a compositionally and structurally representative Puget Lowland floodplain forest. The newly constructed channel reach was not engaged upon initial construction in order to allow riparian vegetation to become established along the channel banks. During the vegetation establishment period from August 1998 to August 2001 the project site was inundated several times due to backwater effects of the Sammamish River during winter high flows. The cost for the entire North Creek restoration project was approximately $6 million.

Results to Date

The new creek channel system was opened to the full discharge of Lower North Creek in August 2001. During the winter of 2001-2002 the creek experienced several peak flows that inundated the floodplain. Students from the Center for Streamside Studies surveyed twenty-five channel cross-sections in October 2001 and re-surveyed them again in January 2002. At the cross-sections, the channel has experienced some net scour and no significant change in width or location. All of the engineered log jams remain intact and are associated with deep pools. The North Creek project shows that a large-scale project involving rehabilitation of a complete channel and floodplain reach is feasible in urbanized areas if sufficient land is available. The project also suggests that unanchored logs can be incorporated into engineered log jams as an integral part of stream restoration, even in an urban stream, although the long-term consequences of increasing channel discharges with progressive watershed urbanization have yet to be evaluated.

Conclusion

River rehabilitation in large portions of fluvial landscapes, including areas within naturally defined channel migration zones, can be severely constrained or even precluded due to agriculture, industry, commercial forestry, residential development, and transportation infrastructure. Because human development affects so much of the fluvial landscape and is likely to continue to do so, meaningful rehabilitation of fluvial ecosystems will require strategies that integrate technology that not only re-establish and sustain natural processes but also maintain infrastructure and protect human life and property. Consequently, strategies are most likely to succeed if based on multi-disciplinary collaboration of physical and biological scientists, civil engineers, planners, and community representatives. Traditional engineering problems can be solved with non-traditional approaches, such as ELJs, that provide specific benefits together with habitat enhancement. In this context, ELJs are versatile in that they can be used for both habitat enhancement as well as general river engineering. However, in the implementation of ELJ projects, it is important to clearly delineate objectives and constraints, establish the spatial and temporal scale of the project, and document what ultimately happens on the ground. The potential risks of applying ELJ technology without adequate scientific assessment and engineering design can threaten not only the success of a single project but also human welfare and future policy decisions regarding the management of instream woody debris. The success to date of ELJ projects in western Washington highlights the potential benefits of this experimental technology for enhancing fluvial ecosystems while protecting infrastructure and property within fluvial corridors.

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