CONCEPTUAL DESIGN GUIDELINES

Application of Engineered Logjams

Prepared for

Scottish Environmental Protection Agency

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Prepared for

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Introduction

Traditional approaches to river engineering in Scotland over many decades have resulted in the damage of important aquatic habitats. With the introduction of new legislation to protect river habitats in Scotland,[1] there is a need for public agencies to develop advice and guidance for a range of stakeholders on alternative approaches to 'hard' engineering. There is also growing recognition of the role degraded physical river habitat plays in suppressing economically important populations of Atlantic salmon.

Engineered logjams (ELJs) have been widely used in Pacific Northwest (PNW) of North America over the past decade as an alternative, more sustainable approach to river management. They have been used for bank protection and habitat enhancement in high-energy gravel bed rivers supporting migratory species of Pacific salmon. Their success indicates similar approaches may offer viable solutions to many river management issues in Scotland.

The objective of this project is to deliver best practice guidance for the use of ELJs within the Scottish river context, including in a future phase, the preliminary design of a pilot scheme on the River Tweed.

This project provides an overview of engineered logjam technology, its scientific basis, potential applications, design guidelines, physical and biological performance of constructed ELJs, and project examples. Engineered logjam (ELJ) technology includes a wide range of instream and floodplain structures that mimic the geomorphic and ecologic functions of natural accumulations of woody debris (Abbe et al. 1997, 2003a, 2003b). Because the underlying principle of ELJ technology is biomimicry, or the imitation of natural conditions, it relies on a strong understanding of fluvial processes (e.g., hydraulics and sediment transport) and landforms, disturbance regimes, historical change, riparian vegetation, and site constraints.

There are many types of ELJ structures, and the selection of a specific set of materials and architecture depends on the particular site, project goals, acceptable levels of risk, costs, and constraints. Experiences with ELJs to date suggest that in certain circumstances they can provide an economical method of bank protection and help in managing debris (especially mobile wood) that may be hazardous to bridges and culverts. At the same time, installation of an ELJ can reestablish important habitat elements of forest streams that have been degraded by conventional river engineering. While there are numerous situations in which ELJ technology can provide a sound engineering solution that delivers measurable environmental and esthetic benefits, there are also situations in which an ELJ structure would be inappropriate.

Natural accumulations of wood debris exhibit distinct size, shape, and orientation, which combine to create various hydraulic and geomorphic effects in different portions of mountain channel networks. Therefore, the design of an ELJ project should include careful scoping of the types of logjams that are likely to prove stable and meet the design objectives in the local geomorphic context.

[1] Water Environment and Water Services (Scotland) Act 2003; Nature Conservation (Scotland) Act 2004.

Assessment of whether ELJs represent an appropriate approach and, ultimately, the final design specifications for a site, depend on both the geomorphic and hydraulic characteristics of the stream reach and floodplain, as well as human objectives and constraints. Consequently, investigations and analyses associated with ELJ design need to address 1) potential local and watershed disturbances that might influence the project, 2) historical planform characteristics and changes in channel, floodplain, and forest patterns in the valley bottom, both upstream and downstream of the project site, 3) results of topographic, geomorphic, and hydraulic analyses of the project reach and the subreach-scale area where the ELJ structures will be built, and 4) size, position, spacing, and architecture of the ELJs and constituent logs. ELJ stability is based upon the composite framework of large key members and stacked logs that provide a foundation for smaller stacked and racked pieces.

Consistent with the objective of imitating natural processes, ELJs are typically built of native wood debris and alluvial soils. However, imported and engineered materials such as piles, rock, or concrete logs have been used in the core structure, so long as the complete structure still looks and acts like a natural structure. All ELJ designs should be based on local conditions.

Although several ELJ projects constructed in western Washington state since 1995 have performed well through several floods, ELJs remain an experimental technology. The projects constructed to date confirm that post-construction inspections and maintenance are needed as an essential component of ELJ projects that are designed to control bank erosion. Whereas these ELJ demonstration projects show the technology to be an environmentally and economically viable alternative to traditional river engineering in certain applications, inappropriate design and application of ELJs can result in locally accelerated bank erosion, unstable debris, or channel avulsion. Continued research and experimental applications of ELJs in a variety of topographic and climatic settings are needed to help refine the design guidelines for their use in rehabilitating and managing river systems.

Wood debris, which is a common element within fluvial environments (i.e., streams and rivers), can have extremely important ecological value. Wood debris also can have both beneficial and adverse effects on land development. The contrasting effects of wood debris have never before been so pronounced as at the present time, due to elevated levels of natural wood recruitment resulting from riparian reforestation, extensive efforts to re-introduce wood, and land development in fluvial corridors planned with little attention to wood debris.

During the period of European colonization of North America, immense quantities of wood debris imposed barriers to navigation and land development. Riparian trees were considered potential recruitment sources, and aggressive federal and local programs to clear wood debris from riparian areas and rivers in the nineteenth century continued through most of the twentieth century. In many parts of the United States outside the Pacific Northwest, channel clearing or de-snagging is still done at considerable cost.

Historical wood removal highlights several important aspects about wood in rivers:

- Not all wood washes through the system; some pieces become lodged in place to form stable flow obstructions (and removal requires massive machinery or explosives)

- Stable accumulations of wood are capable of altering or impounding river channels

- Channel-clearing programs are expensive and have severe impacts on fluvial ecosystems.

It is useful to distinguish several types of wood debris found in rivers. *Snags* are relatively large tree boles capable of forming stable flow obstructions. In large rivers, snags become embedded in the channel bed. Embedment is dependent on the size and shape of a snag; thus most snags form from large or multistem trees with intact rootwads. *Drift* or *flotsam* is relatively small wood that is frequently mobilized and tends to accumulate at sites of stable obstructions such as snags. *Logjams* form where large quantities of wood accumulate, usually at flow obstructions such as snags or bridge piers, although logjams can also form along meander banks or in channel avulsions.

Consequently, the development of logjams depends on boundary conditions capable of initiating wood deposition, such as flow obstructions or sharp bends, and an upstream supply of wood. Given the same quantity of flotsam entering two river reaches, one with abundant snags and the other with few, a larger volume of flotsam is likely to be exported from the reach with few snags. In rivers that have been cleared and are unlikely to diffuse the amount of mobile debris moving downstream, there is an elevated threat of catastrophic accumulations at undesirable locations such as bridges. Thus the presence of stable obstructions can be used as a management tool for controlling the downstream flux of flotsam. Stable obstructions can also provide effective bank protection and can influence channel alignment.

Snags and logjams can form stable “hard points” that last for centuries and are capable of controlling the course of a river. These obstructions provide natural analogs for designing wood structures to protect human infrastructure in a manner that is consistent with natural processes while preserving aspects of the river’s ecological integrity. Such an endeavor requires a qualitative and quantitative understanding of the mechanics of wood stability, wood dynamics, the hydraulic and geomorphic effects of wood in stream channels, and the appropriate settings for using wood structures. This understanding forms the conceptual foundations of engineered logjam technology (Abbe et al. 1997).

During the past two decades, there has been an increasing financial investment in the Pacific Northwest to reintroduce wood to streams and rivers in an effort to rehabilitate salmonid habitat. However, the majority of these efforts lack any scientific or engineering justification or assessment of the potential consequences, despite potential adverse impacts. The scientific foundation and incorporation of engineering design standards underlying engineered logjam technology are unique, and no such comprehensive approach has ever been applied to managing or re-introducing wood debris into fluvial environments.

The serious economic and environmental implications of instream wood debris call for protocols that incorporate sound science and engineering. The proper implementation of engineered logjam technology provides a means to rehabilitate fluvial ecosystems, protect endangered species, and protect infrastructure and human communities.

Summary of Engineered Logjam Technology

The term *engineered logjam* (ELJ) refers to any of a diverse group of engineered instream structures that offer an effective means of restoring habitat and treating traditional river engineering problems such as bank erosion, flooding, bridge damage, and channel incision. ELJ technology is based on the premise that the manipulation of fluvial environments, whether for traditional problems in river engineering or for habitat restoration, is likely to be more economically and environmentally sustainable if the resulting environment emulates the natural conditions and processes to which the landscape and ecological communities adapted. This approach is similar to the emerging field of biomimicry in which natural systems are imitated to solve human problems (Benyus 2002). For centuries, timber has been used to construct instream structures such as check dams, spur dikes, and bulkheads. ELJs are unique in that they are engineering structures that replicate the complexity found in natural systems. ELJ structures were first implemented in 1995 for a private landowner to protect the banks of the upper Cowlitz River in western Washington state in the United States (Abbe et al. 1997). Since 1995, numerous ELJ projects have been successfully implemented to enhance aquatic habitat and protect property and infrastructure. ELJ technology is emerging as a significant new approach to river engineering in the Pacific Northwest of the United States, as reflected in recent awards from the American Council of Engineering Companies and the American Society of Civil Engineers for the application of ELJ technology to provide a long-term, environmentally sustainable means of protecting a major west coast highway along the Hoh River in Washington state.

The concept of ELJs began with the observation that natural logjams not only introduce physical complexity to streams and rivers, which creates productive fish habitat, but also can control the morphology and grade of fluvial systems. Logjams create pools and bars, increasing stream sinuosity and the number of channels. They also form stable “hard points” within channel migration zones (Abbe and Montgomery 1996, 2003; Abbe et al. 2003a, 2003b; O’Conner et al. 2003). These hard points create stable foundations for forest growth within rivers that are subject to frequent disturbance, thereby promoting the development of trees large enough to continue the formation of stable logjams. By increasing the physical complexity of streams and rivers, logjams increase the diversity of available habitat and biological productivity of the system. Logjams result in both localized and reach-scale effects that enhance salmonid habitat. Local effects created by logjams include scour pools, bars, riffles, complex cover (interstitial space within the water column and material overhanging the water), sand and gravel bars with variable substrate, and forested islands. Reach-scale effects include the conversion of bedrock and simple alluvial channels to complex pool-riffle channels (Montgomery et al. 1996; Montgomery and Buffington 1997; Buffington and Montgomery 1999a; Abbe and Montgomery 2003) and the creation of secondary channels and wetlands within the floodplain that can dramatically increase the quantity of aquatic habitat (Abbe et al. 2003a). ELJs have been successfully applied to re-create these effects in addition to treating traditional problems such as bank erosion, channel incision, and bridge damage (Abbe and Montgomery 2003b; Abbe et al. 2003a).

Scientific and engineering studies of 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 sediment supply (Raudkivi 1990; Pitlick 1992; Buffington and Montgomery 1999b), the effect of channel obstructions on flow deflection and scour (Garde et al. 1961; Raudkivi and Ettema 1977; Copeland 1983; Klingeman et al. 1984; Miller et al. 1984; Hoffmans and Verheji 1997), the impacts of debris accumulation at bridge piers (Melville and Sutherland 1988; Melville and Dongol 1992; Diehl 1997; Richardson and Lagasse 1999; Melville and Coleman 2000), and the hydraulic and geomorphic effects of natural snags (Shields and Gippel 1995; Abbe and Montgomery 1996; Gippel et al. 1996; Wallerstein et al. 1997).

Changes in channel planform and obstruction of flow can result in rises in local water elevations that are significant enough to inundate secondary channels and portions of the floodplain during flows that would otherwise not result in inundation (Miller 1995). ELJs can create the same effect as they obstruct flow and control channel planform, thereby serving as one of the principal mechanisms connecting the main stem channel to secondary channels and wetlands within the floodplain. Where ELJs partially obstruct flows, they also create and sustain pools through vortex scour.

The design process recommended for ELJs begins with an assessment of the watershed, followed by an analysis of the hydrology, hydraulics, sediment regime, and channel dynamics of the stream reach within the project site. The reach analysis also identifies opportunities and constraints and evaluates risks associated with particular actions. If opportunities for potential ELJ applications are identified, then appropriate types of natural logjams are selected on the basis of on the project objectives and site constraints. After the general reach-scale strategy and ELJ layout are refined and a risk assessment has been completed, the individual ELJ structures are designed and specifications for the logs and logjams are prepared. Finally, the structures are constructed and evaluated over time.

The materials used in ELJs are primarily (but are not limited to) tree stems (logs) with or without their root mat attached. An ELJ structure may consist of a dozen logs or several hundred logs. The goal of any ELJ structure is first to mimic the functions of natural logjams, such as altering flow patterns, trapping sediment, or creating scour pools, and secondarily to do so in a way that most closely emulates the natural characteristics of the logjams. For example, natural logjams do not have cable chain securing the logs to one another or to rock ballast. Natural logjams secure themselves by the geometry of individual logs, the configuration in which they interlock with each other, and embedment into the river's alluvial substrate. Artificial means of securing a logjam such as rock ballast, chain, or concrete logs should be used only when absolutely necessary.

The logs used to construct individual ELJs fall into four basic structural elements: key logs, stacked logs, racked logs, and piles. ELJs can consist of just one or all of these four elements.

Key logs (or *key members*) are individual logs with rootwads, which are unlikely to move during a bankfull flow, and are used as the foundation of an ELJ structure. 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 previously existing flow obstruction elements (e.g., stable boulders) or opposing banks. Properly situated, key members can transform a bedrock channel into an alluvial channel by trapping sediment either upstream or downstream of their placement.

Stacked logs (or *stack 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 orthogonal layers that link individual members together and increase the integrity of the structure. Most stacked members should retain a substantial rootwad, which prevents logs in overlying and underlying layers from moving out of the structure.

Racked logs (or *racked members*) are the smallest logs, with the largest range in sizes, and are often the only logs that are visible after construction is completed, depending on the type of ELJ. Racked members result in a dense, chaotic pile of debris directly upstream of the key members and stacked members. This accumulation of debris deflects flow around the ELJ and decreases flow through the structure. The pile of racked members should extend from above the bankfull elevation down to the point of maximum scour in order to prevent undercutting of the ELJ structure (Figures 1 and 2). Each racked log adds a solid interface with the water, just like inorganic particles. A large number of racked logs, which is typical for most logjams, dramatically increases the available substrate for invertebrates. Unlike inorganic substrates, racked logs are situated within the water column and thus offer much more interstitial space and cover for fish. The complex cover created by the racked members provides extremely productive habitat for invertebrates, fishes, mammals, and birds.

Piles are an optional component for particular types of ELJs that can significantly increase the stability factor of safety by increasing the total shear resistance of the ELJ structure. Piles are typically placed in the excavated footprint and core of an ELJ, between key and stacked logs downstream of racked logs. Piles can be driven or simply placed within the excavated area (particularly when working in coarse cobble substrates). Piles also provide a means of creating a framework upon which an ELJ can settle intact into the channel bed, a process that is particularly important in cases where scour risk is high. Piles can be placed vertically or inclined. Inclined piles are used to limit vertical displacement of other log elements and can be used to retain racked logs.

No artificial materials are necessary for the construction of an ELJ but they can be used for special circumstances or to alleviate constraints due to the availability or cost of materials. If artificial materials are used, they should not alter the basic appearance or function of the ELJ. Native trees and alluvium at the site are all that is needed if the trees meet the design specifications for size and shape. ELJ construction typically requires significant excavation and grading. Most projects will require the importation of trees to the site because sufficient quantities are typically not available locally and it is preferable to preserve the existing riparian trees and instream wood. ELJs have been constructed with the use of both timber and steel pilings, rock cores, and even concrete logs. To facilitate the implementation of ELJ projects, a range of adaptive solutions have been developed. For example, cost constraints on a small landowner along the Methow River of Okanogan County in eastern Washington required an adaptive approach to the acquisition of a sufficient number of trees to construct of a series of three ELJ structures. A plan was developed to selectively harvest adjacent forestland, with the secondary benefits of accelerating growth of native conifers (through thinning of mature cottonwoods). Forest thinning reduced the fire risk (by reducing fuel accumulations on the forest floor) and improved the aesthetic and recreational values at the site.

Most ELJ projects involve a series or array of structures within the selected stream reach and its channel migration zone. The ELJ design (type, size, and position of ELJs) depends on an understanding of the geomorphic, hydrologic, and hydraulic conditions of the project site that is sufficient to characterize the river's dynamics and predict the likely range of future conditions. This information is compiled during the reach analysis, which includes documentation of historical changes in the river and, if possible, characterization of the pristine conditions that prevailed before human alteration of the landscape occurred.

Applications of ELJs in the United States and Australia have demonstrated that wood debris can reintroduced to create stable instream structures that emulate natural processes and preclude the use of artificial anchors or cables. These ELJ projects have created valuable aquatic and riparian habitat, while simultaneously ameliorating traditional problems such as bank erosion, channel incision, erosion of bridge abutments, and reducing mobile wood debris (drift) accumulations on bridge piers (through upstream drift capture and improved conveyance through bridge crossing by channel alignment). The success of these projects is attributed to a comprehensive design approach that integrates an understanding of the geomorphic, hydrologic, hydraulic, and ecological characteristics of each site, the watershed associated with the site, and site constraints associated with infrastructure and development. The experience gained from the application of ELJ technology on two continents has demonstrated the versatility of the approach in different river conditions, provided that reliable knowledge of local conditions is incorporated into the design process. More than three dozen individual ELJ structures have been subjected to several overtopping flows, some by as much as 2 meters and velocities exceeding 4 meters per second. Physical monitoring has provided valuable information on the performance of ELJs, failure mechanisms, and the most important structural elements to consider in design. Biological monitoring has provided evidence that these structures are heavily used by invertebrates and juvenile and adult fishes, representing a diverse assemblage of species; in Australia, an increase in total fish abundance has been demonstrated at the reach scale. Inspections after ELJ construction at several project sites have led to improvements in design with each new generation of ELJs.

ELJ technology offers a possible alternative to traditional river engineering and management for addressing as the following:

- Rehabilitation of aquatic and riparian habitat in forested fluvial environments
- Environmentally beneficial bank armoring and flow deflection to halt or reverse bank erosion

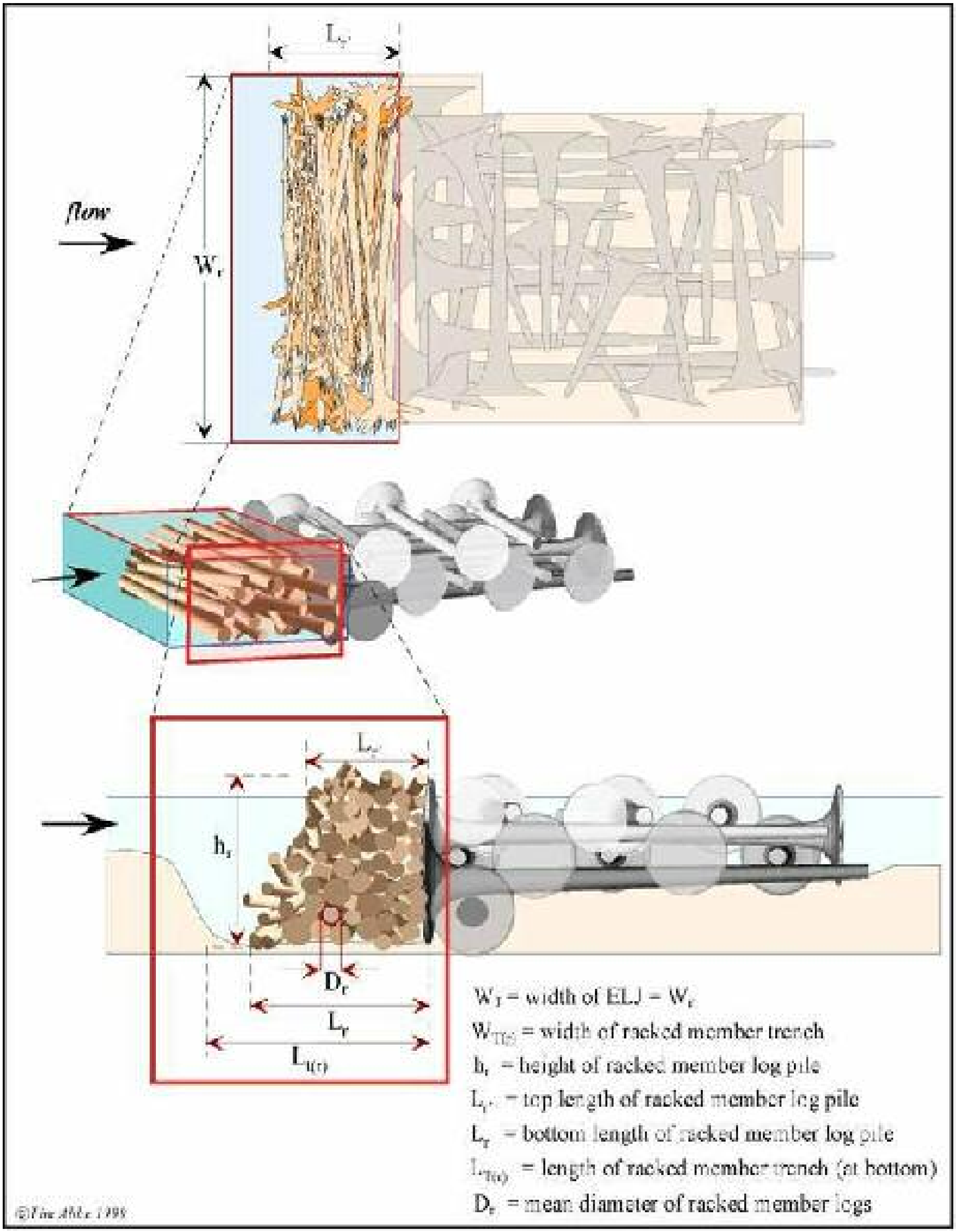


Figure 1. Illustration of flow deflection ELJ designed to deflect flow, showing placement of racked logs at upstream end of the structure. Core of structure is typically backfilled and planted with native floodplain trees.

Photo by Tim Abbe (1998).

Figure 2. Typical design of flow deflection ELJ and example of as-built structure protecting the left bank (facing downstream) and creating pool, riffle, and complex cover for fish in the North Fork Stillaguamish River, Snohomish County, Washington (flow is left to right). Racked logs are visible but core of ELJ is buried.

- Flood protection by diffusing flood peaks, deflecting flow away from critical sites, and reconnecting floodplains
- Grade control to limit or reverse channel incision and gully formation
- Stable instream structures to limit debris flow run-out
- Control of landsliding triggered by river bank erosion
- Bridge and culvert management and protection:
  - Abutment protection
  - Improved conveyance (channel alignment with crossing)
  - Debris management
- Rehabilitation of floodplain systems, particularly side channel and slough hydraulics and habitat
- Implementation of long-term sustainable strategies for restoration, development, and infrastructure within fluvial environments
- Improvement in hyporheic exchange by introducing local hydraulic gradients at the ELJ and between side channels. Increasing hyporheic exchange contributes to better lower water temperatures and improved water quality.
- Increased shade/cover by splitting the river into narrower channels separated by forested islands, decreasing the amount of solar radiation that reaches the water surface
- Increased quantity and quality of fish habitat, including edge habitat, pools, spawning substrate, and cover.

Biological Value of Logjams

Woody debris is a natural part of woodland stream ecosystems. Understanding the important ecological function of woody debris is an important step in restoring river ecosystems while reversing the adverse effect of development (particularly within the context of the recovery of salmonid populations).

Large woody debris is a critical component of high-value habitat for anadromous and resident fish, and it affects fluvial dynamics. Also, a variety of aquatic species depend on the natural accumulation of snags, branches, and rootwads. When a tree or part of a tree falls into a stream, it has an immediate effect on the physical habitat. Once in the stream, a tree serves as an important part of the habitat in that such large woody debris is a structuring factor that enhances habitat complexity. Large woody debris slows the flow of water, dissipates energy, traps sediment and organic matter, and creates microhabitats for fish and macroinvertebrates (Dolloff 1994). Since woody debris is closely linked to the habitat requirements and food availability for salmonid fish species and aquatic invertebrates, its presence may be of crucial importance for stream ecosystems.

In the form of overhanging logs, rootwads, and especially logjams, large woody debris creates pools, partitions habitat, and provides complex cover. Pools form around any material that creates friction and resists displacement by flowing water. While virtually everything in the channel creates friction, including the stream bottom and sides, large woody debris, boulders, and bedrock protrusions are the dominant pool-forming elements. However, large woody debris (particularly when part of a logjam) is the most conspicuous of these elements and may play a role in the formation of up to 100 percent of the pools in small- to medium-sized streams that flow through undisturbed forests (Harmon et al. 1986).

Logjams influence habitat at a various scales ranging from the microscopic, to substrate grain size, to bedforms, to channel width, to meander wave lengths (reach scale). Because of their direct and indirect effects, logjams can substantially improve conditions for a wide range of aquatic organisms (e.g., insects, fish, and amphibians) and terrestrial organisms (e.g., reptiles, mammals, and birds), from juvenile to adults. The physical complexity of logjams and their effect on hydraulic conditions result in wide range of habitats within a very small area. Natural logjams and ELJs typically consist of several large tree boles and dozens or hundreds of smaller pieces of large woody debris, increasing the surface area along a bank several orders of magnitude. Large woody debris can affect channel processes at all scales, from pool formation to valley bottom landforms and floodplain formation.

Salmon habitat is influenced by landscape processes that govern the supply and movement of water, sediment, and wood to and through rivers and streams. According to the UK Biodiversity Action Plan (2005), years of anthropogenic habitat modifications have resulted in degradation of the processes that control the supply and movement of water, sediment, and wood to and through important rivers systems in the United Kingdom:

> *Few rivers in the UK have not been physically modified by man and such rivers represent a very valuable resource. Erosion of banks has also been caused by canalization and the removal of tree cover in historic times. Such activities have resulted in changes in the frequency and magnitude of flooding, altering seasonal patterns of flows and hydrograph form. In addition, flow regulation has altered patterns of sediment transport and nutrient exchange in river systems. Any resulting eutrophication can have detrimental effects on floodplain habitat which still retains some connection with the main stream.*

In Scotland, anthropogenic habitat modifications that have been induced by development have resulted in the damage of important river systems, which has contributed to the decline of salmon fisheries (Soulsby 2004):

> *As with salmon rivers elsewhere in Europe and North America, recent decades have seen a decline in salmon catches on many Scottish rivers. These declines appear to be associated with a range of factors, including increased mortality during the marine phase of the salmon life cycle. However, changes have also occurred in water and land management practices in the catchments of many salmon rivers. These include changed flow and sediment regimes in rivers affected by intensified agriculture, commercial forestry and flow regulation for hydro-electric power production.*

Land use changes typically result in the loss of potential for recruitment of large woody debris and the removal of large woody debris from streams (natural accumulation of trees, branches, and rootwads). Removal of large woody debris typically results in habitat simplification and fewer, smaller fish. More specifically, removal of large woody debris typically results in a loss of pool habitat (e.g., Bilby 1984), a decrease in habitat complexity (e.g., Lisle 1986), and a reduction in fish numbers, average size, and biomass for salmonid fish species (e.g., Dolloff 1986; Coulston and Maughn 1983; Elliott 1986; Fausch and Northcote 1992). Habitat simplification (e.g., simpler channels with fewer scour holes and fewer eddies and meanders) after timber harvest and subsequent decreases in residual loading and input of large woody debris also has been linked to long-term changes in the species composition (diversity) of fish communities, including shifts in dominance and the disappearance of formerly common species (Reeves et al. 1993).

The sustainability and restoration of habitats and species require protection and restoration of the ecological processes that sustain them in addition to direct protection of the habitat themselves. Without adequate habitat protection, development will result in further reductions in the amount and complexity of habitat; increased scouring of the stream channel; reduction or loss of channel migration, sediment supply, and recruitment of large woody debris; and decreased productivity and species diversity (Bolton and Shellberg 2001).

Like in lowland forest rivers of the coastal Pacific Northwest before colonization in the late 1880s, river systems in the lowland forests of Scotland likely occupied vast geographic areas and were interspersed with complex networks of perennial and ephemeral channels. Floodplains consisted of complex mosaics of forest patches and wetlands were integrally linked to these channel networks. One of the principal components driving the complexity of these systems was the presence of logjams, which split flow, raised water levels, created pools, and provided abundant cover for fish, particularly salmonids. Consequently, a reintroduction of large woody debris (particularly in the form of ELJs) in rivers systems of Scotland will help to improve the now declining salmon populations.

The reintroduction of large woody debris can provide benefits in the forms of infrastructure protection and habitat creation. There are numerous benefits and advantages of strategically placed, well-designed ELJs. These benefits include support for the food web, increased hyporheic connectivity and exchange, sorting of stream gravel, creation of salmonid spawning habitat, rehabilitation of refuge habitat, bank protection, grade control, debris retention, and diffusion of flood peaks.

A small ELJ constructed in the lower Big Quilcene River in western Washington is an example of an ELJ solution that resulted in immediate benefits to salmon populations in a river that had undergone significant historical change. The local head differentials introduced by the constructed ELJ enhance downwelling and upwelling into the substrate and connectivity with hyporheic flow. Upwelling areas improve the survival of eggs and emergent fry by modulating the egg incubation environment and increasing the water exchange around the egg pocket, thereby replenishing oxygen and removing metabolites (Bjornn and Reiser 1991; Freeze and Cherry 1979). Hyporheic flow helps to modulate the temperature inside redds (spawning nests) by providing an input of water that is warmer than the river, thereby protecting the eggs during periods of extreme low temperature and ensuring emergence at optimal times (Berman and Quinn 1991). Several weeks after the ELJ was constructed in the lower Big Quilcene River, there were seven redds within 10 meters of the structure and none 10 to 50 meters farther upstream or downstream (Figure 3). Currently, the ELJ promote localized variations in bed topography, substrate material, and hyporheic flow, which in turn influence where salmon spawn in this river reach. Increased use of ELJs by fish for cover, food, or hydraulic conditions has been observed at almost every ELJ project.

The beneficial effects of ELJ are not restricted to adult salmon fish. In an ELJ project implemented in the lower Elwha River in Clallam County, Washington, a large, complex pool formed by the ELJ provides critical rearing habitat for juvenile salmonids (Figure 4). Since project implementation, large schools of juvenile salmon are commonly found associated with the pool. The complexity and habitat partitioning created by the ELJ likely decrease predation and increase fish-holding capacity (Figures 5, 6, and 7). In the lower Elwha River, pools with ELJs consistently show greater species richness than pools, riffles, glides, or edge habitat with no ELJs (Figure 8). Construction of five ELJs in a 200-meter segment of the North Fork Stilliguamish River in Washington led to a more pronounced geographic distribution of adult salmonids, which reduced fishing pressure at an easily accessible bridge crossing (Figure 9).

Other measures of biological productivity, such as periphyton biomass and invertebrate density, are higher at sites with ELJs than at control sites without ELJs (Figures 10 and 11). ELJs have been found to be particularly important for providing cover for salmonids during daylight hours, with fish tending to venture along the channel edge during the night (Figure 12). While there is a great deal of scientific research yet to be done on river ecology and quantification of habitat improvements such as ELJs, it is clear that these structures are one of the single most effective ways to directly and indirectly rehabilitate fluvial ecosystems and benefit salmonids.

Field studies by Sundbaum (2001) in River Ammerån in the county of Jämtland, Sweden, found large woody debris to be an important physical feature of the habitat for brown trout (*Salmo trutta*), influencing their abundance during the growth season. According to Sundbaum's findings, increased habitat complexity may increase abundance by enhancing the visual isolation of brown trout, which acts to decrease intraspecies competition for space. In addition, Sundbaum demonstrated that an increased amount of woody debris in the stream has a positive effect on the abundance of brown trout during the summer. The fish also distributed themselves in relation to the large woody debris, indicating use of the woody debris, probably for cover, feeding, or both. One of the most large-scale effects of logjams on habitat is the creation of multichannel (anastomosing or anabranching) systems, which increase the total available habitat by several factors (e.g., through an increase in cumulative channel length and number of pools).

The results of biological monitoring within the Pacific Northwest rivers (Coe et al. in preparation; Pess et al. 1998; 2002; Peters et al. 1998; Beamer and Henderson 1998) indicate a positive fish response to the introduction of complex woody debris structures (Figures 7 through 9). ELJs in the lower Elwha River have increased the abundance of juvenile salmonids, and almost all species of salmonids were more likely to occur at higher densities in channel segments with logjams than channels without logjams (Figure 7). Fish species richness was highest in primary and secondary habitat created by logjams such as pools and side channels (Figure 8). Pess et al. (2002) also documented a redistribution of adult chinook and adult salmonids in general around ELJs constructed in the North Fork Stillaguamish River in 1998, which was interpreted as a response to improved habitat quality within the treatment reach (Figure 9) (river mile [RM] 21.0 to RM 21.5). Constructed ELJs in the North Fork Stillaguamish have resulted in increased pool frequency, pool depth, and in-channel wood cover. Immediately after the ELJ construction, pool frequency in the treatment reach increased from one pool per kilometer to five pools per kilometer and remained at that level through 2004. Residual pool depth in the treatment reach also increased, from an average of 0.4 meters before ELJ construction to 1.5 meters after ELJ construction. After the ELJs construction, adult chinook salmon used the increase in pool availability and quality to disperse throughout the treatment reach instead of congregating in one pool as they did before the installation of the ELJs (Figure 9). Diurnal shifts in fish populations around logjams have been documented, with fish focusing in on the logjams for cover during the day (Figure 12) (Peters 2002).

In an analysis by Coe et al. (in press), they found that total invertebrate density in the ELJ treatment reach of the Lower Elwha River was significantly higher than the density in the reference reach. A similar trend was found in the Stillaguamish River, with higher invertebrate density in the ELJ treatment reach relative to the reference reach. There was no significant difference in the mean concentration of organic matter between the treatment and reference reaches on the Elwha River. However, in August, the concentration of organic matter in the treatment reach was the highest of any other month, and in the reference reach it was the lowest

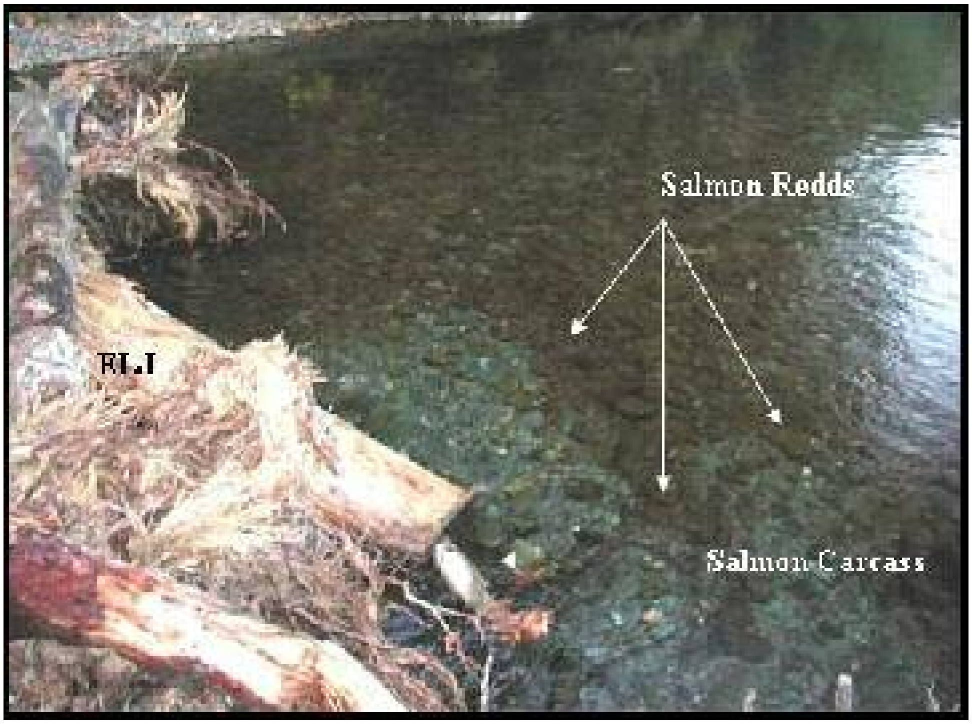


Photo by Tim Abbe (2001).

Figure 3. Chum salmon redds adjacent to ELJ in the Big Quilcene River, Jefferson County, Washington.

Photo by Roger Peters (2001).

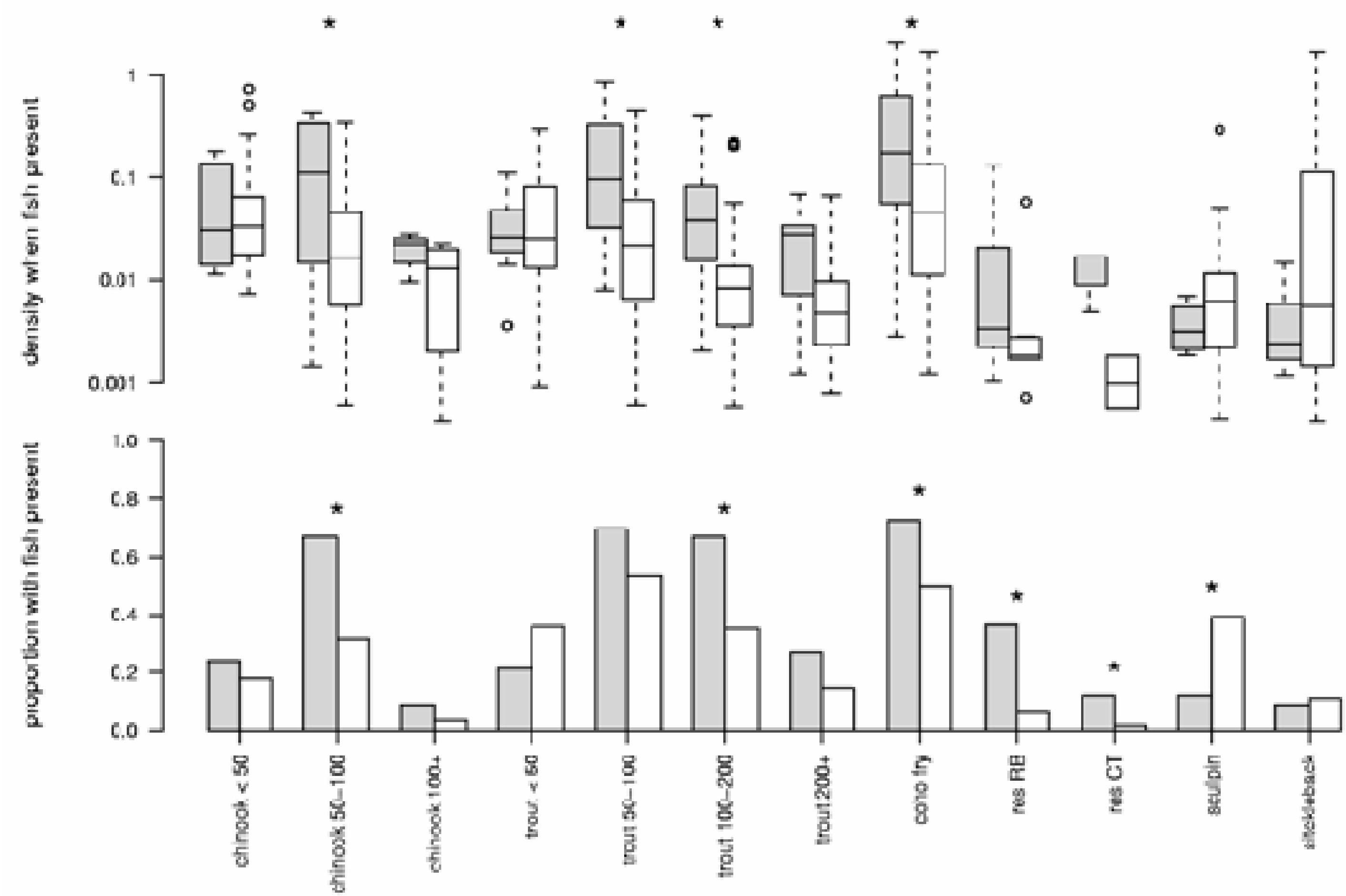
Figure 4. School of juvenile salmon in pool immediately upstream of ELJ in the lower Elwha River, Clallam County, Washington.

Photo by Michael McHenry (2001).

Figure 5. Collection of salmon carcasses and organic debris on ELJ in the lower Elwha River, Washington.

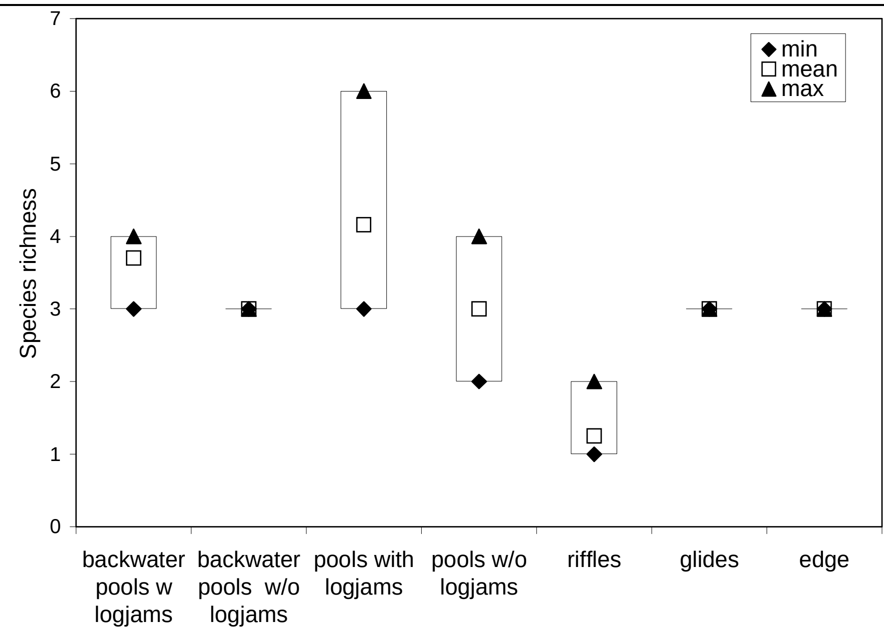
Photo by George Pess (2001).

Figure 6. Male and female chinook salmon beneath ELJ in the North Fork Stillaguamish River, Snohomish County, Washington.



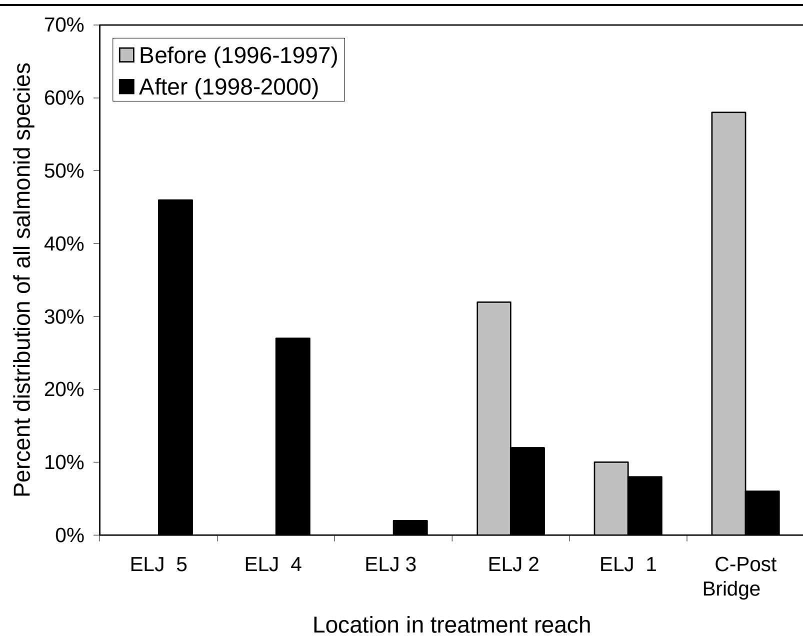
Source: Pess et al. (2002).

Figure 7. Fish densities in channel segments of the lower Elwha River with ELJs (shaded bars) and without ELJs (white bars) from 2000 to 2002, showing an increase in fish densities in segments with ELJs, with the exception of trout less than 50 millimeters long, sculpin, and stickleback.



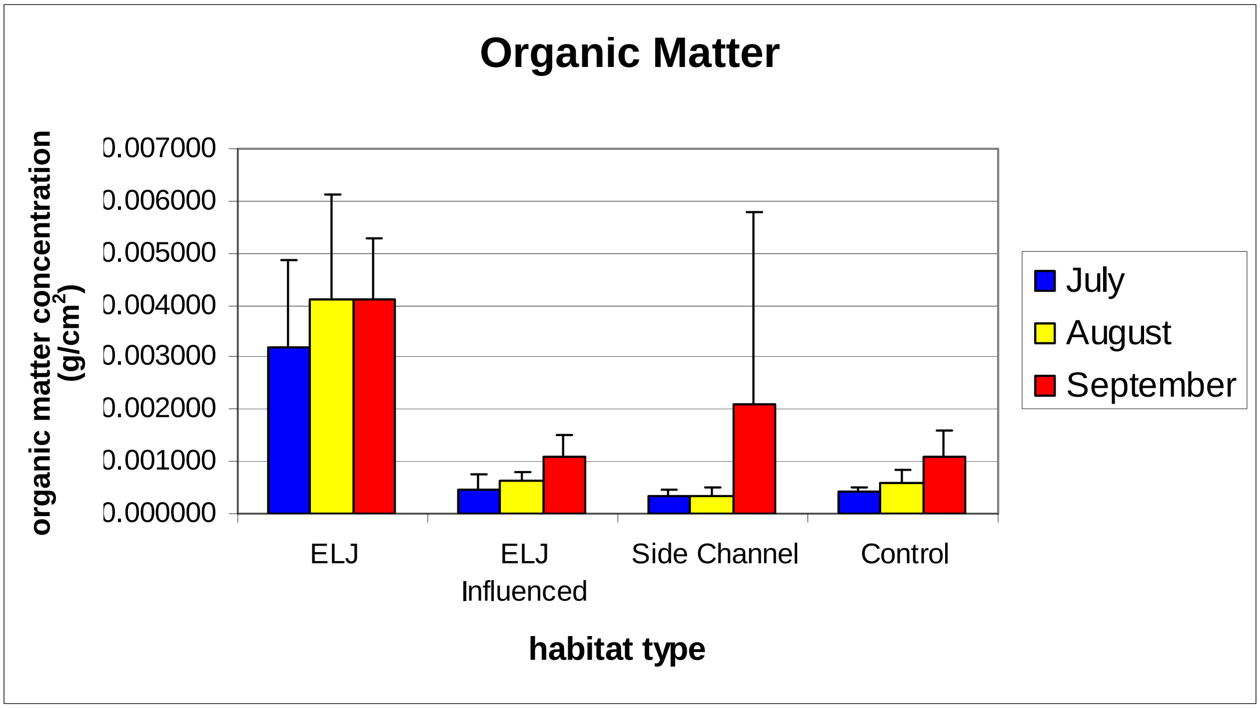
Source: Pess et al. (2002).

Figure 8. Fish species richness in the lower Elwha River in habitat units with and without logjams.



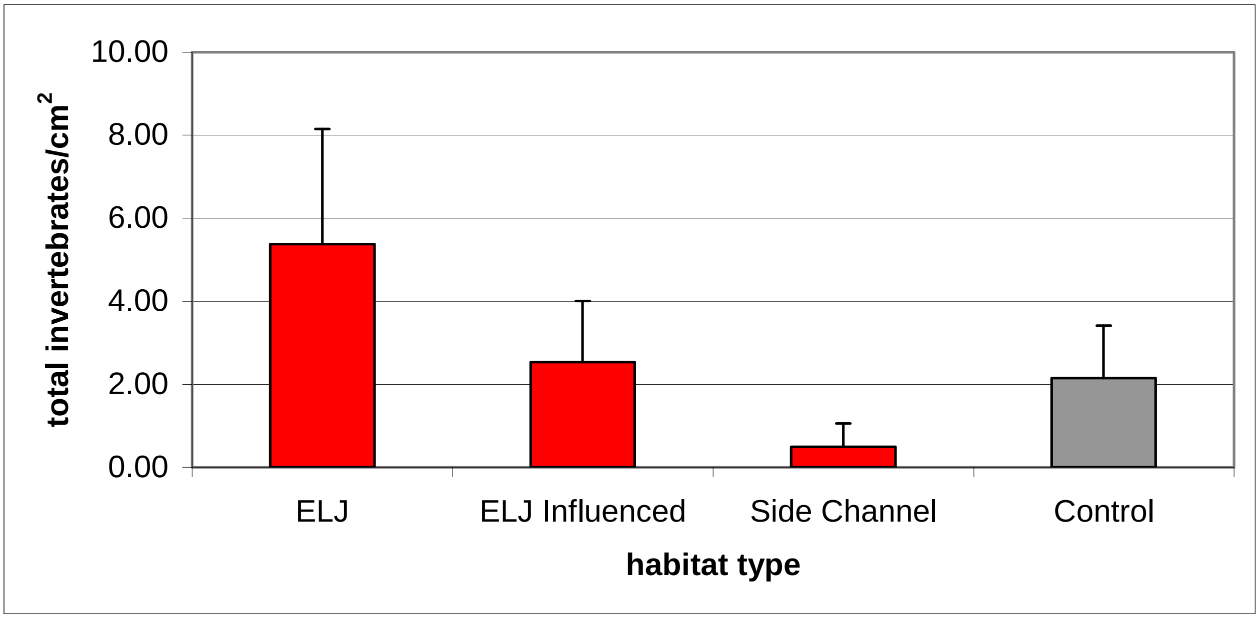
Source: Pess et al. (2002).

Figure 9. Redistribution of adult salmonids throughout the channel segment of the North Fork Stillaguamish River in which ELJs were constructed and away from a deep pool beneath the C-Post bridge, where poaching was a serious problem. The only preexisting natural logjam within the treatment reach was at ELJ 2; each of the other ELJs was constructed along alluvial banks with little or no large woody debris.



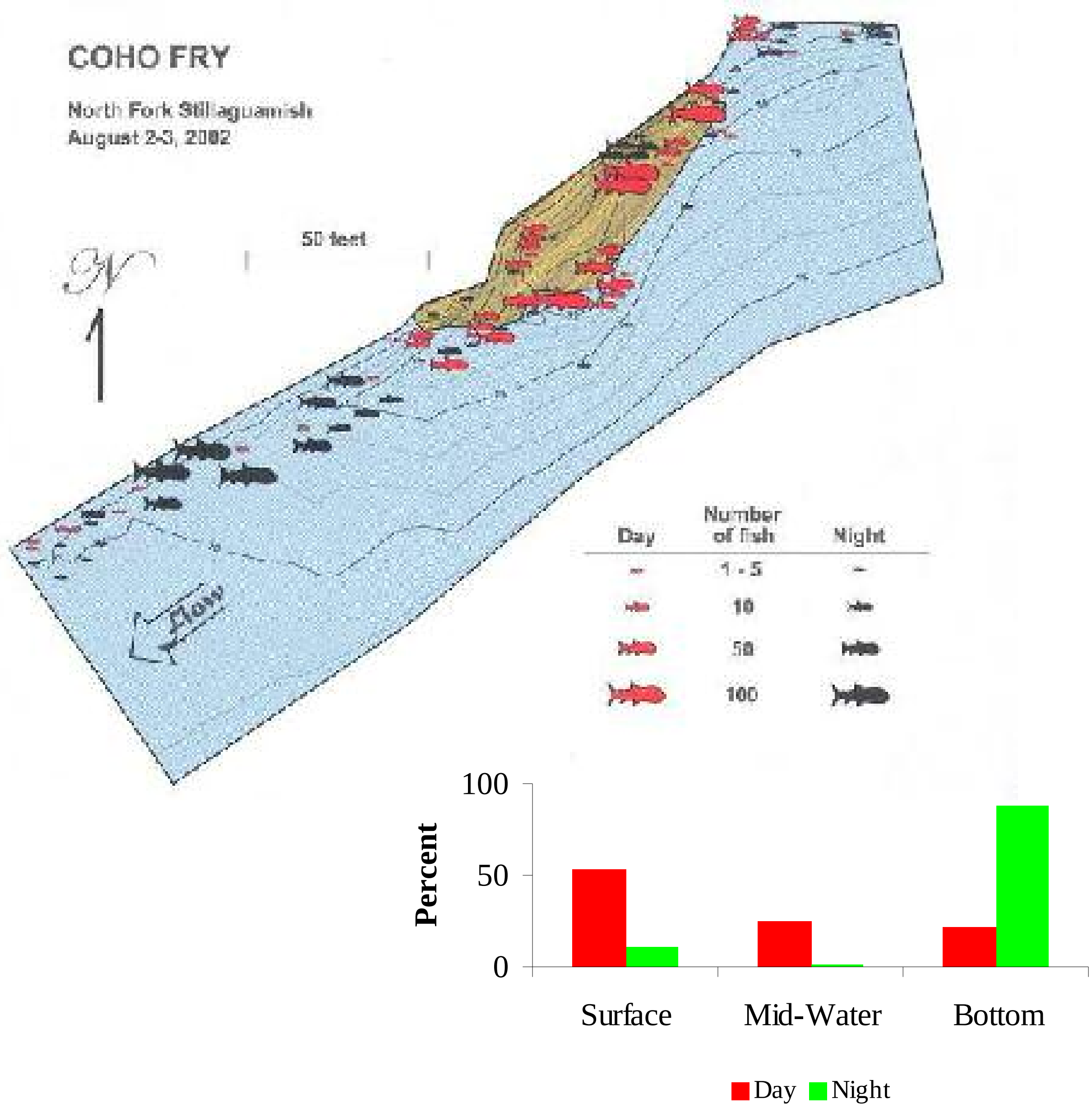
Source: Pess et al. (2003).

Figure 10. Periphyton biomass at ELJs compared to that in other habitat types.



Source: Pess et al. (2003).

Figure 11. Invertebrate densities at ELJs compared to those in other habitat types.



Source: Peters (2002).

Figure 12. Results of day and night snorkeling surveys in the North Fork Stillaguamish River in Snohomish County, Washington, indicating a distinct difference in diurnal use of different habitat types by coho fry.

of any other month. Coe et al. also found that whereas there was no significant difference between the two reaches in terms of mean chlorophyll concentration, there was a significant difference in chlorophyll between months within each reach. Chlorophyll concentration in the treatment reach was highest in September, and in the reference reach it was lowest in August. Coe et al concluded that complex wood structures such as ELJs can support high levels of productivity in large river systems by serving as both a physical refugium during high flows and an important substrate for primary and secondary producers.

Higher periphyton biomass and invertebrate densities in ELJ habitats suggest higher productivity by lower trophic levels in these habitats and potentially more food for salmonids (Figures 10 and 11) (Coe et al. in preparation). ELJs support a unique community of invertebrates (meiofauna) scarcely found in other habitats (Figure 11) (Coe et al. in preparation). Meiofauna have been shown to affect the processing of organic matter and nutrient dynamics in aquatic systems. Other biological monitoring is showing that wood debris accumulations directly benefit macroinvertebrates (Sudduth and Meyer 2006) and fish (Bond and Lake 2005).

ELJ technology can be used in the river systems in Scotland to address known needs related fisheries management. For example, Soulsby (2004) identified the following management strategies as key to improving fish habitat in rivers in Scotland:

- Restoration of spawning habitat
- Increasing fish cover
- Removal of artificial barriers to migration
- Bank stabilization
- Pool management
- Management of bank side vegetation
- Management of channel vegetation
- Construction of fishing platforms.

All these key management strategies can be addressed either directly or indirectly through the implementation of ELJ technology. ELJs are now widely accepted as a principal component of salmonid habitat restoration and have been correlated with increased salmonid density in fluvial systems.

One of the largest scale effects of logjams on habitat is the creation of multichannel anabranching systems that increase the total available habitat several times (i.e., channel length and number of pools). Examples of the formation and maintenance of habitat by ELJ analogs (natural logjams) can still be found in Europe. The Gearagh in Ireland, one of the last wooded, seminatural anastomosed postglacial alluvial forest systems in western Europe, is characterized by hundreds of small islands separated by interconnected channels of low slope. These include channels that cross islands at right angles to the main flow and blind anabranching channels. The islands are relatively stable and wooded, with evidence of division by channel erosion and growth by in-channel sedimentation. In the Gearagh, wood debris jams, tree root masses, and tree-throw pits play a key role in the partitioning of flow and cause variations in channel velocities and overbank velocity distribution (Harwood and Brown 1993). Natural logjams are integral to the creation and sustainment of anabranching channel systems such as that illustrated in Figure 13.

The decline in salmon populations in Scotland likely has other ecological consequences. For example, in addition to agricultural and industrial pollution and the loss of habitat due to river engineering, the decline of freshwater pearl mussels can be correlated with the decline of salmon and trout populations. Freshwater pearl mussels need healthy salmonid populations to complete their life cycle. Mussel larvae (glochidia) live as parasites in the gills of salmon and trout, and only larval mussels that find such a host will survive. As the populations of salmon and trout decline so does the population of freshwater pearl mussels. Hence, the introduction of large woody debris through the construction of ELJs results in cascading benefits for productive fluvial ecosystems.

Photo by Tim Abbe (2001).

Figure 13. Example of the branching Taiya River in southeastern Alaska, where natural logjams and riparian forests sustain the channel morphology. These systems are extremely productive with respect to the availability of diverse habitat used by salmonids.

Engineered Logjam Applications

During the last decade, several types of ELJs have been constructed in the Pacific Northwest of the United States, examples of which are included in Appendix A. These structures have been designed with the goal of emulating and enhancing natural riverine features, increasing habitat complexity and hydraulic diversity, modifying degraded channels, reducing ongoing erosion of river banks, and protecting infrastructure and human life. ELJ projects have benefits on multiple levels. For example, ELJs can be used to control channel grade and reverse channel incision that is threatening infrastructure such as pipelines. Additionally, by providing protection with the use of an ELJ rather than more traditional grade control measures, the potential deleterious effects of the traditional method are prevented.

River systems in Scotland experience similar issues to those found in the Pacific Northwest which would naturally lead to opportunities to take advantage of ELJ technology. ELJs can be classified into four broad functional categories analogous to naturally occurring logjams: grade control ELJs, habitat enhancement ELJs, bank protection ELJs, and bar apex ELJs. The type of ELJ selected for a particular project depends upon the goal of the design, local geomorphologic conditions, flow regime, habitat requirements, and available budget. Likely goals for ELJ projects in Scotland include habitat enhancement or creation, bank protection, infrastructure protection, flood protection, and maintenance of grade control of riverbeds. The lack of available wood in Scotland may necessitate modification of ELJ designs to maximize the use of local materials and rely less heavily on wood. The major ELJ archetypes that may be appropriate for use in the waterways of Scotland and have been designed and/or constructed in the Pacific Northwest are habitat enhancement ELJs, bank protection ELJs, bar apex ELJs, and grade control ELJs, which are described in the following subsections.

Habitat Enhancement ELJs

ELJs can be constructed specifically to enhance habitat and increase the hydraulic diversity of river and creek systems. As discussed above, increasing the wood in a river system provides additional cover and high-quality habitat for fish (Figure 14). Habitat enhancement ELJs can be designed with varying levels of complexity and can function over a wide range of flow conditions. Simple structures can be created by adding one or several pieces of wood to a system, with the expectation that the structure may be deformed during high flows and, therefore, may not be permanent. More complex and stable habitat enhancement ELJs can be designed to the desired level of stability, to withstand for example the 50-, 100-, or 200-year flood (or higher), with a proportionate increase in costs. ELJs can be used to provide local habitat with minor effects on the channel, or they can be used to significantly alter the river channel. For example, habitat enhancement ELJs can transform relatively simple homogenous channels into one or more channels with a greater density and diversity of habitat units (Figures 15 and 16).

Bank Protection ELJs

ELJs can be used as an alternative to traditional bank protection measures such as rock revetments, groins, spur dykes, or vanes. In the right situations, ELJs can protect roads and property in a manner that significantly improves aquatic and riparian habitat (Figure 17). The goal of bank protection ELJs is to protect a section of bank that may be vulnerable to erosion by defusing some of the energy of the river or deflecting flow away from an endangered bank. Bank protection ELJs can be placed intermittently as a series of flow deflectors or as a continuous revetment.

Bar Apex ELJs

Bar apex ELJs are intended to bifurcate flow to either side of the structure; therefore, they are typically constructed in the middle of a channel (Abbe and Montgomery 1996). These structures can be used to influence channel planform and alignment; diffuse energy; increase the quantity and quality of aquatic habitat by increasing channel length, depth, pool frequency, and cover; trap mobile woody debris (drift); and increase floodplain connectivity. Natural bar apex ELJs typically form when one or two key members or large trees with their rootwads facing upstream become embedded in the river and trap mobile large woody debris that is moving down the river (Figure 18). A bar apex ELJ looks almost exactly the same externally, with dozens or hundreds of “racked” logs but an engineered core that extends deep into the riverbed.

Over the last decade, bar apex ELJs have been successfully constructed in several rivers in Washington and Oregon. The habitat benefits of bar apex ELJs are enormous since the river interacts on all sides of the structure, typically resulting in the development of a crescent-shaped scour pool on the sides and upstream and the formation of a bar upstream and downstream of the ELJ. Sample engineering drawings of bar apex ELJs are provided in Appendix A (South Fork Nooksack River and White River projects). The effectiveness of bar apex ELJs at redirecting river flows can be seen in the aerial photos of the Hoh River project where the structures were intended to deflect river flow away from the highway, diffuse the river’s energy, and increase the amount and quality of aquatic and riparian habitat. The four ELJs in the Hoh River have successfully reduced the risk to U.S. Highway 101 by deflecting flow into a chute cutoff channel and diffusing the river’s energy before it reaches the highway while also increasing the number of pools and cover for fish (Figure 19).

Grade Control ELJs

Grade control ELJs are designed to arrest channel downcutting or incision by providing a grade control that retains sediment, lowers stream energy, and increases water elevations to reconnect floodplain habitat and diffuse downstream flood peaks. Grade control ELJs also serve to protect infrastructure that is exposed by channel incision and to stabilize over-steepened banks. Unlike traditional weirs or grade control structures, a grade control ELJ is a complex broad-crested

Photo by Tim Abbe (2000).

Figure 14. Example of complex cover and diverse hydraulic and substrate conditions created by natural wood debris accumulation in the South Fork Hoh River, Jefferson County, Washington (flow is from right to left).

Photo by Mike McHenry.

Photo by Tim Abbe.

Figure 15. Bar apex ELJ in the east reach of the lower Elwha River, Clallam County, Washington, looking downstream: (a) preexisting conditions before construction in 2002 and (b) 1 year after construction in 2003, showing change in channel segment from a simple plane-bed to pool-riffle morphology and increase in number of habitat units from one to five.

Photo by Mike McHenry.

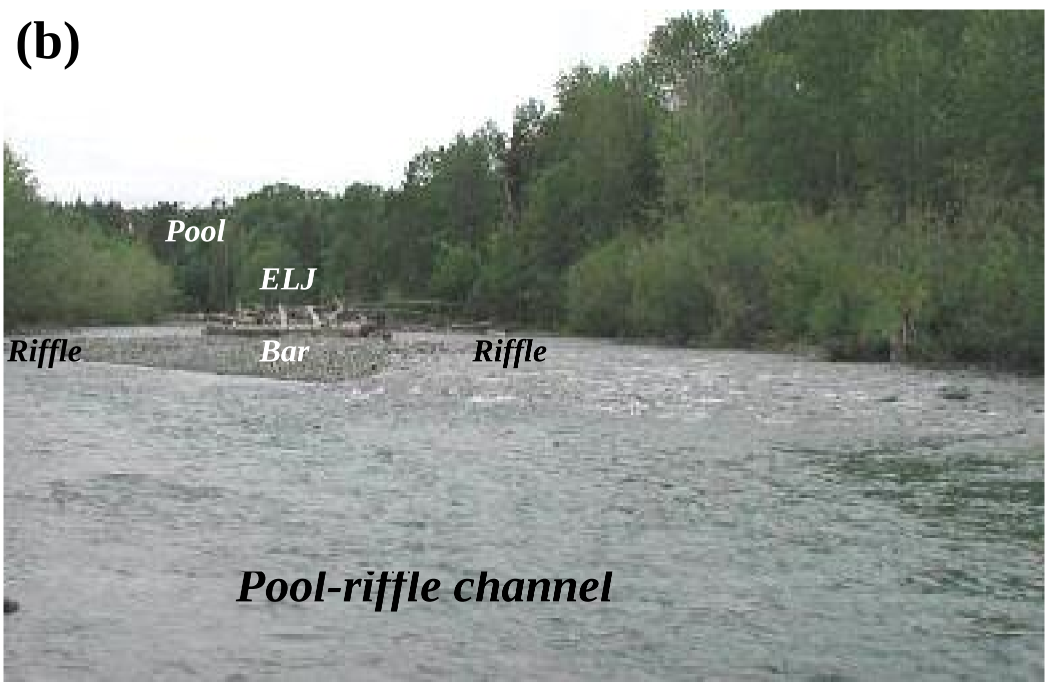


Photo by Tim Abbe.

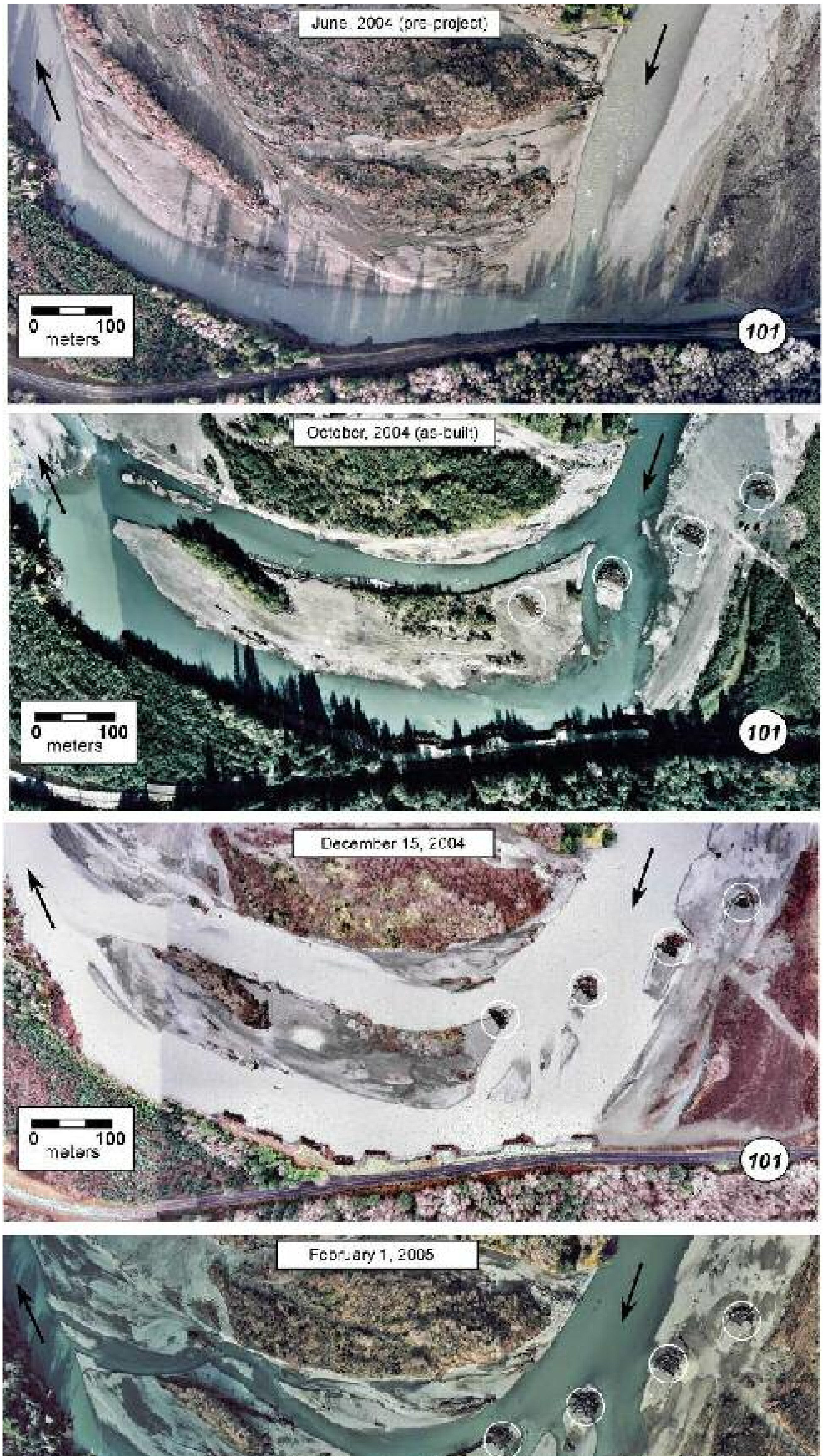
Figure 16. Same channel segment of lower Elwha River looking upstream: (a) before construction of bar apex logjam in 2002 and (b) 2 years later in 2004, showing increased channel complexity and diversified habitat within the reach after ELJ construction.

Photo by Tim Abbe (1999).

Figure 17. Example of bank protection ELJs along the Cispus River, Lewis County, Washington, showing as-built construction along Forest Road 23 in Gifford Pinchot National Forest, September 1999 (flow is from lower left to upper right).

Figure 18a. Example of natural bar apex ELJ bifurcating flow in the Cispus River, Lewis County, Washington, November 2004.

Figure 18b. Example of bar apex ELJ constructed in September 2004 in the Hoh River, Jefferson County, Washington, showing conditions in March 2005 after two peak flows of approximately 850 centimeters.



Photos courtesy of Washington State Department of Transportation.

Figure 19. Channel changes in response to construction of six bank and four bar apex ELJs (circled)in the Hoh River in 2004. Bar apex ELJs (circled) were constructed upstream of threatened highway to deflect flow through chute cutoff channel and diffuse flow in main channel. Bank ELJs were constructed to create "hardened" riparian buffer along highway.

structure that dissipates energy more gradually and maintains low-flow channels for fish passage (Figures 20 and 21). Similar to traditional grade control structures, these ELJs result in upstream sedimentation and aggradation of the streambed and downstream scour pools (Figure 22). Where natural grade control has been removed, channels become simplified and degraded (Figure 23). As in the case of all grade control structures, the ELJ structures should extend into the adjacent banks to maintain the grade even if the channel cuts around the structure, or they should include components to prevent lateral stream migration around the structure. Examples of grade control ELJs are included in Appendix A (Bronson Creek project). In unconfined systems with floodplains and side channels, these ELJ structures can be used not only to significantly increase the quantity and quality of aquatic habitat (e.g., inundation frequency of side channels) but also to diffuse and slow flood peaks by increasing the frequency of overbank flow events.

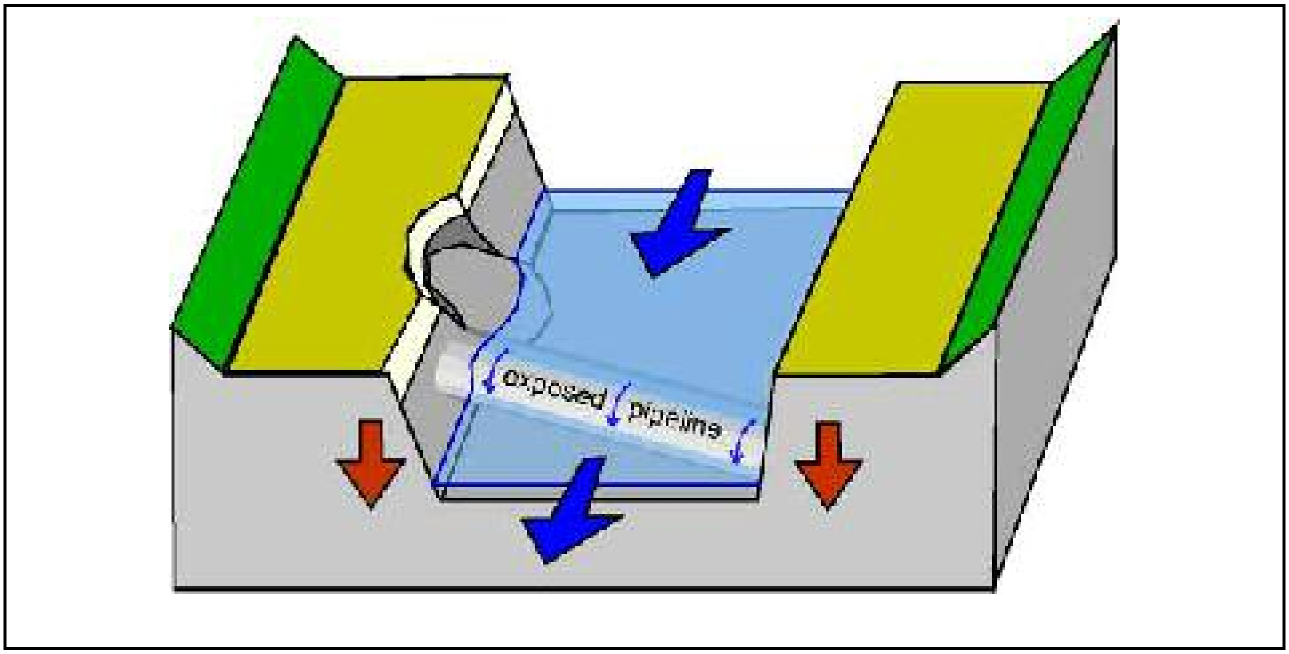


Figure 20. Incised channels result in the loss of ecological value, amplify downstream flood impacts, and can threaten infrastructure such as buried pipes, bridge piers and abutments, and road embankments.

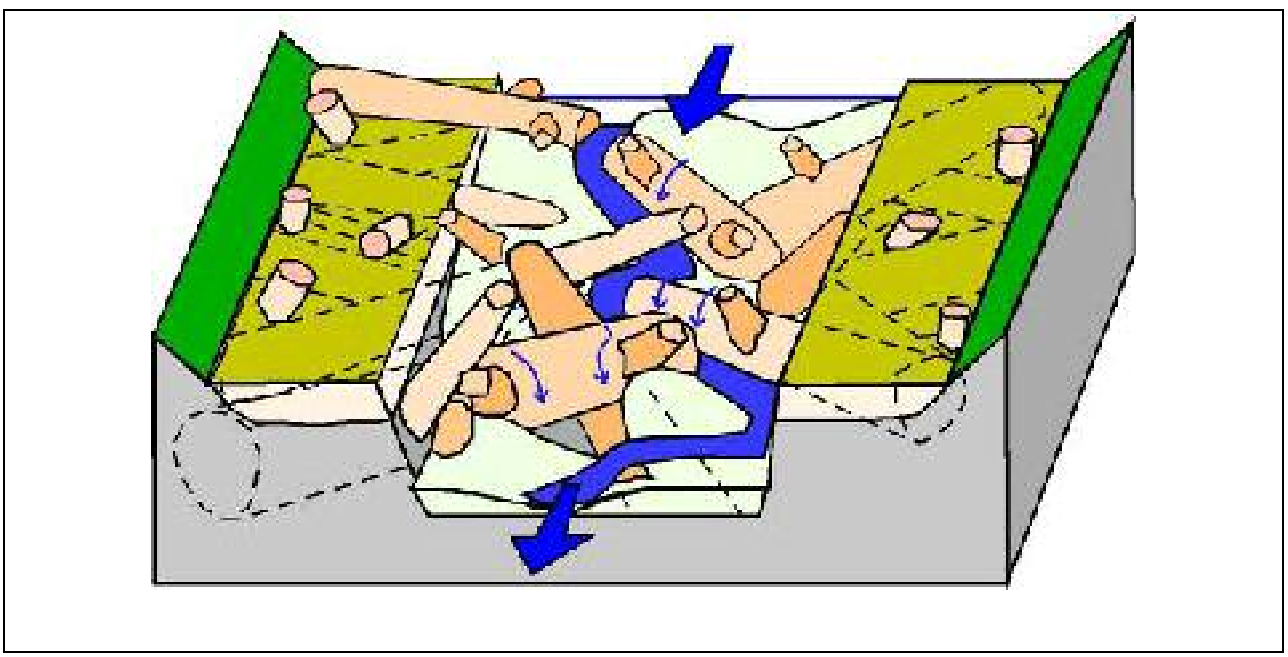


Figure 21. Treatment of incised channels with complex wood grade control structures can restore aquatic habitat, reconnect floodplains, diffuse flood waves, and protect infrastructure.

Photos by Tim Abbe (2001).

Figure 22. Examples of natural logjam structures controlling stream grade and increasing the quantity and quality of salmon habitat: (a) Sygitowicz Creek, Whatcom County, Washington, and (b) upper Rickreall Creek, Lane County, Oregon.

Photos by Tim Abbe (2001).

Figure 23. Examples of simplified creeks due to channelization and incision: (a) Sygitowicz Creek, Whatcom County, Washington, and (b) Rickreall Creek, Lane County, Oregon.

Design Process for Engineered Logjams

The design process used for ELJ structures follows a formal civil engineering design approach similar to that used in traditional infrastructure development. The design process includes a formal quality assurance and quality control program, a reach analysis, data collection and verification, the establishment of a design basis, modeling, iterative design development with risk assessment, public relations efforts and education, regulatory approval, and contract package development.

A reach analysis provides the necessary background information on historic and current conditions including channel geometry, substrate, hydrology, hydraulics, wood loading, and disturbance processes. Risk assessments can be relatively brief for projects where there are no risks to property, infrastructure, or life and can be critical to projects where there are potential risks.

A risk assessment includes all aspects of the project to evaluate the risks associated with achieving goals within the constraints of the project (Figure 24). Initially, the results of the reach analysis (including a geomorphic analysis and a review of field data) serve as the platform for determining the risk associated with the preliminary conceptual plan. The description of historical channel dynamics and flooding formulated during the reach analysis is essential for documenting preexisting conditions and risks at the project site if no ELJs were constructed.

If the results of the risk assessment indicate that the preliminary conceptual plan falls within an acceptable range of risk and meets the goals of the project, the preliminary conceptual plan then undergoes a hydraulic and scour analysis. Hydraulic modeling is done to evaluate flow regimes under current conditions and under potential build-out scenarios. The modeling and scour analysis are an iterative process that allow for changes in the number and location of proposed structures. The designs are modified to achieve the goals of the project and to minimize the risk associated with the designs. When the results of these analytical tools indicate that the proposed design will achieve the goals of the project within the acceptable risk level, the client prepares preliminary design plans for review.

The reach analysis, which determines the physical boundary conditions of the river and the relationship of the boundary conditions to fluvial processes and habitat, typically serves as the basis of the ELJ design. A reach analysis must be performed at spatial and temporal scales that are adequate for describing these relationships. Conceptual design alternatives are prepared, and a feasibility analysis is performed to compare the habitat benefits, cost, and initial risk associated with achieving the performance objectives of the project with each of the design alternatives.

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, channel dynamics, and habitat. With this understanding, ELJs can be designed and placed in such a way that they achieve the desired goals, accommodate natural processes, and even diminish risks to infrastructure and property. In a reach analysis, areas of physical constraint are identified and demarcated. These areas are then incorporated into the design alternatives; for example, differentiating areas within the channel migration zone where the main stem channel can freely move, areas in the channel migration zone where only secondary channels are acceptable, areas that can tolerate inundation but no channels, and areas in which no erosion or inundation is acceptable.

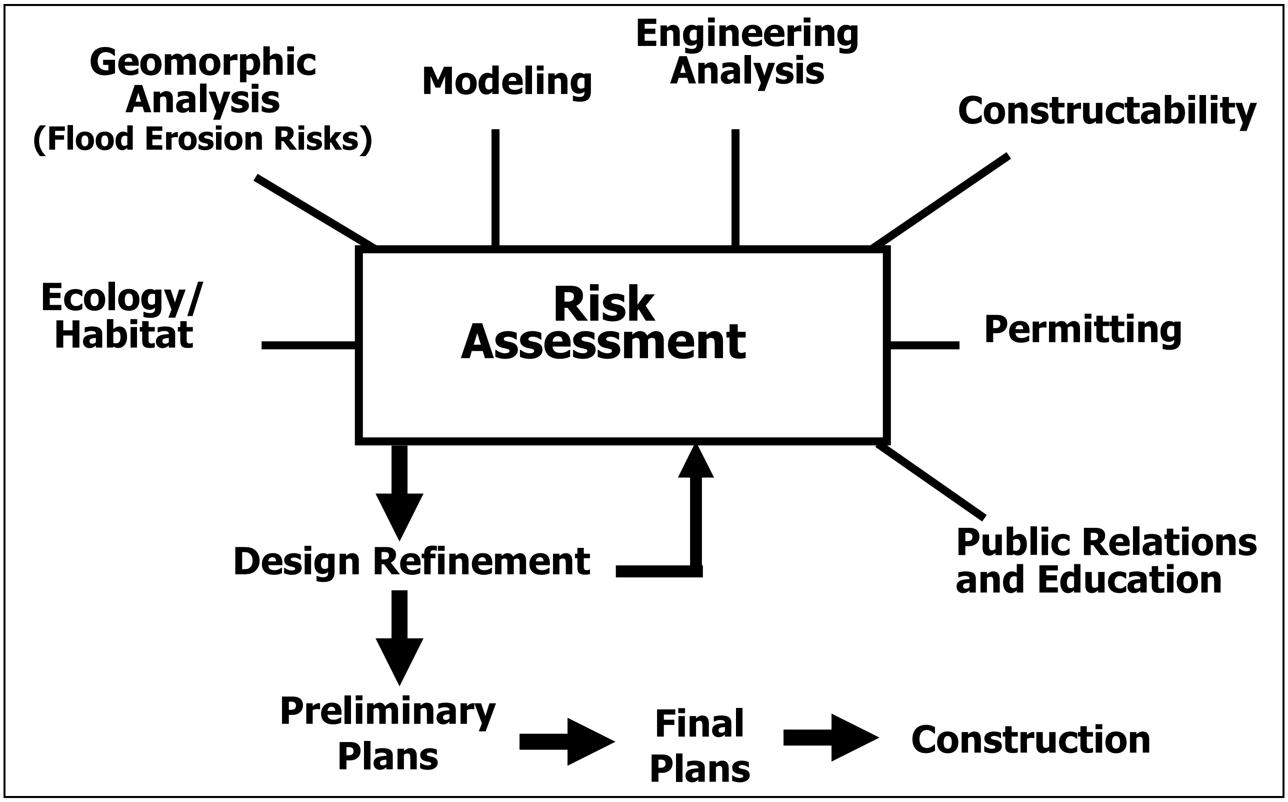


Figure 24. Iterative ELJ design process.

A reach analysis links project site conditions to disturbance patterns in the watershed. For example, industrial forestry can significantly increase sediment delivery to the river system (Kelsey 1980; Stott 1997a, 1997b), which in turn can result in channel aggradation (Stover and Montgomery 2001) and textural fining (Buffington and Montgomery 1999b). Other reach-based factors influencing design could be changes in base level such as isostatic rebound, flow regulation, urbanization or upstream impoundment. 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 (Brooks and Brierly 1997). The most dramatic increases in the frequency and magnitude of peak flows are associated with rapidly urbanizing watersheds (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 the design strategies.

Modeling

A hydraulic analysis is conducted to assess the design components of the proposed project. The hydraulic analysis includes the development of a hydraulic model of the project reach to provide an understanding of how the proposed ELJ structures will affect velocities, water surface elevations, basal shear stress, and potential bed deformation along the project reach. In cases of low risk and limited budget, analytical hydraulic calculations can be peformed in lieu of more complex numerical modeling.

High-resolution topographic mapping is desirable to assess the hydraulic conditions at a site and establish the channel geometry and boundary conditions for numerical modeling. One-dimensional modeling programs, such as the U.S. Army Corps of Engineers HEC-RAS and geoRAS, are typically used. However, more complex two- and three-dimensional hydrodynamic models, such as the Finite Element Surface Water Modeling System (FESWMS-2DH), are available, and their use is contingent upon the scale, cost, and factor of safety required for the project. HEC-geoRAS is typically used in a geographic information system (GIS) environment to cut cross-sections from digital maps, which are then “fitted” with surveyed sections of a main channel. These data are used to develop a model of existing conditions that is suitable for establishing baseline conditions for a range of discharges. The model typically includes the project reach and extends downstream to assess downgradient impacts and upstream as necessary to predict any backwater impacts. The model is calibrated to any available high water mark data from historical events or, at the very least, adjusted to replicate reasonable results from historical recollections. Modeling usually assumes a set of boundary conditions (channel planform, cross-section geometry, and grade) and does not consider how hydraulics and water elevations would change under different boundary conditions. Therefore, careful professional judgment should be used to evaluate how historical or future differences in channel planform, cross-section geometry, and grade would influence the modeling results.

During design development, the model of the existing reach is modified to simulate the proposed ELJ layout and to determine any hydraulic impacts due to the design. Solid blockages (blocked obstructions within HEC-RAS), a standard assumption, are added to the model to represent each ELJ structure, with additional cross-sections added as necessary. The results of the modeling runs predict immediate hydraulic impacts due to the proposed ELJ design. These results are used to fine-tune the location and orientation of the ELJ structures. On the basis of the risk assessment input regarding longer term changes in channel morphology, sediment transport, morphology, and the ELJ structures, particularly the effect of fluctuating sizes (blockage coefficients) due to accumulation of drift, the model is also modified to approximate future changes in channel planform that are likely to develop and to assess the project performance under a range of representative conditions.

Two-dimensional hydrodynamic models such as FESWMS-2DH facilitate better predictions for manipulating flow paths and local hydraulics that are responsible for bank erosion. Two-dimensional models serve as a predictive tool for evaluating spatial variations in flow conditions and how flow may respond to the placement of flow obstructions such as ELJs (Figure 25).

Natural Logjam Architectures

Distinct types of logjams, or instream woody debris accumulations, are found in different parts of a channel network (Abbe et al. 1993; Wallerstein et al. 1997; Abbe and Montgomery 2003). Using observations from the Queets River basin on the Olympic Peninsula in Washington, distinct types of logjams have been classified according to the presence or absence of key members, source and recruitment mechanism of the key members, logjam architecture (i.e., log arrangement), geomorphic effects of the logjam, and patterns of vegetation on or adjacent to the logjam (Abbe et al. 1993). Six of these logjam types provide naturally occurring templates for ELJs intended for grade control and flow manipulation (Figure 26). Logjam types primarily applicable for grade control include log steps and valley jams; types more applicable for flow manipulation include flow deflection, bankfull bench, bar apex, and meander jams.

Design Development

After a thorough understanding of the project reach and watershed, a clear definition of project opportunities and constraints, and the selection of appropriate natural analogs, the engineering design can proceed (Figure 27). Design development begins by refining the conceptual plan on the basis of the performance goals of the project. The results of the initial geomorphic analysis, risk assessment, hydraulic modeling, and scour analysis are incorporated into the preliminary design plans to refine the number of structures, structure archetypes, orientation, and predicted channel response. Design development typically follows a conceptual (10 to 30 percent), 60 percent, and final design submittal and review process. Final design includes the preparation of a basis of design report, contract design plans, specifications, and an engineering estimate of probable cost.

This approach provides a draft design package (60 percent design) for permit acquisition and a final design package (100 percent design) for construction. The 60 percent draft design uses hydraulic modeling to provide for adjustments of the layout and orientation of the ELJ structures as required. Output from the hydraulic model is used to design the ELJ structures and to provide hydraulic parameters included in the basis of design report. The basis of design report is developed from the conclusions of technical memorandums that analyze the results of the modeling, scour analysis, and risk assessments. The report includes detailed calculations and a structural stability (force balance) analysis of the ELJ structures.

The final design plans include plans for temporary erosion and sedimentation control, construction sequencing, traffic access, ELJ locations, grading for the ELJ structures, and planting, as well as detailed cross-sections of the ELJ structures.

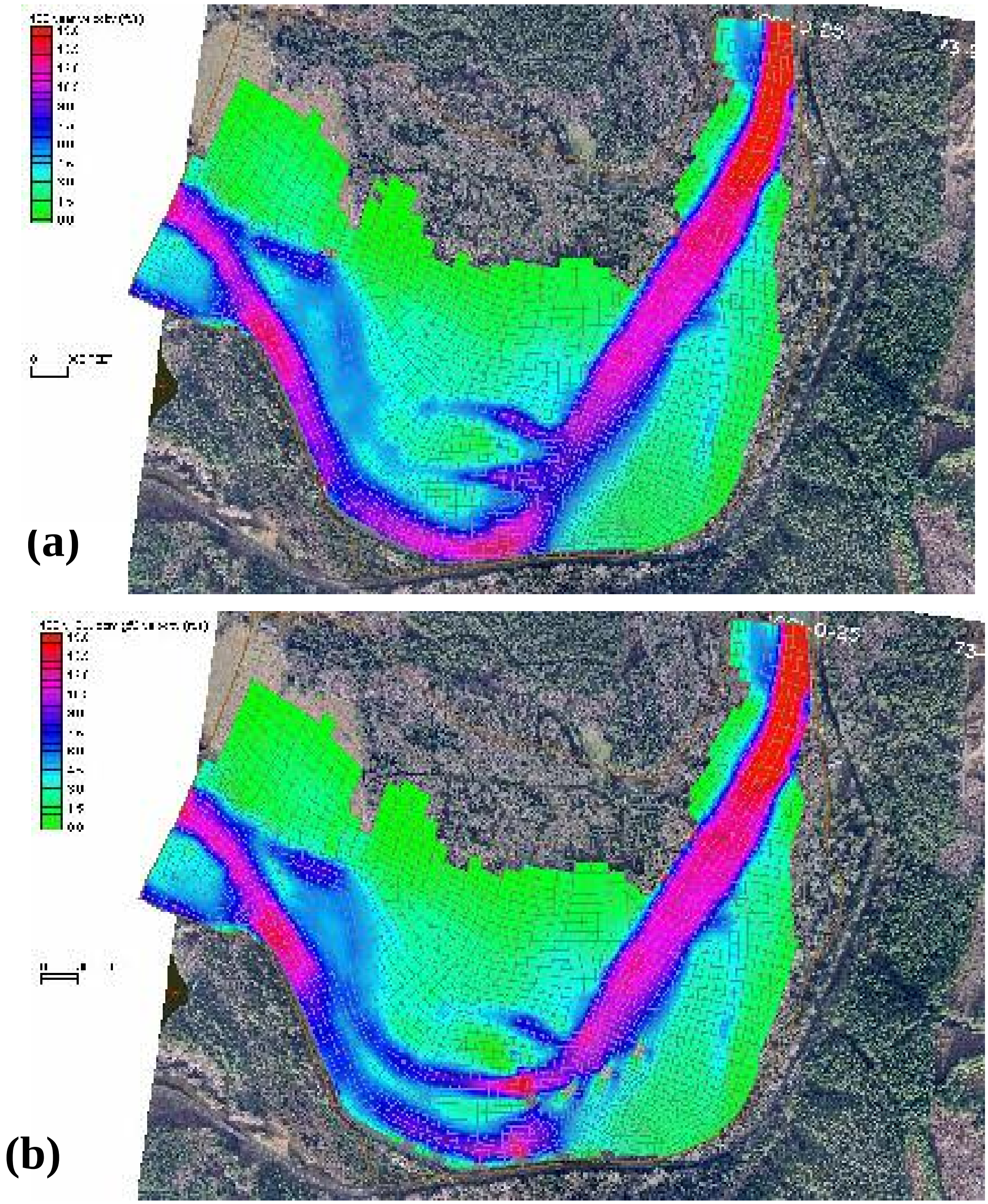
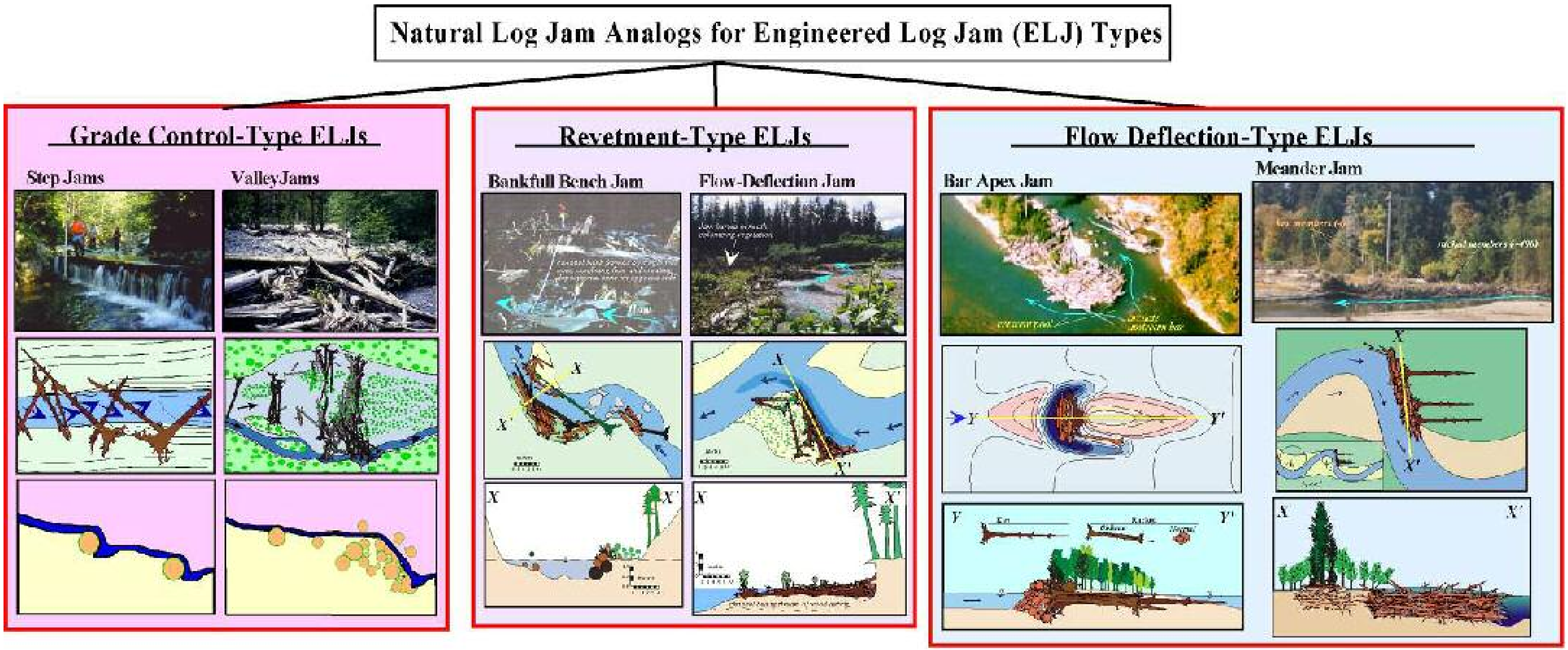


Figure 25. Example output of two-dimensional hydrodynamic modeling (FESWM 2D) performed for Hoh River ELJ project: (a) existing conditions before construction and (b) predicted changes after ELJ construction, showing lower velocities along road and increased complexity of river channel.



Sources: Abbe and Montgomery (2003); Abbe et al. (2003b).

Figure 26. Some of the basic natural logjam analogs for ELJs.

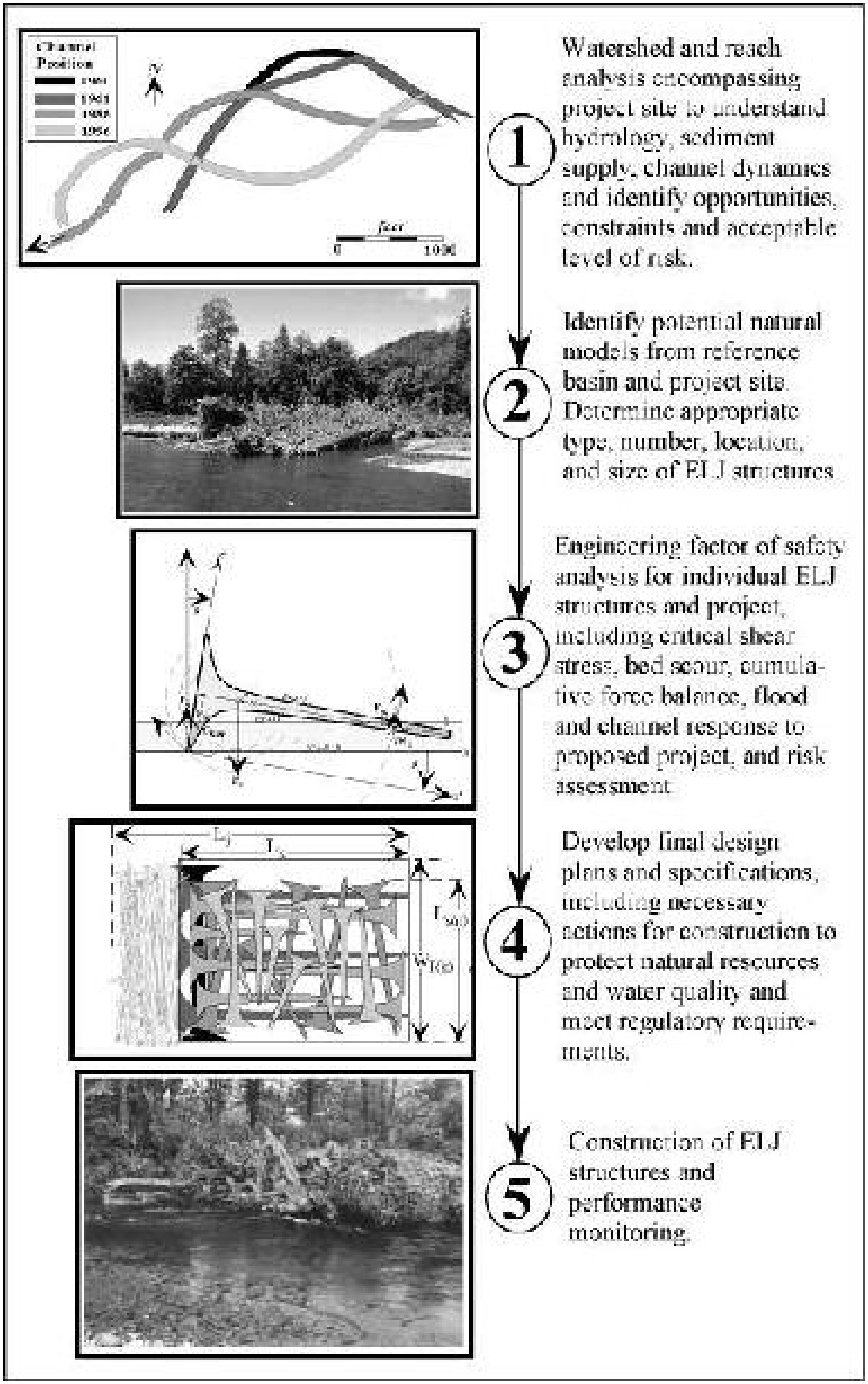


Figure 27. Basic ELJ design process.

Scour Analysis

Channel bed scour is probably the most common failure mechanism of instream structures, including ELJs. Monitoring inspections of constructed ELJs have revealed that scour has been responsible for the most significant structural damage and the greatest threat to the longevity of structures. A scour analysis is conducted to assess the long-term stability of proposed ELJ structures that will be placed within a channel or floodplain. A scour analysis includes the following variables: channel geometry, hydraulics, substrate grain size distribution, discharge, and ELJ structure size (typically as a percentage of channel cross-sectional area). The scour analysis is used to estimate contraction scour (bank and midchannel structures), abutment scour (bank structures), and local pier scour (midchannel structures) for proposed in-channel structures. Several different equations can be used to estimate scour under a range of parameters. In addition to the analytical analysis, an empirical analysis is also performed to determine the probable, expected and observed scour depths for proposed structures up to the design flood event (e.g., 100-year flood).

Structural Design

ELJ structures are designed to be stable against lateral velocity (drag) and vertical lift and buoyancy forces. The parameters used as input to the calculations of these forces include coefficients of drag and lift, cross-sectional area of the part of the structure projection that is perpendicular to flow, volume of wood material in the structures, density of water, specific weight of water, specific gravity of wood, flow velocities as noted above, and water surface elevations. ELJ structures are used in a variety of situations and can be subjected to a wide range of loading. The structures are engineered to allow changing load paths by the strategic orientation and interlacing of individual structure members. One way to increase the structural stability and the factor of safety is to incorporate inclined or vertical timber or steel piles.

For example, piling is designed for bending loads rather than axial loading. The loads are treated as a point load acting at the midpoint of the pile, and the piles are treated as cantilevered beams. The pile loading consists of static head, velocity head, and drag load. The angle at which forces from the river would act on the logjam is based on historical channel planforms and the channel migration zone. The worst-case flow, perpendicular flow, is used in the load calculations. The calculations are based on two separate conditions: (1) maximum probable scour with the pile exposed and (2) predicted scour with one-third of the pile exposed.

- **Static head.** Static head is used in the calculations, assuming water is backed up behind the entire height of the structure, which would cause the largest load (height of the ELJ compared to water elevations during the design flood event, e.g., 100-year flood).

- **Velocity head.** Velocity head is based on hydraulic modeling, typically using flows from the 25- and 100-year flood events.

- **Drag load.** Drag load is induced by flowing water that hits the upstream face of the ELJ.

- **Lift.** Lift consists of upward forces to consider for individual logs that will experience overtopping flow.

In actual ELJ design, each element of the structure, such as key, stacked, and racked logs, are individually and cumulatively analyzed with respect to failure mode.

Plan Development

Plan development occurs throughout the design process. Design plans are intended to be stand-alone documents, allowing contractors to determine means and methods of construction directly from the plans. The final plans are used to prepare a contract package for bidding. The plans clearly identify temporary as well as permanent structures and controls. Temporary controls such as dewatering, shoring, site access, and erosion and sedimentation control are included and sequenced to ensure compliance with permit stipulations and regulations and to ensure quality in construction. Detailed plans addressing each construction phase and structure construction sequence are essential in ensuring the designed structural stability and factor of safety.

Contract Package Development

After a final review of the 100 percent design package, contract plans, specifications, and cost estimates are prepared. The contract documents (plans and specifications) are an important part of the design process to ensure that the client receives a fair and accurate bid from the contractor. Well-written and detailed specifications can protect the client financially and ensure a high-quality product. They also establish a level playing field for the contractors who will bid on a project and, just as important, for those who will select the contractor on the basis of the bids.

As part of the contract package, bid tab estimates are prepared for bid comparison. The cost estimates should be prepared from industry estimating guides and vendor quotes, with the use of professional judgment. A key element in the success of ELJ projects is periodic technical assistance during construction so that the intent of the design is achieved. Minor changes due to field conditions occur during most river restoration projects, and the ELJ structures may need to be slightly modified. This is especially important when there are multiple ELJs that not only perform specific functions but also are linked with respect to the cumulative function of all the ELJs in the project reach.

Construction Sequencing and Oversight

The construction sequencing should be clearly laid out in the final plan set, detailing site access, staging, dewatering, and order in which individual structures will be constructed. For projects in which the wood debris may not meet the specified dimensions and quantities or projects in which special circumstances arise, design decisions will need to be made during construction. A basic construction sequence for a large flow deflection ELJ is presented in Figure 28. Appendix B presents topics to consider in ELJ demonstration projects.

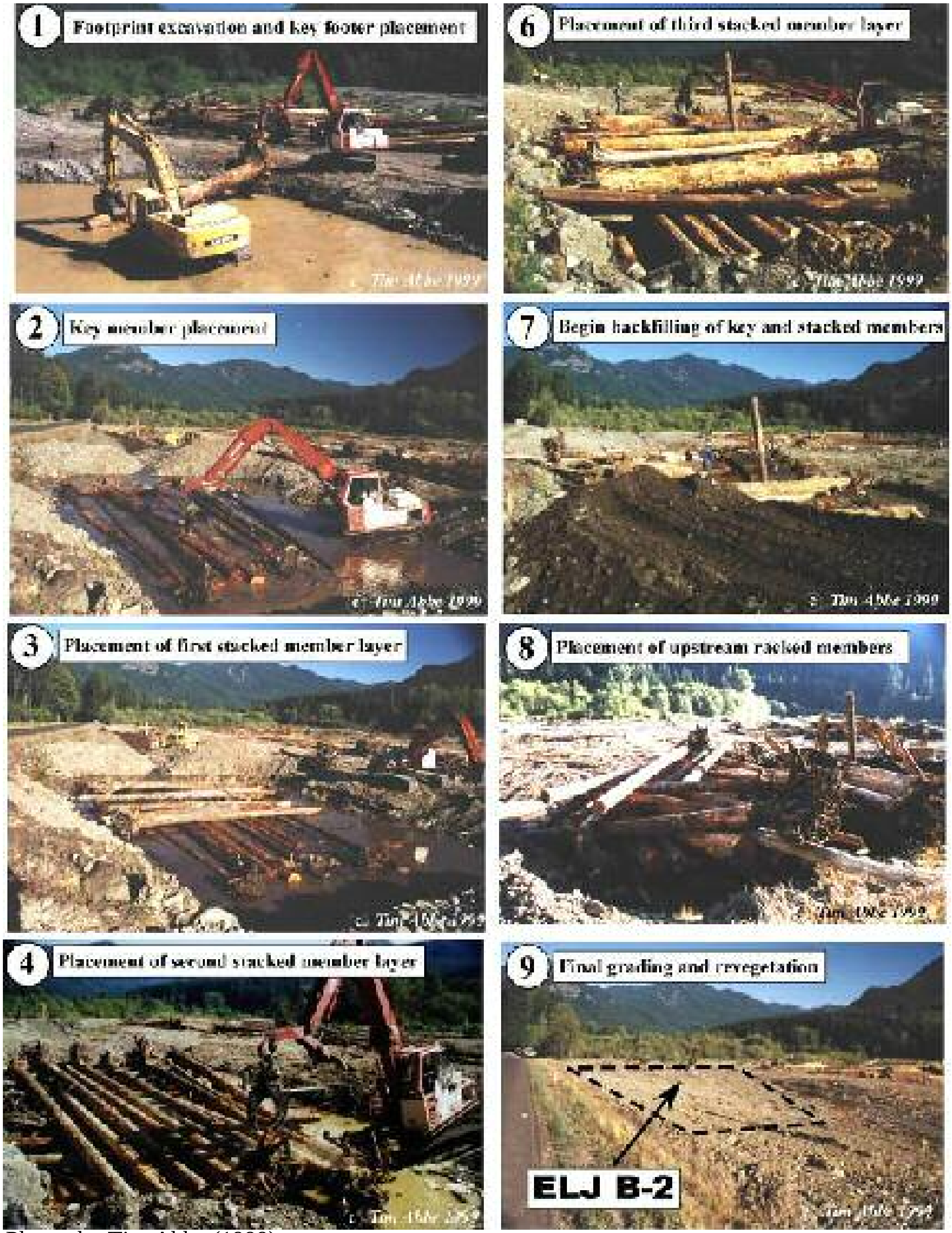
Summary of Recommended ELJ Protocol

1. **Reach analysis—**attempt to answer questions such as the following. Why is the road or infrastructure at risk? What are the processes causing the damage? Are things getting worse or better? The analysis should document historical changes in rivers, sediment transport and deposition, bank materials and stability, hydrology and hydraulics, ecologic and biological conditions and opportunities, riparian conditions, and infrastructure constraints. The reach analysis should provide sufficient information to make predictions about the river's future under different scenarios so that sustainable logjam designs can be developed that emulate natural conditions and processes.

2. **Feasibility study—**evaluate actions that should be considered and assess solutions that are realistic, from a cost and constructability perspective. The feasibility study should help answer important questions such as the following. Can the threatened infrastructure be moved out of harm's way? How much of the channel migration zone can be preserved? Can habitat be enhanced as part of solving traditional problems, such as bank protection and flood control? Are local construction materials available? Will partnerships with other stakeholders benefit the project?

3. **Risk assessment—**evaluate and predict how the project will perform under both normal and adverse conditions and evaluate the accuracy of the scientific data to be used in the project design. The risk assessment should also determine the potential effects on changes in the river channel (including flood levels, scour, sedimentation, and bank erosion), and evaluates potential short- and long-term impacts on humans, infrastructure, and natural habitat. The assessment should include appropriate public outreach and involvement, during which project stakeholders and affected groups and individuals are educated about the project and provide project managers and experts with feedback, insights, and ideas.

4. **Design—**build in factors of safety that are equivalent to those applied to any other civil engineering project. In doing this, engineers should determine the type, size, location, and strength of the structures needed to withstand maximum forces and achieve the highest level of public protection.



Photos by Tim Abbe (1999).

Figure 28. Construction sequence for one of a series of four flow deflection ELJs in the Cispus River, Lewis County, Washington.

5. **Construction—**prepare the site and delineate the specific construction sequence, including site access, flow diversions and dewatering, major excavation and grading, careful placement of structural elements, fish removal and protection, water quality and erosion control, and revegetation. Construction of ELJs can range from relatively simple placement of large woody debris directly into a stream or river to more complex structures, like the Hoh River logjams. The construction can be accomplished in many different ways, which greatly affect the cost, regulatory compliance, and final outcome.

6. **Monitoring and maintenance—**provide periodic monitoring and maintenance of the structures. Monitoring should include an evaluation of structural integrity, scour, drift accumulation, and their ecological effects, such as surveys of fish use similar to those conducted by the U.S. Fish and Wildlife Service. Maintenance can include culling, repairing any structural damage, and revegetating, as needed. Too often, this phase is underemphasized or ignored.

Example Engineered Logjam Projects

Descriptions of several ELJ projects are presented to illustrate different types of applications and how they have performed. Examples range from grade control structures to halt channel incision to large flow deflection structures. All of the examples involve significant environmental improvements to the treatment sites. Additional examples of ELJ plans are presented in Appendix A.

Rickreall Creek, Dallas, Oregon

Rickreall Creek in Dallas, Oregon (United States), is an urban creek that has experienced significant historical impacts such as splash damming (the transport of logs through the creek by dam-break floods), watershed deforestation, construction of a water supply reservoir, and channelization. Much of the creek through Dallas has been transformed from a gravel-bedded pool-riffle into an incised bedrock channel with very little complexity. A habitat restoration project was implemented in 2003 to enhance aquatic habitat and prevent further channel incision, stabilize adjacent over-steepened banks, and trap bedload gravels and large woody debris. The project included significant grading of the left bank to improve flood conveyance and stabilize the bank to prevent erosion. Due to limitations on project cost and the high factor of safety required by the city, grade control structures composed of concrete were constructed to simulate log steps (Figures 29 through 32). The cores of the two grade control structures, which were set approximately 70 meters apart, consisted of cast-in-place concrete logs with a low-flow channel between them (Figures 29 and 31). Real logs were integrated with the concrete logs, placed adjacent to them, and used to create additional bank protection structures. The project also used 1-meter basalt boulders to provide scour protection, ballast, and additional channel complexity.

During the two wet seasons since project construction, the conditions that have been observed include recruitment of woody debris, increased flow depth, reduced velocity, and more diverse flow patterns, providing improved habitat conditions and stabilizing the streambed (Figure 33).

Upper Cowlitz River, Washington

Three unanchored ELJs were installed in December 1995 to halt erosion and reduce property loss from channel migration along 430 meters of privately owned land along the upper Cowlitz River in Washington (United States). Cost was a substantial constraint for the landowners, who nonetheless expressed a clear desire to maintain or improve the aquatic and riparian habitat. The unvegetated width of the channel at the site is 195 meters; the average bank erosion rate from 1990 to 1995 was 15 meters per year. From 1992 through 1995, erosion along the shoreline on the site resulted in as much as 50 meters of bank retreat and the loss of about 1 hectare of forestland. After bank erosion resulting from a 12-year recurrence interval flow in November 1995, the landowners became concerned that 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. Currently the forest cover is dominated by a 50- to 80-year-old mixed-conifer and deciduous forest with basal stem diameters up to 2.2 meters and averaging about 0.4 meters. Bank erosion along the upper Cowlitz River is common, and several large, conventional bank revetment projects have been constructed (and reconstructed) since the 1960s. An analysis of historical aerial photographs indicates northward channel migration and progressive widening of the Cowlitz River since 1935.

The three ELJs built along the upper Cowlitz River (in summer 1996) were based on bar apex and meander logjams described by Abbe and Montgomery (1996) that are common in large alluvial channels and occur naturally in the Cowlitz River. Both types of logjams 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 one or two key members that direct flow to either side of the jam. Meander logjams usually are considerably wider, with three to six key members, and they are situated such that they force a change in channel direction.

Five weeks after construction, the ELJs were subjected to a 20-year recurrence interval flow of approximately 850 cubic meters per second (Abbe et al. 1997). Each of the three 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. The enhancement of physical habitat included the creation of deep pools at each ELJ. This experimental project has continued to perform over the last 9 years, demonstrating that ELJs can achieve local bank erosion control objectives while helping to rehabilitate riverine habitat in a large alluvial river.

Cispus River, Washington

From 1998 to 1999, the U.S. Forest Service and the Lower Columbia Fish Recovery Board collaborated on an ELJ project in two side channels in the Cispus River near Randle, Washington (United States). The project objectives were (1) to protect a U.S. Forest Service road that was 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 of the Cowlitz River, had the potential for 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 were constructed along the Cispus River in 1999. Four ELJs were constructed directly adjacent to Forest Road 23 at RM 20 (Site B) (Figure 34 and 35), and another set of three ELJs was constructed upstream at RM 21 (Site C).

Photo by Tim Abbe (August 2003).

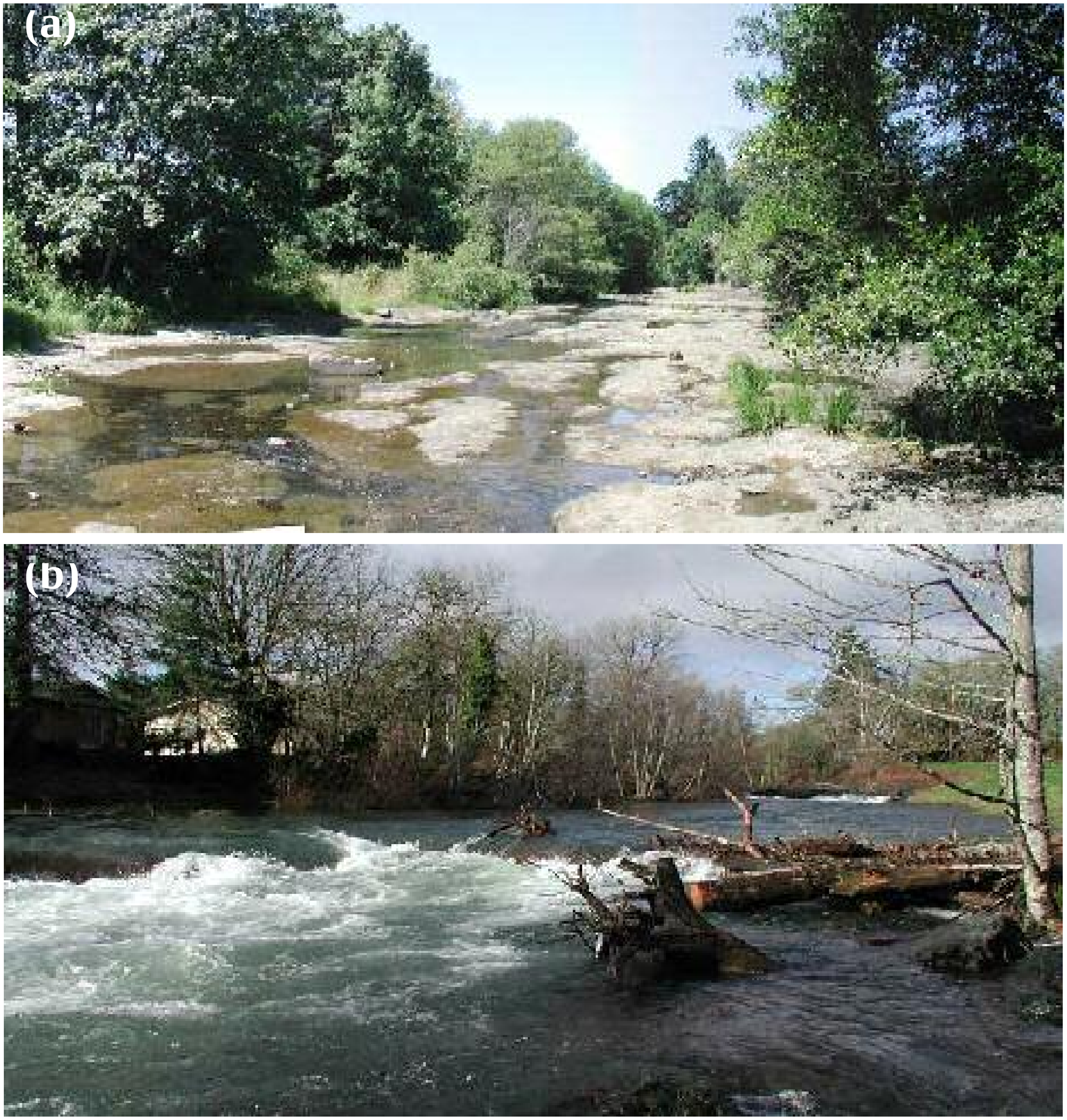
Figure 29. Example of concrete cast-in-place log weir for treatment of an urban incised creek channel in Rickreall Creek, Lane County, Oregon.

Photo by Tim Abbe (September 2003).

Figure 30. Same site on Rickreall Creek after flow was reintroduced to creek.

Figure 31. Same site on Rickreall Creek after flow was reintroduced to creek in winter 2004.

Figure 32. Same site on Rickreall Creek during moderate flow in winter 2004, showing accumulation of flotsam on the structure and the natural appearance of a complex logjam.



Photos by Tim Abbe.

Figure 33. Conversion of incised bedrock channel to step-pool and pool-riffle channel using ELJ grade control structures in Rickreall Creek, Dallas, Oregon: (a) conditions during summer low flow in 2002, before project construction and (b) conditions during winter peak flow in 2004, after project construction (flow is from upper right to lower left).

Figure 34. Site B on Cispus River in 1999 before ELJ construction where 150-meter road segment was washed out in 1996.

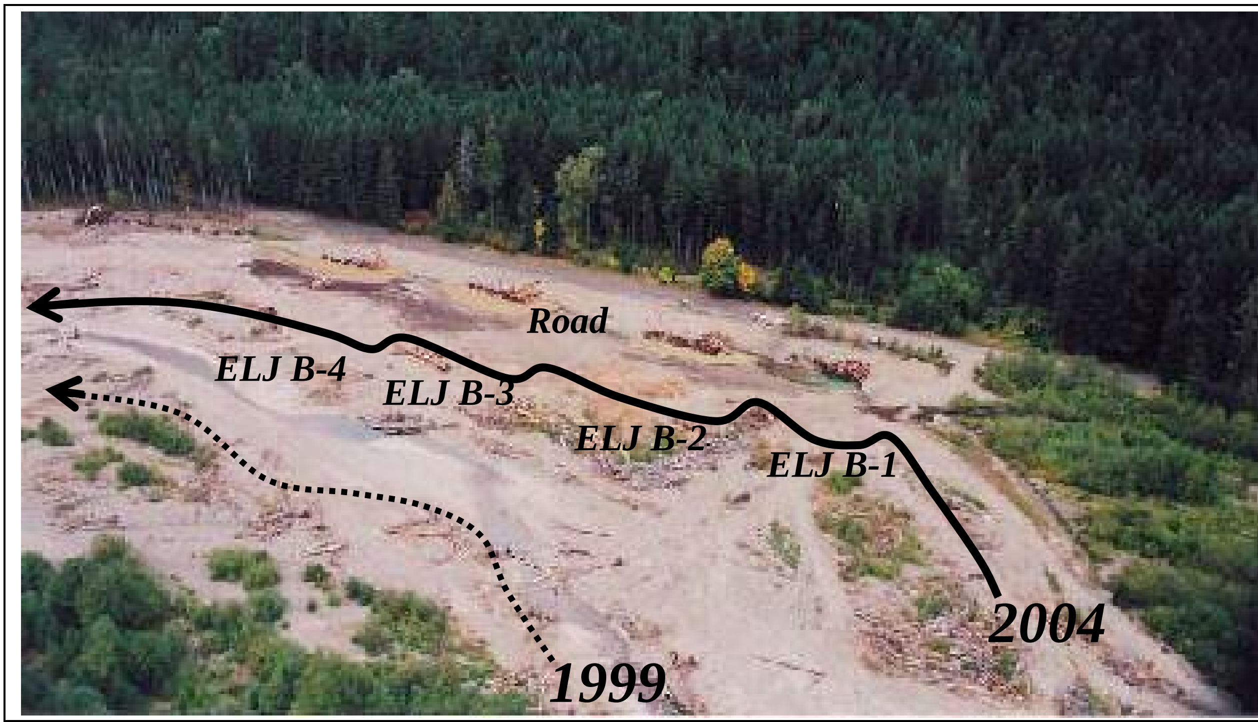


Figure 35. Site B on Cispus River in 1999 after construction of four ELJs and new riparian buffer along road.

All the structures were part of a strategy to protect Forest Road 23, because the February 9, 1996, flood, reportedly an event with a greater than 100-year recurrence interval,washed out approximately 150 meters of the road at Site B and threatened the road at Site C. Preexisting rock revetments failed at both sites. An emergency rock revetment was constructed along Site B as part of the replacement of the road washout. A reach analysis began 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 in two side channels. Plans for the upstream site (Site C) included the placement of three large structures, and the downstream site (Site B) called for the placement of four debris jams. 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 spring of 2000, winter high flows had scoured the base of the structures at Site B but had little effect on Site C. At both sites, numerous adult coho salmon (*Oncorhynchus kisutch*) were observed holding in the pools at the structures. Over 100 redds were counted between the four ELJs at Site B. At Site C, 12 redds were observed, but they were located upstream and downstream of the construction site. In 2000, one steelhead redd was observed at Site B. In the spring of 2001, only 12 redds were observed at Site B, and none was observed at Site C due to lower than normal flows. From 1999 to 2003, the four ELJs at Site B were located in a secondary channel. Since 2004, the main stem river has moved up against the ELJs.

Snorkeling surveys were performed in cooperation with Washington Department of Fish and Wildlife staff in July and August 2000 to evaluate the use of the site by juvenile coho salmon. 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 pool depth for the juvenile fish. Use of the reach between Sites B and C by juvenile coho was limited because of local sediment deposition that reduced flow depth. At Site B, 92 percent of the young-of-the-year coho observed were associated with the structures, and only 8 percent were found in the area upstream or downstream of the structures at Site B. Many of the fish observed between the structures were juvenile steelhead. At Site C, 61 percent of the 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.

Five years after construction, the ELJs were all performing as intended, creating pools and cover, protecting the road, and allowing a riparian buffer to become reestablished between the road and river (Figure 36). In 1996, channel migration to the east side of the river valley destroyed 150 meters of road. By 1999 the main stem of the river had moved to the west side of the valley, significantly reducing the cost of ELJ construction because temporary flow diversions were not necessary. In the winter of 2003, the channel moved back across to the east side of the valley and fully engaged the ELJs (Figure 36). Without the ELJs, the river would have surely moved back up against the roadway.

North Fork Stillaguamish River, Washington

The North Fork Stillaguamish River is located along the southwest margin of the North Cascades, approximately 85 kilometers northeast of Seattle, Washington (United States). The ELJ project site is located about 8 kilometers east of Oso, north of Washington State Highway 530 in a 200-meter channel reach upstream of the C-Post bridge (Figure 37). The project was first conceived in 1996 for the enhancement of salmon habitat. This goal was based on a comprehensive assessment of habitat conditions and historical changes 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 before spawning. A key observation is that the location of chinook spawning strongly correlates with pool frequency and size. Specifically, more than 80 percent 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 logjams, which also had three times the instream cover than areas without log jams (Pess et al. 1998). Historically, logjams 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 ELJs in the North Fork Stillaguamish to create and enhance holding pools for summer chinook.

The ELJ project reach has a drainage area of approximately 300 square kilometers and is a low-gradient (less than 0.01) meandering gravel-bedded channel that has repeatedly migrated across the floodplain during the past century. Natural logjams historically stabilized gravel bars in the North Fork Stillaguamish, allowing vegetation to take hold and create forested “islands” that in turn formed an anastomosing network of narrow channels with abundant cover and high pool frequency. Some homes on agricultural land occupy a significant portion of the floodplain and channel migration zone south of the river in the project reach near the C-Post bridge. Estimates of the 1- and 5-year recurrence interval peak flows at the U.S. Geological Survey gauge at Arlington, Washington, are 257.5 and 424.5 cubic feet per second, respectively.

The upper North Fork Stillaguamish has gone through large-scale channel changes over the last 70 years. A four- to fivefold increase in sediment input from the hillslope (primarily as landslides) between 1978 and 1983 from the upper portion of the North Fork Stillaguamish basin upstream of 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 (Kelsey 1980; Lisle 1995). Channel aggradation and widening, combined with the loss of

Figure 36. One of four flow deflection ELJs in Cispus River constructed to increase pool frequency and cover, improve riparian conditions, and protect the road, 5 years after construction (November 2004).

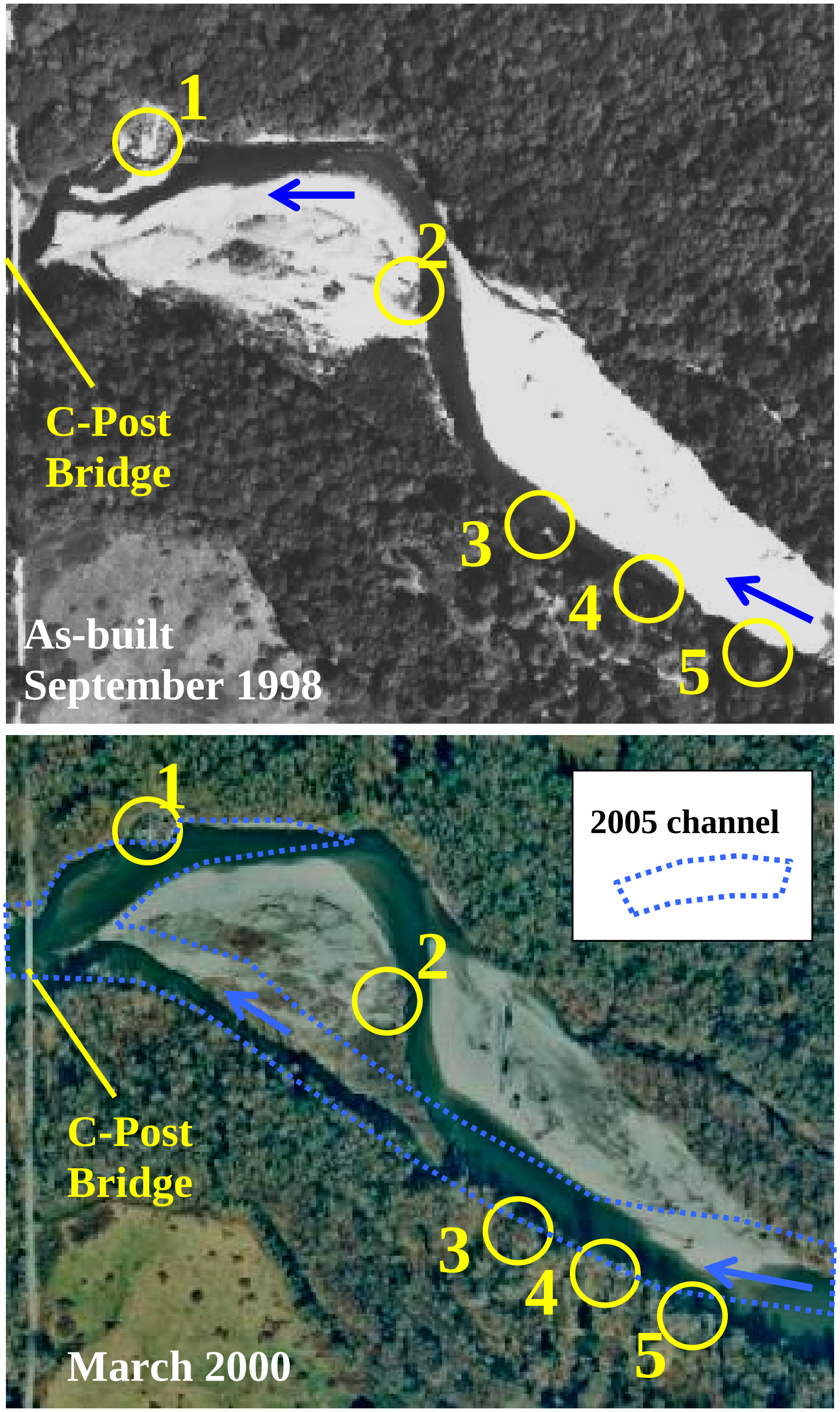


Figure 37. North Fork Stillaguamish project site in 1998 before construction of ELJs 1 through 5 and in 2000 after 15 peak flows equal to or exceeding stage at which structures are completely inundated.

pool-forming structures such as logjams, are 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 the migration and spawning timing for steelhead and possibly summer chinook (Kraemer 1953).

Project Objectives, Constraints, and Opportunities

The primary goal of the project was to increase the 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 identified.

Objectives

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

Constraints

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

Opportunities

- Introduce a multichannel system for both perennial and ephemeral flow conditions
- Incorporate ELJ structures to:
  - Emulate instream structures that are representative of a low-gradient Puget Sound river

- Limit channel migration at sensitive locations
- Stabilize and help sustain the secondary channel system
- Increase the physical and hydraulic complexity within the channel
- Increase bank protection in specific locations using an approach that emulates naturally occurring structures (e.g., logjams) and incorporates natural physical processes (e.g., channel migration and wood accumulation).

Implementation

In the summer of 1998, five experimental ELJs designed to mimic natural logjam hydraulics were constructed upstream of the C-Post bridge (Figure 37). Four of the ELJs were meander-type jams designed to deflect flow on only one side. The other ELJ was a bar apex jam designed to accommodate flow around either side. Each ELJ is completely inundated during bankfull flow. The North Fork Stillaguamish ELJ project also included the acquisition of 69 hectares of conservation easement within the channel migration zone. This area has been set aside to allow natural migration of the channel and migration induced by the presence of the ELJs.

In 1997 and 1998, information was collected on the characteristics of wood naturally occurring within the project reach and wood that could be used for ELJ construction. Wood surveys conducted in 1999 after the ELJ construction included a field reconnaissance of approximately 10 kilometers 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). Data for imported logs also included measurements of cut geometry when applicable. These data were used to measure the stability, movement, and recruitment of individual logs and the structural integrity of the ELJs and evaluate ELJ performance in terms of the project design and objectives.

Results to Date

Between September 1999 and February 2000, at least 15 flows equaling or exceeding bankfull stage occurred (Figures 38, 39, 40, and 41). In 2005, 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 member that was lost. With nothing to support the saturated log from below, it sank, broke in half, and was carried 10.5 kilometers downstream, where it was found in the summer of 1999. The loss of the outer key member of ELJ 1 was confirmed only when the structure was inspected from below, since there was almost no change in the appearance of the structure from above (Figure 42). Even with the loss of a key member, ELJ 1 remained in place and continued to perform as predicted. Each of the five ELJs has formed and maintained scour pools ranging from 2 to 4 meters in depth. Sand deposition has occurred

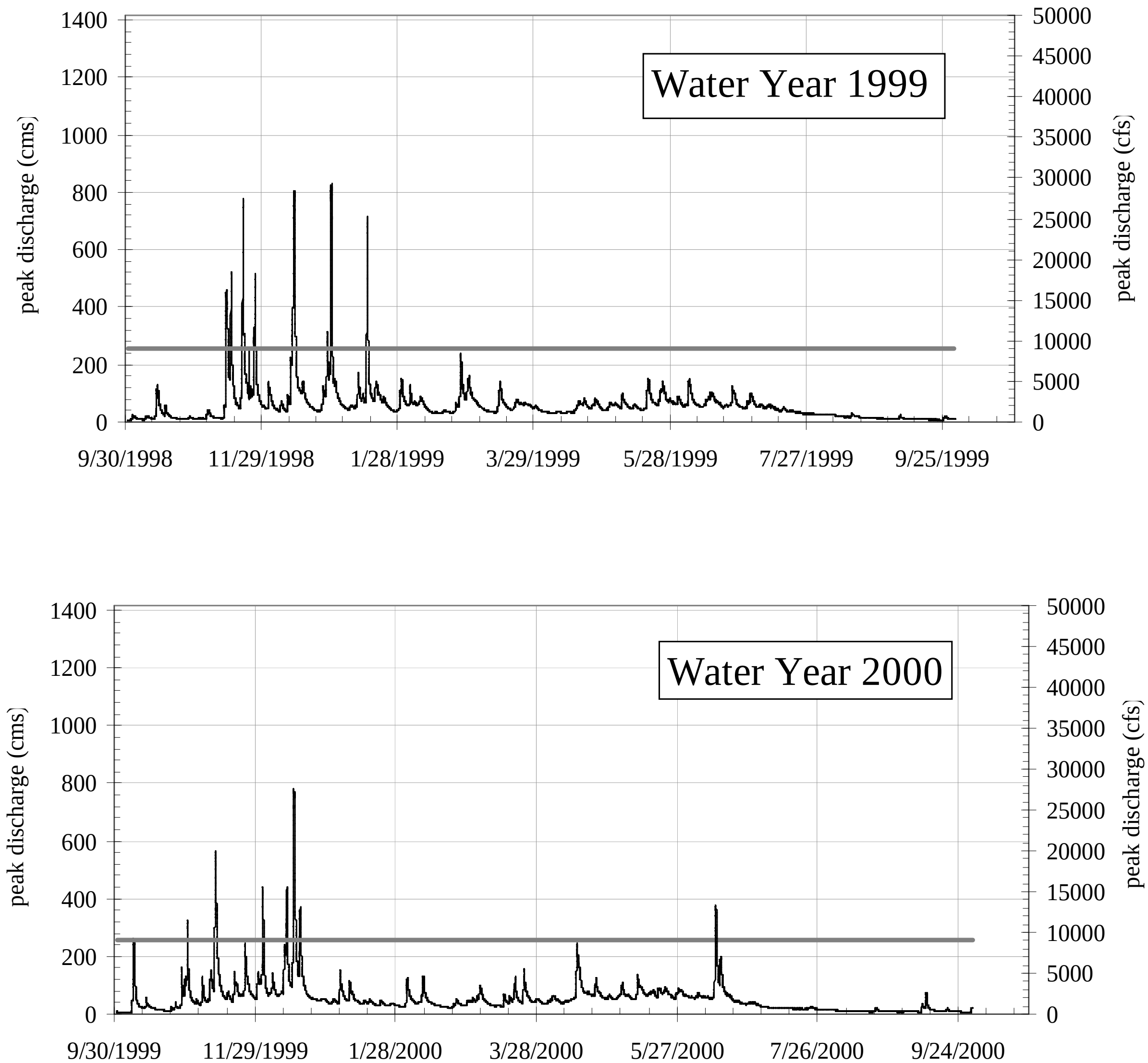


Figure 38. Hydrographs of peak flows in North Fork Stillaguamish in water year (October 1 to September 30) 1999 and water year 2001. There were eight peak flow events equal to or exceeding bankfull stage at the North Fork Stillaguamish ELJ project site in 1999 and seven in 2000. The ELJ structures are immersed at bankfull flows.

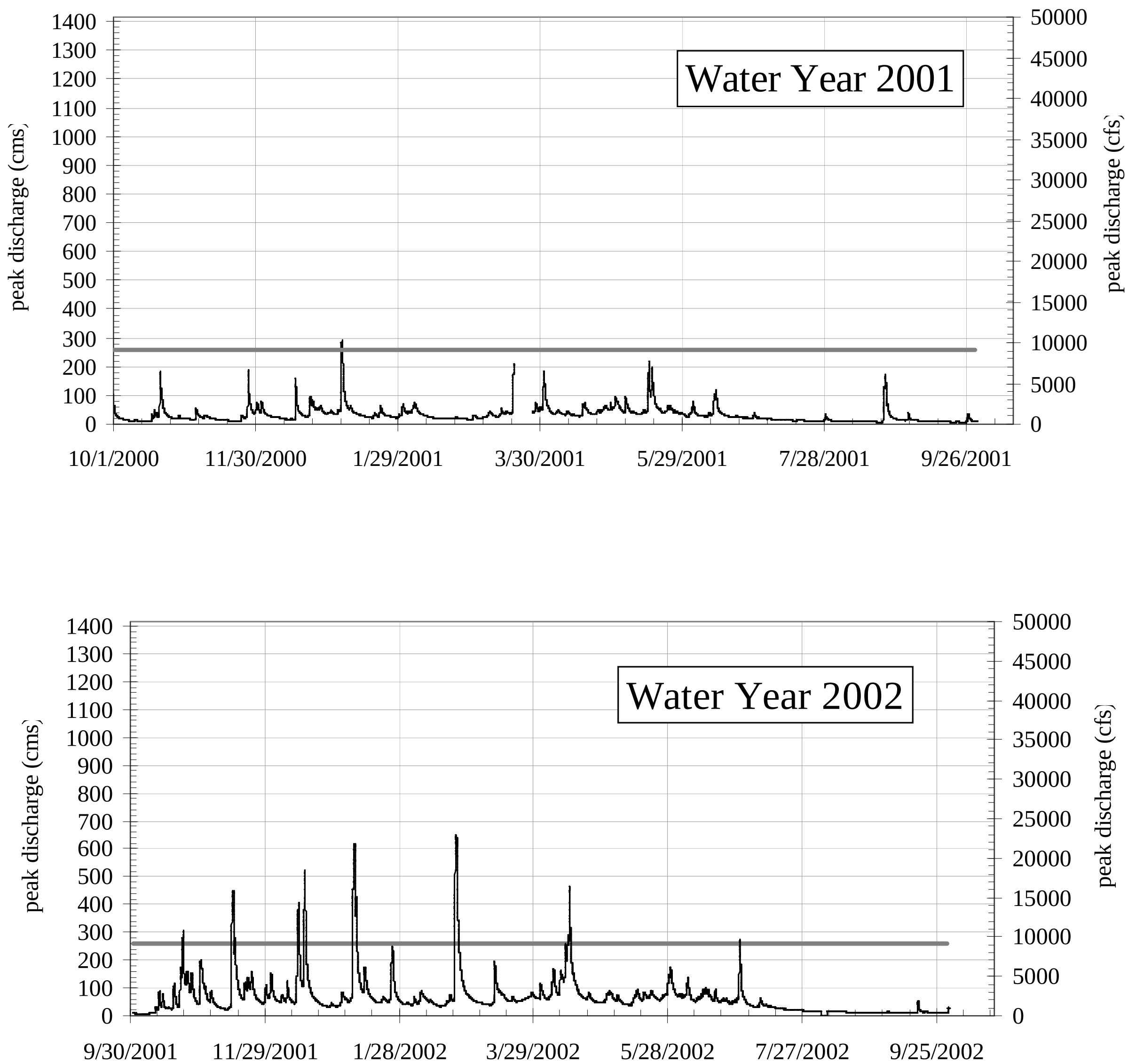


Figure 39. Hydrographs of peak flows in North Fork Stillaguamish in water year (October 1 to September 30) 2001 and water year 2002. There was one peak flow event equal to or exceeding bankfull stage at the North Fork Stillaguamish ELJ project site in 2001 and eight in 2002. The ELJ structures are immersed at bankfull flows.

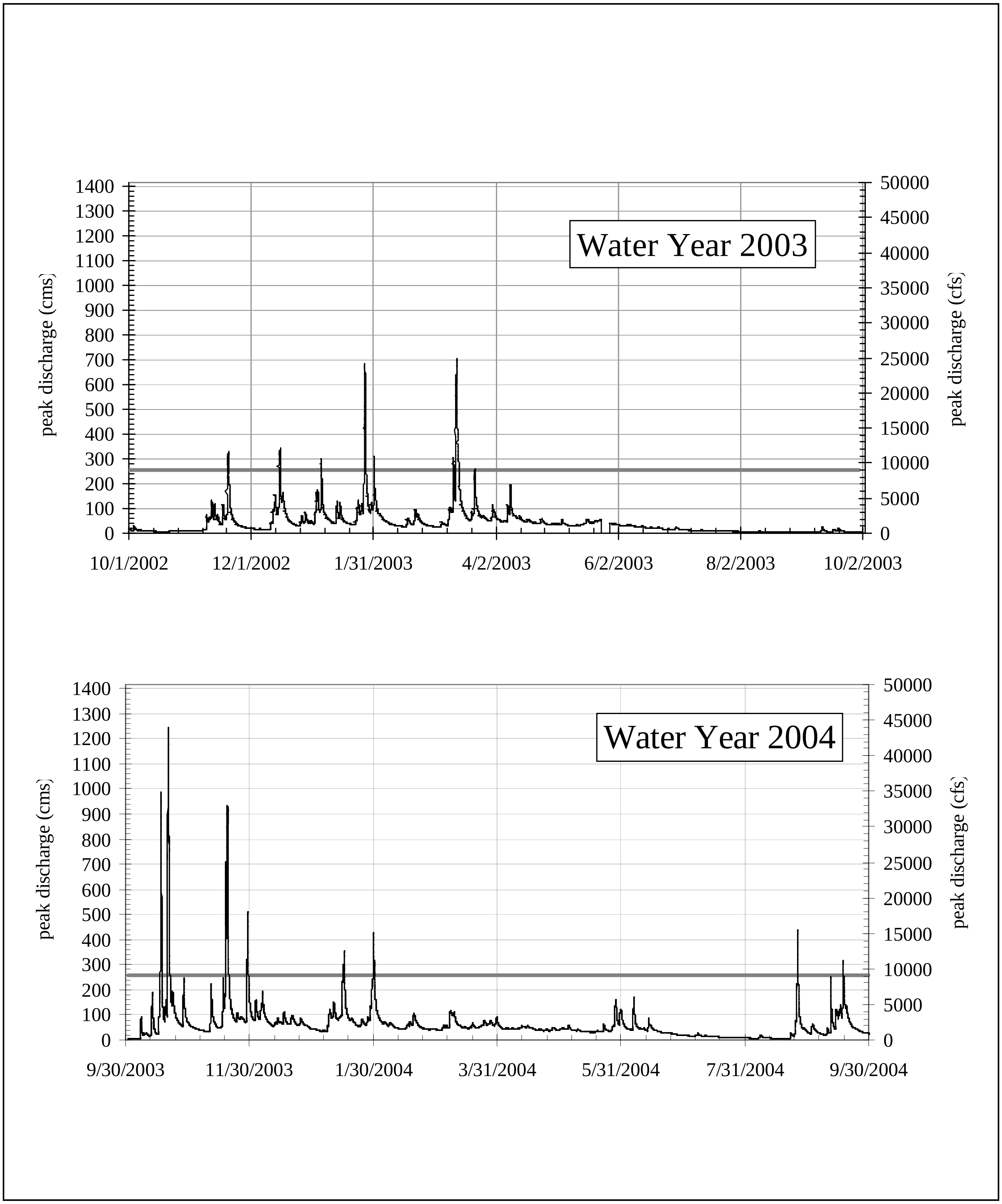


Figure 40. Hydrographs of peak flows in North Fork Stillaguamish in water year (October 1 to September 30) 2003 and water year 2004.

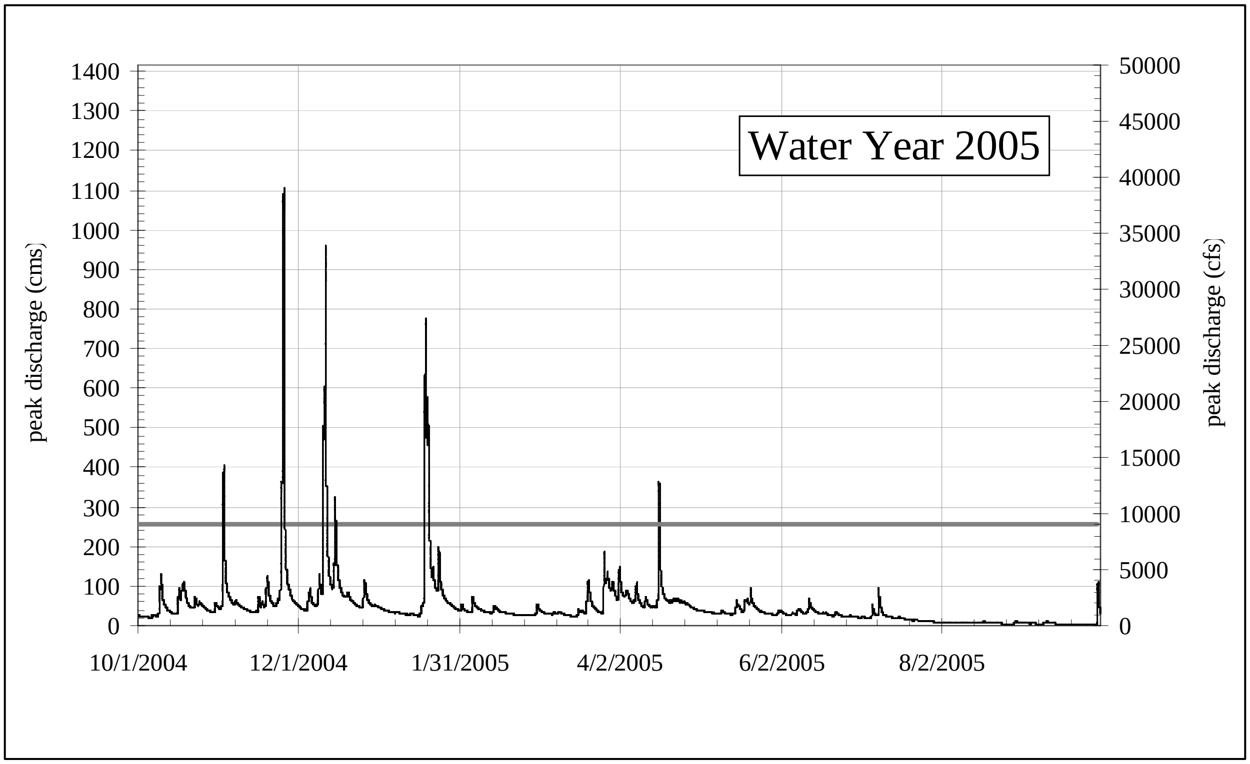


Figure 41. Hydrographs of peak flows in North Fork Stillaguamish in water year (October 1 to September 30) 2005. From 1999 through 2005, there were 43 peak flow events equal to or exceeding bankfull stage at the North Fork Stillaguamish ELJ project site. The ELJ structures are immersed at bankfull flows.

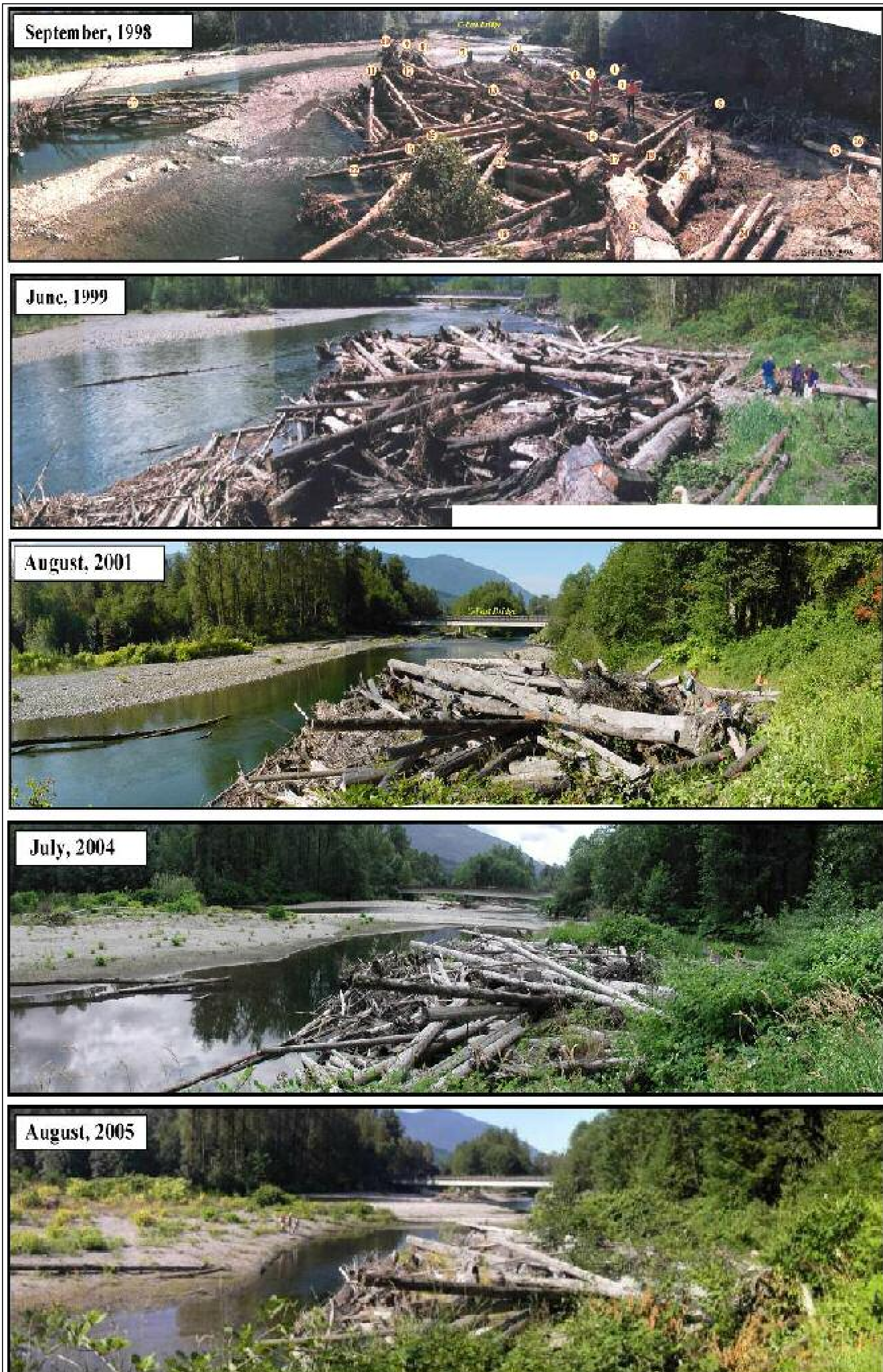


Figure 42. Photo sequence of ELJ 1 constructed in 1998 in North Fork Stillaguamish River, Snohomish County, Washington, 1998-2005.

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 southern 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 more than 2 meters long. Drift accumulation upstream of ELJ 2 effectively increased the structure's breadth sixfold and contributed to the development of a perennial secondary channel south of the main stem channel, thereby creating a forested island. The effectiveness of the North Fork Stillaguamish ELJs in collecting drift is revealed by data on log displacement distances during water year 1999 (October 1 to September 30). Of the logs that moved, those that had to pass at least one ELJ had average displacement distances an order of magnitude less than the logs that passed downstream of the C-Post bridge. Downstream of the C-Post bridge, the North Fork Stillaguamish is a relatively simple, clear channel with no stable logjams. At the time of field surveys in September 1999, 98 percent of the 350 logs used in the five ELJs had remained in place through eight peak flows equal to or exceeding bankfull stage. In August 2005, 7 years after construction, all the ELJs remained intact and were providing beneficial habitat. In 2002, the main stem river channel moved from the north to south side of ELJ 2. This change in channel position left ELJ 1 in a backwater channel where it has continued to sustain a pool that is 4 meters deep. Although ELJ 2 remained intact in 2005, it was situated in an ephemeral or high-flow channel and had lost most of its racked logs. In 1998, the main stem channel flowed directly into ELJ 5. Since 1998, the river channel has slowly migrated down the valley to more directly engage ELJs 4 and 3, respectively.

The main structural lesson of the North Fork Stillaguamish project is the threat scour can pose to ELJ structures. ELJ 1 lost a key member during the first winter (1998–1999). In the winter of 2004–2005, ELJ 3 lost a key member when the structure was undercut as a result of scour. Both structures settled approximately 1 meter into the river bed. In addition to the replacement of the lost log at ELJ 1, minor repairs of wood were performed during the summer of 1999, and the structure has experienced no additional structural damage despite maintaining a deep (more than 4 meters) pool when last inspected in August 2005. At the time of the August 2005 inspection, ELJ 3 remained intact and functioning but had experienced significant settlement and a loss of sediment surcharge that had exposed the structure's interior log matrix (Figure 43). Overall, the performance of the ELJs over the first 7 years has met or exceeded expectations (Tables 1 and 2).

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 in August 2005 only minor amounts of drift had accumulated on the center pier of the bridge, despite a major change in channel position to the southern side of its historical migration zone.

The biological response to ELJ construction was evaluated by comparing baseline data related to physical habitat and fish populations to data collected during surveys after construction. Baseline data include estimates of adult chinook and other salmonid populations determined by means of snorkeling surveys, quantitative measures of habitat characteristics (e.g., number of pools and 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 a redistribution of adult chinook salmon within the treatment reach. ELJs in the North Fork Stillaguamish have resulted in increased pool frequency, pool depth, and in-channel wood cover. Immediately after ELJ construction, pool frequency increased from one pool per kilometer to five pools per kilometer 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 to 1.5 meters. The response of chinook salmon was immediate and has been consistent from the summer of 2002 to the summer of 2005. Instead of congregating in one pool, they have redistributed themselves throughout the treatment reach, taking advantage of the increase in pool availability and quality.

Table 1. Preliminary assessment of North Fork Stillaguamish ELJ habitat enhancement project in 1999, 1 year after construction (during which ELJs were subjected to eight peak flows equal to or exceeding bankfull discharge).

ELJ	Change in Pool Depth	Change in Pool Area	Change in No. of Key Members	Change in No. of Racked Members	Sediment Deposition on ELJ	Sediment Deposition Downstream of ELJ	Change in Cover	Avulsion Predicted?/Occurred?
1	(+)	(+)	(-)	(+)	(-)	(+)	(+)	No/no
2	(+)	(+)	(=)	(+)	(+)	NA	(+)	Yes/yes
3	(+)	(+)	(=)	( )	(+)	(+)	(+)	No/no
4	(+)	(+)	(=)	(+)	(+)	(+)	(+)	No/no
5	(+)	(+)	(=)	(+)	(+)	(+)	(+)	No/no

(+) increase in pool depth and area, increase in # of logs, net deposition within and along ELJ increase in amount and complexity of cover.
(-) decrease in pool depth and area, decrease in # of logs, net erosion within and along ELJ, decrease in amount and complexity of cover.
(=) no change.
( ) no perceptible difference identified upon preliminary inspection, June 1999.
NA data not available, not yet observed.

Table 2. Preliminary assessment of North Fork Stillaguamish ELJ habitat enhancement project as of 1999–2004.

ELJ	Change in Pool Depth	Change in Pool Area	Change in no. of Key Members	Change in no. of Racked Members	Sediment Deposition Downstream of ELJ	Change in Quantity of Aquatic Cover
1	(=)	(=)	(-)	(+)	(+)	(+)
2	(-)	(-)	(=)	(-)	(+)	(-)
3	(+)	(+)	(-)	(-)	(-)	(-)
4	(+)	(+)	(=)	(+)	(+)	(+)
5	(-)	(-)	(=)	(+)	(+)	(+)

(+) increase in pool depth and area, increase in # of logs, net deposition within and along ELJ increase in amount and complexity of cover.
(-) decrease in pool depth and area, decrease in # of logs, net erosion within and along ELJ, decrease in amount and complexity of cover.
(=) no perceptible change.
( ) no perceptible difference identified upon preliminary inspection, June 1999.
NA data not available, not yet observed.

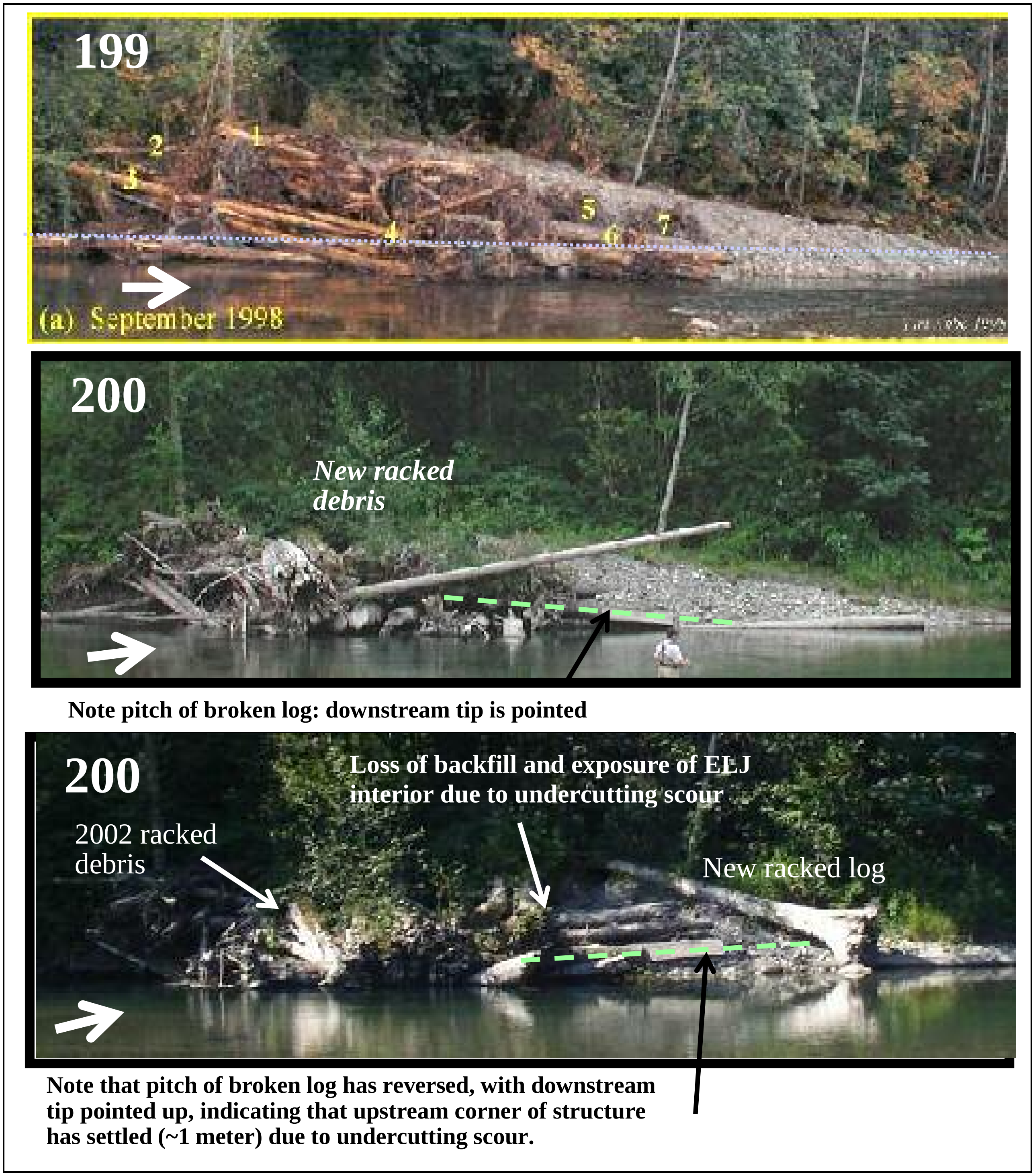


Figure 43. ELJ 3 in the North Fork Stillaguamish River, as built in 1998, 6 years later in 2004, and 7 years later in 2005. A change in channel planform between 2004 and 2005 resulted in an increase in flow against the structure, which led to significant scour. The scour undermined the structure, resulting in settlement, loss of sediment, and exposure of the inner structure, evident in 2005 photograph.

Lower North Creek, King County, Washington

North Creek drains a 7,300-hectare suburban catchment northeast of Seattle and flows into the Sammamish River. The lower 1,000 meters of North Creek runs through the new University of Washington Bothell–Cascadia Community College campus in Bothell, Washington (United States). Before its restoration in 1998, this lower segment of North Creek was a straight channel confined by levees. The 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 impacts on 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 that required by federal regulatory agencies.

The restoration site covers about 24 hectares of the original floodplain of North Creek immediately upstream of its confluence with the Sammamish River (Figure 44). At the turn of the century, the watershed experienced a period of intensive timber harvest, which was followed by a long period of agricultural development. The watershed is rapidly urbanizing and current estimates of the percentage of impervious surface area within the North Creek watershed vary from 14 to 27 percent. The estimated 100-year flood in lower North Creek is 41 cubic meters per second based on 16 percent effective impervious area.

Historically, the landscape of the North Creek and Sammamish River confluence was a complex mosaic of very low-gradient floodplain channels and depressional ponds and marsh, scrub-shrub, and forested wetlands. The presettlement 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 with a deciduous forest matrix consisting of black cottonwood (*Populus balsamifera*) and red alder (*Alnus rubra*). By the early twentieth century, the site had been logged and the North Creek channel had been straightened and levied 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. Before construction in 1998, the site was covered by reed canarygrass (*Phalaris arundinacea*). The net result of this historical land use was a significant decrease in the quality and abundance of salmonid habitat in North Creek.

Project Objectives, Constraints, and Opportunities

The reach of North Creek on the campus is typical of many urbanized, low-gradient stream and floodplain environments in the Puget Sound region. The restoration design was constrained by single points of channel entry and exit to the campus property and a floodplain limited in extent by the road corridors of Highways 405 and 522 (Figure 43). Given the degraded status and

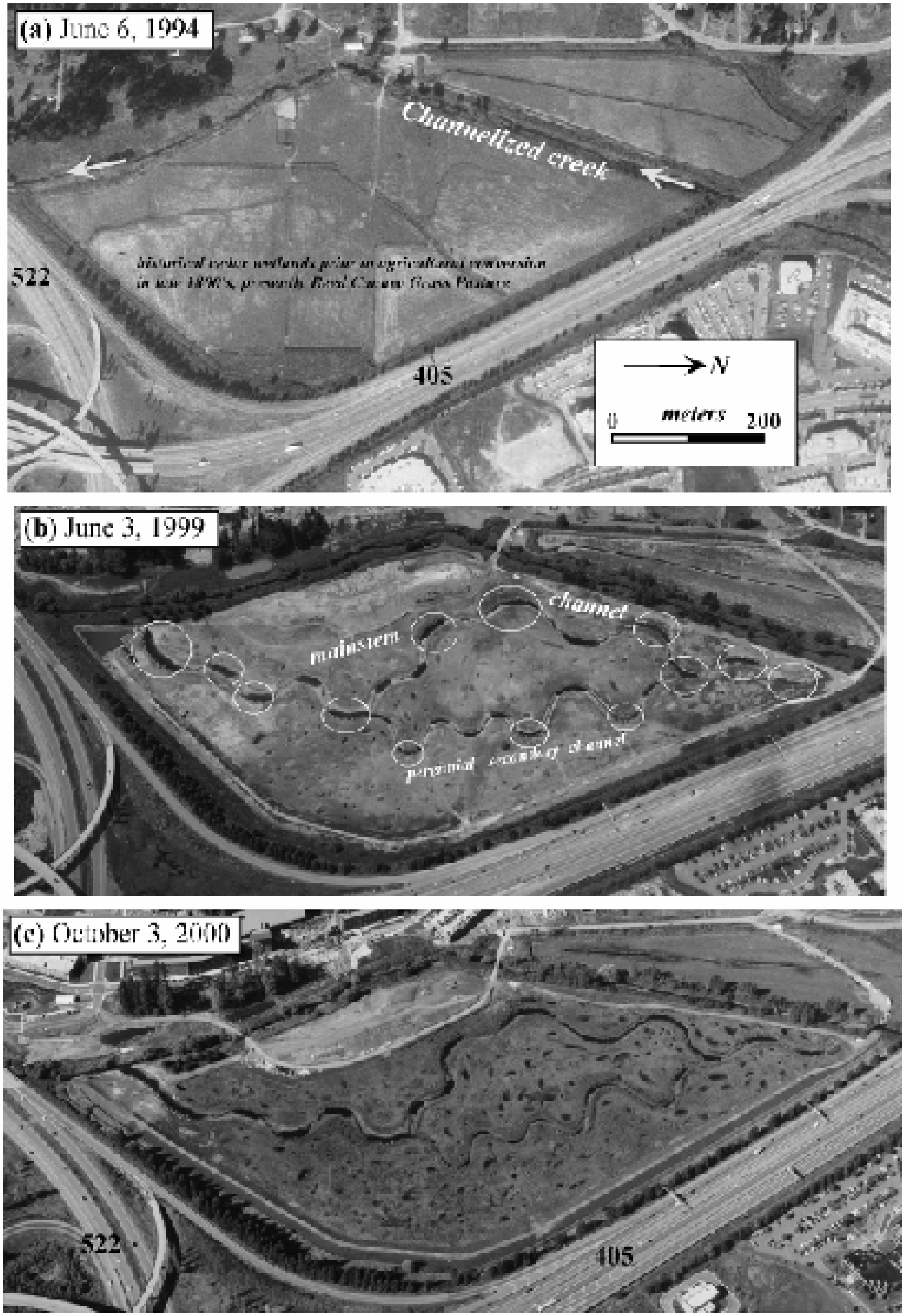


Figure 44. North Creek restoration site, Bothell, Washington.

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 on historical site information, hydrologic modeling, and an extensive sampling effort to characterize the structural characteristics of ecosystem at similar Puget Sound lowland riverine reference sites.

Objectives

- Hydrologically reconnect North Creek with its floodplain
- Reintroduce large wood to the stream channel and floodplain
- Restore the native plant community in the floodplain forest
- Increase the quantity, quality, and diversity of aquatic and terrestrial habitat
- Provide visual access from the campus and highway corridors
- Increase linkages between the channel system and riparian floodplain forest and wetlands by:
    - Maximizing the length of the perennial channel system
    - Maximizing the contact time between water and wetlands
    - Maximizing the linkages between the channel system and floodplain.

Constraints

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

Opportunities

- Introduce a multichannel 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 the secondary channel system
  - Increase physical and hydraulic complexity within the channel.

It was decided that a more natural stream channel morphology would be established in North Creek by the construction of a new channel system that provided a greater diversity of habitat such as that 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 was used 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 be engaged at different flow stages.

Project Design

The North Creek project involved the construction of a sinuous new main stem and a perennial side channel (Figure 44), four types of ELJs incorporating approximately 1,200 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. Toward this end, tree bole revetments and crib structures were used to stabilize the critical banks and meanders; a bar apex ELJ was built to raise local 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 main stem channel.

The restoration design for the floodplain plant community was based on quantitative characterization of similar floodplain forests at 58 Puget Sound reference sites. Based on the data from the reference sites, 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 representative Puget Lowland floodplain forest, both compositionally and structurally. The newly constructed channel reach was not engaged upon initial construction in order to allow the riparian vegetation to become established along the channel banks. However, 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.

Results to Date

The new stream 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 25 channel cross-sections in October 2001 and resurveyed them again in January 2002. At the cross-sections, the channel experienced some net scour and no significant change in width or location. All of the ELJs remained intact and were associated with deep pools (Figure 45). The side channel acted as a high-flow channel and sustained perennial pools. The North Creek restoration 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 ELJs as an integral part of a 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.

Williams River, New South Wales, Australia

Applications of ELJ technology have not been limited to the Pacific Northwest of the United States. In 2000, a large ELJ project was implemented in the Williams River of New South Wales, Australia. Within the project reach, the Williams River is a high-energy cobble-bedded river with moderate gradient and confinement (Brooks et al. 2004). Bank protection, bar apex, and grade control ELJs were constructed in the project reach to increase pool frequency and habitat complexity, as well as limit ongoing channel incision and bank erosion. All 15 of the ELJ structures were constructed with only trees and native alluvium; no cable or large rock was used. The ELJs have been subjected to more than 2 dozen overtopping flows and remained intact and functioning as intended in 2005 (Figure 46).

Bronson Creek, Hillsboro, Oregon

The Bronson Creek enhancement project introduced woody debris into a small suburban creek in Hillsboro, Oregon (United States), enhancing fish passage in the creek, maintaining current channel elevations, and providing bank protection within the project reach. The goals of the project were achieved by designing wood structures that would modify the channel by creating a plunge-pool profile, provide increased cover for fish, and maintain the grade of the creek by preventing a headcut at a grade control structure downstream of the pool. Bronson Creek is a first-order creek with a 4.75-square-mile (12.30-square-kilometer) watershed that has been severely modified by urbanization. The flow regime has been influenced by stream straightening, high-energy stormwater inputs, and a decrease in stream complexity as wood has been removed from the creek by humans and substrate has been transported downstream by high-velocity flows. The stream bed material has few remaining gravels or cobbles and is primarily composed of silt, loam, and clays. One-hundred-year flows in Bronson Creek average approximately 320 cubic feet per second (9.061 cubic meters per second).

The grade control structure was constructed from a series of logs that were buried across the channel, toed into both banks, and placed at a controlled elevation (see Bronson Creek drawings in Appendix A). Several variations of woody debris complexes were used to provide fish cover (habitat) and protect the banks from erosive flows. The woody debris complexes consist of wood that spans the channel and projects downward into the channel bed to interact with the creek over a range of flows. They provide aquatic habitat and diffuse the energy of the creek (see Details B and C on Bronson Creek drawings). Log weirs were used to reestablish a plunge-pool profile along the restored reach of the creek. The weirs, which are constructed of wood that spans the channel and is toed into the banks, cause water to pool upstream and plunge over the structure. The plunge-pool profile emulates natural features in local streams that allow migrating fish to rest in the pools and then progress upstream, jumping to the next pool. These log weirs were constructed with a scour pad composed of angular rocks that was placed downstream of the weir to prevent the plunging water from undermining the structure (see Details E and F on Bronson Creek drawings).

South Fork Nooksack River, Washington

The South Fork Nooksack River habitat restoration project consisted of the removal of approximately 360 feet (109 meters) of a 700-foot (213-meter) revetment that separates Hutchinson Creek from the South Fork Nooksack River in northwestern Washington (United States). The South Fork Nooksack River drains a basin of approximately 181 square miles (46.87 square kilometers) that has been severely affected by a century of heavy timber harvesting operations. The river substrate is composed of river cobbles and gravels overlying glacial till. The 100-year flows in the South Fork Nooksack average approximately 22,000 cubic feet per second (622.97 cubic meters per second). The project reach has been increasingly constricted by a series of discontinuous levees and revetments, leading to severe constrictions and flooding at several locations and a general degradation of aquatic habitat.

When the revetment was removed, it was replaced by two ELJs along the alignment of the existing revetment and four ELJs downstream of the revetment. The partial removal of the revetment allowed a portion of the flow from the South Fork Nooksack River to enter the channel and floodplain area of Hutchinson Creek, which parallels the South Fork Nooksack. The four ELJs were built behind the revetment in the lower portion of Hutchinson Creek to deflect the river’s flow toward the west (the area was previously occupied by main channel) and dissipate the energy of flows through the floodplain. In addition, an ELJ “plug” was constructed along the existing river bank to prevent the river from reoccupying a relic channel and endangering infrastructure. Wing structures extended from the “plug” to prevent erosion from the project site along the bank.

The ability to access additional off-channel habitat is a crucial element in the recovery of native fish of Washington state. The removal of the existing revetment allowed the Nooksack River to occupy additional floodplain habitat in an area where the river was severely constricted. The ELJs were designed to emulate naturally occurring logjams that were found in the Nooksack

Photos by Tim Abbe.

Figure 45. Example of log revetments, bar apex ELJ, and buried log weir all interlocked around the outside of a meander bend to create an inlet to a secondary channel in North Creek, King County, Washington: (a) as built in 2000 and (b) 7 years later in 2005. Addition of secondary channel into restoration design doubled the amount of habitat available to fish within the reach.

Figure 46. Photo sequence of two ELJs constructed along right bank of Williams River, New South Wales, Australia: (a) as-built in 2000, (b) during peak flow overtopping ELJs, and (c) same site in 2001 after six peak flows equal to or exceeding that shown in Photo b. The structures are still performing as intended in 2005.

drainage in the past. These natural logjams, many of which have been removed from the river, form high-quality fish habitat and reduce the energy of the river, acting as the nexus for point bar formation and as roughness elements in the system. In addition to creating additional fish habitat, the ELJs were designed to diffuse the energy of the river in a manner similar to that of baffle blocks in a spillway. Water strikes the upstream faces of the structures, mounds up, and then flows around the left and right faces of the ELJs. Backwater conditions are created behind the ELJ structures, resulting in sediment deposition. The ELJ structures were conservatively designed to be stable during the 100-year flood depths, velocities, and scour events, which were determined from one-dimensional modeling and several scour analyses.

Hoh River, Washington

The Washington State Department of Transportation recently completed the installation of 12 ELJ structures in the Hoh River to protect U.S. Highway 101 from being severely damaged by erosion of the river bank. This project represents the largest ELJ installation ever accomplished in the Pacific Northwest of the United States. In the vicinity of the project site, Highway 101 is aligned generally parallel with the Hoh River valley, in an area where the river has a natural tendency to migrate laterally across a wide, alluvial floodplain. The project site is situated on an outside meander bend of the river, where there has been a history of repetitive bank erosion problems. Past attempts to stabilize the site under emergency conditions failed to provide a long-term solution and resulted in adverse impacts on aquatic and riparian resources, including salmon habitat. The Hoh River drainage is about 300 square miles (777 square kilometers), flowing from the Olympic Mountains to the Pacific Ocean. The 100-year flows in the south fork of the Hoh River average approximately 60,000 cubic feet per second (1,699cubic meters per second). The river substrate is dominated by alluvial gravels, sands, and cobbles, with intermittent clay lenses.

The ELJs provide structural protection for the highway, while enhancing aquatic and riparian habitat in and adjacent to the Hoh River. The project design was complex and required extensive engineering and geomorphic analysis, including flow and scour modeling, river sinuosity calculations, logjam design, and structural calculations. Two types of ELJs were designed and constructed at different locations on the project site: midchannel and bank ELJs. The midchannel ELJs were designed to deflect 40 to 50 percent of the flood-stage river from its current alignment into a newly constructed side channel on the right bank to lessen the flow that adversely affects the road prism. The bank structures were designed to prevent further erosion of the road prism by reinforcing the interface of the road and the river, while providing additional fish habitat.

The main structure of each of the four midchannel structures consists of 100 key logs with 50- to 60-inch-diameter (1.25- to 1.5-meter-diameter) boles and intact rootwads. Fourteen steel *h*-piles were embedded 50 feet (15.25 meters) below the riverbed to anchor the structure and form a framework through which the key logs would be laced. Permanent steel sheet piling was driven and left in place to resist the scouring effects of the river. The structures were provided with

2,200 tons (2,230,000 kilograms) of rock for ballast against the buoyancy and velocity forces 100-year flood conditions. It was anticipated that in the future the river would change direction; therefore, the ELJs were designed to accommodate various angles of attack by having three upstream faces capable of resisting flows. Material excavated from the newly constructed channel was used to fill the interstitial spaces between the rocks and trees, form a bar downstream of the ELJ, and dress the top of the structure for revegetation plantings.

Eight bank ELJs were also constructed to protect the bank from further erosion. These logjams act as barbs along the river margin, intercepting and breaking up high-velocity flows on the upstream faces and allowing the deposition of alluvium in the downstream backwaters.

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APPENDIX A

Examples of Engineered Logjam Projects in the Pacific Northwest of the United States

Table A-1. Engineering Plans for Example Engineered Logjam Projects.

Type of ELJ Project	Type of Channel	Location	Year Built	Type of ELJ Structures	Number of Key Log Elements	Number of Racked Log Elements	Relative Complexity of Structure	Stability Design Flow (years)	Figure
Habitat enhancement	Flow-regulated gravel pool-riffle	White River, Washington	2005	Simple bar apex type jams	12 to 16	30 to 50	Moderate	100	A-1, A-2, A-3, A-4
Grade control and habitat enhancement	Suburban incised sand- and gravel-bedded channel	Bronson Creek, Portland, Oregon	2004	Log weirs and porous dams	3 to 6	0 to 10	Simple	100	A-5, A-6
	Urban incised gravel-bedded channel	Johnson Creek, Portland, Oregon	2006	Complex log and pile weirs with rock apron scour protection	20 to 50	0	Complex	100	A-7, A-8, A-9
Bank protection and habitat enhancement	Large gravel-bedded pool-riffle river	South Fork Nooksack River, Washington	2005	Bar apex jams	40 to 60	75 to 100	Complex	100	A-10
	Large gravel-bedded pool-riffle river	South Fork Nooksack River, Washington	2005	Complex pile and log revetment	200	0 to 10	Moderate	100	A-11
	Very large gravel bedded pool-riffle channel	Hoh River, Washington	2004	Bar apex jams and bank flow deflection jams	40 to 60	75 to 100	Complex	100	A-12, A-13, A-14, A-15

APPENDIX B

Topics to Consider for Engineered Logjam Demonstration Projects

Topics to Consider for ELJ Demonstration Projects

Implementation of ELJ pilot projects should be documented and monitored to evaluate how well the technology achieves the project objectives. Compilation and analysis of factors such as initial, as-built, and post-construction boundary conditions (channel, flood plain topography and roughness), flow conditions, existing and imported wood debris, faunal surveys, and habitat are necessary to test design strategies, evaluate ELJ performance, identify hazards, and refine ELJ technology. Demonstration projects for implementing and evaluating ELJs will be considered based on the site, objectives, project management, and the commitment to participate and support the appropriate data collection and design analysis, implement construction, and initiate post-construction evaluations of the site and ELJs.

Some examples of data collection and topics to consider in contemplating an ELJ project include:

- Projects usually require at least one year of lead time prior to construction.
- Key conditions of a channel reach that should be documented as part of the design process include:
- General channel and flood plain morphology, forest cover, flow conditions, gradient, physical conditions, landuse constraints.
- Are project objectives, goals, constraints, and resources compatible with an ELJ project? Is the objective to rehabilitate habitat, limit incision, halt bank erosion, etc.? Are there property boundary limitations? How much of the channel migration corridor can be maintained or returned to the river? Is there adequate funding for analysis, acquiring the necessary trees (wood debris), and construction?
- Geomorphic mapping of study reach (e.g., bankfull channel, floodplain, migration zone, potentially active terraces, present and old log-jams, pool survey)
- Documenting topographic boundary conditions through detailed surveys of the project reach (installation of permanent benchmarks, profiles, and transects across both the active channel and flood plain). Surveys done at least year prior to construction (necessary for design work) and directly before and after construction. Subsequent surveys are recommended if possible, either directly after bed mobilizing flow events, once a year, or when possible).
- Wood debris surveys at same time as topographic surveys and directly after major flow events if possible (location, position, size, species,

condition, and permanent marking of key pieces and jams in project reach).

- Survey of wood supply for project. Is imported material of sufficient size or will "key members" need to be constructed? All logs imported also should be permanently tagged for post-construction surveys and evaluation.

- Compilation and analysis of available historical records (hydrology-flow records, aerial photos & maps, changes in channel planform, profile, riparian forest (general characteristics of tree size, sp. etc. old-growth vs. managed tree size and sp. distributions).

- Installation and monitoring of stage wells and development of associated stage-discharge curve. These wells are crucial for documenting flow conditions (i.e. depth) site and ELJs are subjected to, a critical factor in ELJ design. Minimum objective is to establish a relatively accurate means of predicting the water surface profile through the project reach (thus depth) associated with a particular flow at an established gauging station (e.g., USGS, State). This involves constructing gauging sites at the downstream and upstream margins of the site, but the more, the better. Since ELJs inherently influence local hydraulic gradients, high resolution of local water surface elevation in the vicinity of ELJs are desirable (e.g., installation of well grid). When the project cannot afford to install remote sensors and data loggers for recording stage, a well can be installed which simply records the high water elevation over the time sampling interval.