Evaluation of Engineered Log Jams as a Soft Bank Stabilization Technique: North Fork Stillaguamish River, Washington.

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Abstract:

Engineered Log Jams (ELJs) can be used as a “Soft” alternative to traditional streambank hardening methods of bank stabilization, and have been identified as a means of rehabilitating riverine and floodplain environments. The merits of delineating, designing, and implementing this experimental technique are being evaluated in the North Fork Stillaguamish River (NFSR) where 5 ELJs were constructed, in the summer of 1998. The project reach is a gravel-bed, pool-riffle channel with a drainage area of 374 km^2, bankfull widths 60-90m, bankfull depths 1.8-2.4m, and an average gradient of 0.0023. Project objectives focused on enhancing habitat, protecting a bridge pier, and preventing an imminent, undesirable avulsion. In all cases, logjam placement will address local habitat concerns by creating large, deep pools for Chinook salmon holding. Two of the jams were designed to function individually, and are intended to provide bridge protection by means of flow deflection and by separating the main flow to form a forested island. The remaining 3 jams should provide reach-scale bank protection to prevent the channel from re-occupying a floodplain side-channel and incorporate a more experimental approach in which the jams are intended to function as a unit. For the purposes of this study, evaluation will be limited to these 3 structures. The design-spacing and length of these 3 jams was based on traditional design criteria for rock groins/barbs such as those summarized in Klingeman 1984. The Length /Width (L/W) ratio for jam placement was 7:1. The objectives of this study fall into two distinct categories: comparison of local scour and deposition associated with ELJs and traditional rock structures, and the applicability of rock groin design criteria to ELJs. Extensive bathymetric data was collected prior to construction to characterize pre-existing conditions. After high-water conditions that include at least one bed-moving event have subsided, the project reach will be resurveyed; and the magnitude and spatial distribution of local scour and deposition will be documented. These results will be compared to solutions derived from predictive equations that predict local scour around rock structures. The accuracy of these equations to predict the magnitude and spatial distribution of local scour and deposition around ELJs will be assessed. Unseasonably high water levels have prevented the completion of this analysis to date. In addition, examination of the flow separation envelopes and the spatial distributions of local scour and deposition, will be used to assess the appropriateness of using groin and spur dike design parameters for ELJ designs. Preliminary results suggest that ELJ placing (length between structures) can be greater than for traditional rock structures of equal design width (W).

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Introduction:

Traditional river management techniques aimed at protecting channel banks and limiting channel migration include rock revetments, rock groins, submerged rock barbs, and occasionally pile dikes and bulkheads using logs (WDOT 1996). While these alternatives can be successful in accomplishing specific engineering objectives, such as channel training and bank protection, increasing scrutiny has been directed toward the aesthetic and environmental consequences associated with their implementation. Recent efforts to develop Engineered Log Jam (ELJ) technology are directed toward restoring vital ecological functions to impacted river systems, while also achieving human objectives. ELJs emulate naturally occurring large wood debris (LWD) accumulations found in pristine fluvial environments such as the Queets River on the Olympic Peninsula (Abbe et al 1997, 1998). These accumulations have historically been a part of many forested river systems in North America (Maser, C. and J.R. Sedell. 1994), and influence pool formation and channel morphology (Montgomery et al. 1995). Flooding, navigation hazards, fish passage, and concern about damage from debris impacts have resulted in river managers routinely removing these accumulations (Shields, F.D. and N.R. Nunnally. 1984). Until recently, little consideration was given to the ecological ramifications of large-scale wood removal. Previous studies indicate that juvenile salmonids and resident stream fishes rear in side-channel habitat (Nickelson 1992) and that the structural complexity of a channel enhances the species diversity (Lonzarich and Quinn 1995, Hicks et al 1991). The ecological role of in-stream wood debris has led to significant efforts in the Pacific Northwest during the last decade to re-introduce wood and incorporate it into traditional structures. Despite a dramatic increase in the number of projects putting wood debris back in streams and rivers, very little research has been done to document the hydraulic and ecological effects of wood installations.

Engineered Log Jam (ELJ) technology is still in the development stage. While much can be learned about the potential effects of an ELJ project by investigating a natural jam within a similar reach, significant difficulties do arise when trying to forecast channel response to wood re-introduction. Few U.S. river systems remain in pristine condition for the study of natural log jams. Even where human development is not a factor, logging practices have removed virtually all old-growth trees within river migration zones. This has dramatically altered the size and amount of wood delivered to rivers and stopped much of the natural formation of log jams. In addition, natural jams tend to be difficult to access, extremely complex, and initial conditions are essentially impossible to document. An additional concern is the flow field variability and the morphological changes that wood accumulations impose on the system. Backwater effects can result from piling up of water upstream of a debris accumulation. This can raise the water surface, resulting in an increase in the frequency and magnitude of flooding in the vicinity of the log jam. ELJs can also have significant downstream effects on the system. Often the thalweg of the river will be altered or re-directed as a result of the re-introduction of large wood. This transformation of the location of the high-energy flow also can have significant local effects. Log jams have also been linked to numerous avulsions in small streams and large rivers.

In contrast, it is important to note that traditional river engineering has also resulted in river channels that possess numerous undesirable traits. The alteration of wood in a river system can lead to dramatic physical and biological channel modifications. For example, wood-pour plane-bed channels that have few bedforms and therefore few pools can be converted into morphologically complex forced-pool riffle channels with the introduction of abundant large wood debris (Montgomery et al. 1995). The physical evolution of a channel is biologically significant since the conversion of forced pool-riffle channels to plane-bed channels reduces the amount of preferred spawning habitat in a river basin (Montgomery et al. 1998).

In summary, there are many instances where wood accumulations have been responsible for dramatic changes in the local river system. Since the fundamental canon of a Civil Engineer is to serve in the best interest of society, it has been the responsibility of river engineers to protect bridges, public transportation routes, and personal property. Therefore, it is understandable that river managers have removed these accumulations in the past. However with the implementation of the Endangered Species Act (ESA), which addresses declines in Pacific Northwest Salmon and Steelhead populations, public needs and perceptions are shifting. This broadens the scope of river management activities and alters the way in which a river manager must evaluate engineering alternatives including ELJs.

Background:

The term Engineered Log Jam (ELJ) refers to a distinct group of experimental in-stream hydraulic structures that can be used to solve common river engineering problems involving grade control and flow manipulation. The design premise of ELJs is to emulate naturally occurring structures and processes. Distinct types of in-stream wood debris accumulations or log jams are found in different parts of a channel network (Abbe et al. 1993, 1998; Wallerstein et al. 1997). Using observations from the Queets River basin, eleven distinct types of log jams have been classified based on the presence or absence of key members, the source and recruitment mechanism of the key members, log arrangement, geomorphic effects, and patterns in vegetation on or adjacent to the jam (Abbe et al. 1993, Abbe and Montgomery 1996a, Abbe et al. 1997, 1998). Six of these jam types offer natural models for grade control and flow manipulation and the templates for ELJ designs. Jam types primarily applicable to grade control include log steps and valley jams. Types more directly applicable to flow manipulation include flow deflection, bankfull bench, bar apex, and meander jams (Abbe et al. 1998). Similar to natural jams, ELJs are composed of several distinct structural components. Key members are individual logs unlikely to move during a design flow and used as the foundation of all ELJs. Stacked members are used in some ELJs to interlock key members and thereby increase the integrity of the structure. Racked members have the largest range in sizes and are usually the only logs visible after construction is completed. They act to decrease the permeability of the structure and deflect flows. An ELJ can be constructed entirely without the use of exotic materials such as cable, large rock, concrete, etc. Once completed, an ELJ can perform as an effective revetment or groin, with the benefit of introducing significantly more complexity to the channel while appearing to be part of the natural system.

The large quantities of wood debris once typical of pristine forest channels introduced significant temporal and spatial controls on channel texture, form, and position. Beginning with the natural model, ELJs are engineered to achieve an appropriate factor of safety and adapt to project constraints. Based on the longevity of natural jams, we anticipate that ELJs can have a design life that equals or exceeds traditional structures (Abbe and Montgomery 1996b), but they will change through time and re-introduce some of the natural chaos and complexity of a river system. For this reason and due to the experimental nature of ELJs, a commitment to inspection monitoring and maintenance is a highly recommended criterion for proceeding with ELJ implementation at sites where infrastructure is situated within the fluvial environment (e.g., original channel migration zone). Public policies such as the limiting of floodplain encroachment and creation of riparian easements will increase design options and decrease risks associated with ELJs.

Site Description:

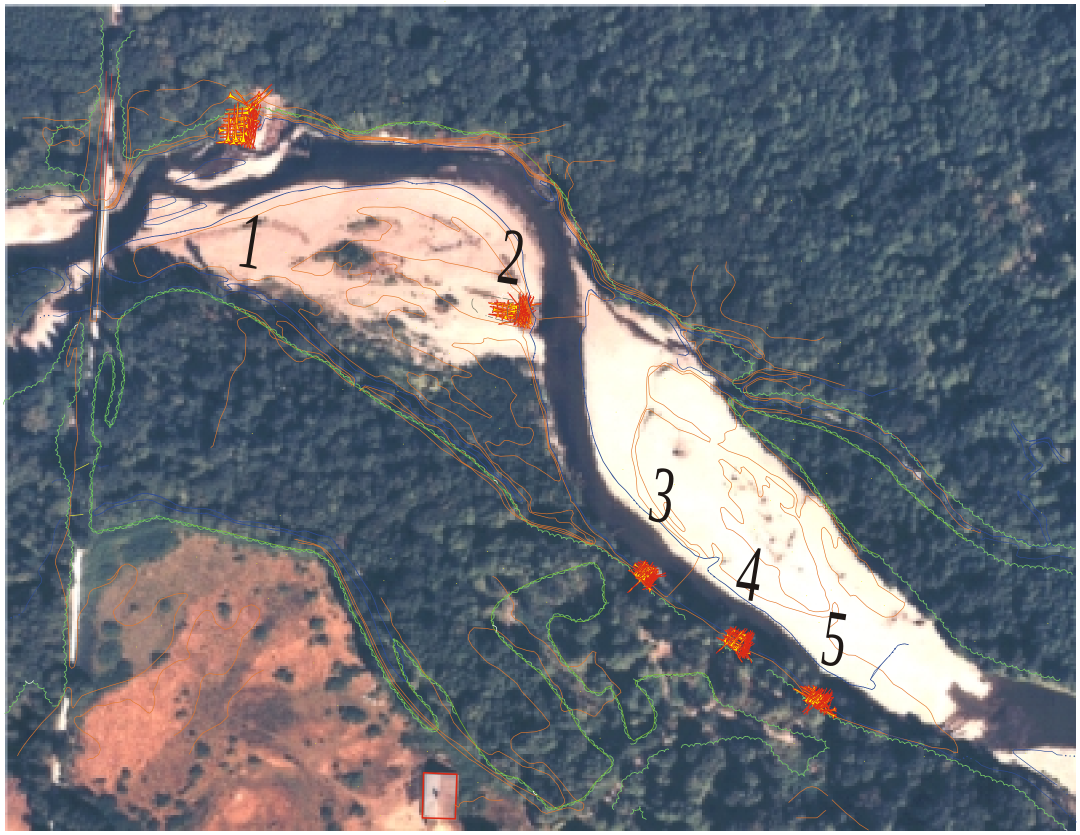

Figure 1: 1998 Engineered Log Jam Project Site, September 1998
North Forth Stillaguamish River, Washington. River Mile 21.0 – 21.5.
Engineered Log Jams are in Red and Labeled 1 through 5.

The project site is located in the northwest quarter of T32N R8E approximately 12 miles west of Darrington, Washington in northeast Snohomish County (*Figure 1*). The project reach is located between river mile 21.0 – 21.5 of the North Fork Stillaguamish River (NFSR) and is a gravel-bed, pool-riffle channel with a drainage area of 374 km^2, bankfull widths of 60 to 90m, bankfull depths of 1.8 to 2.4m, and an average gradient of 0.0023. The one-year return bankfull discharge at this site is approximately 450m^3/s. Channel migration rates in the project reach have averaged 5 to 10 m/yr from 1933 to 1998, but translation as high as 100m/yr has been identified (*Figure 2*).

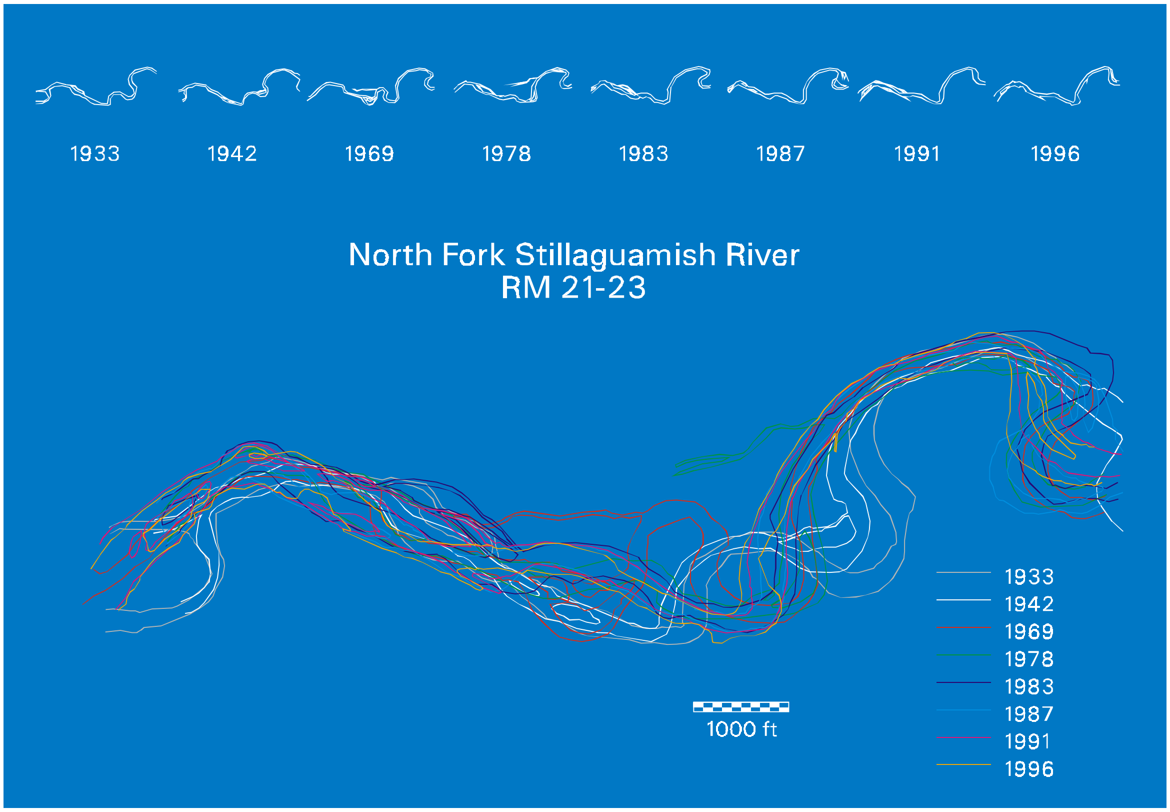

Figure 2: NFSR channel migration record 1933 to present

An evaluation of habitat conditions and historic changes in the NFSR identified the need to develop and maintain pool habitat as a key component in recovery efforts for Stillaguamish Summer Chinook (*Oncorhynchus tshawytscha*) (PSSSRGR 1997). Summer Chinook salmon are large bodied fish that spend months in deep, cool pools during low flow prior to spawning. It is hypothesized that loss of pool area can be linked to large scale changes in channel morphology and bed particle size (Pess and Benda, 1994). These changes have been attributed to an increase in coarse sediment supply that altered channel conditions in the main-stem NFSR between 1978 and 1987. A six-fold increase in sediment supply to the NFSR has been attributed to an increase in landslide activity in the upper region of the river (Pess and Benda, 1994). Approximately 92% of the landslides have been correlated to timber harvest and road construction activities. In addition, 17 of the 20 largest peak flows on record have occurred over the last 20 years. This increase has commonly been attributed to land-use changes, however additional studies aimed at quantifying land-use effects and overall changes in weather patterns for the Stillaguamish basin need to be completed.

Project Specifics:

Five strategically placed ELJs were designed to create critically holding pools for salmonid habitat, provide reach scale bank protection, align the channel approach with a downstream bridge, and collect mobile debris that historically accumulated on the bridge pier. The ELJs were constructed in July and August of 1998 over a period of 3 weeks using traditional construction equipment. For a portion of the construction period, river flow was partially diverted to enable ELJ placement under dry conditions. Each of these ELJ structures was composed of 4 to 7 key members, 15 to 30 stacked members, and approximately 40 to 100 racked pieces. Key members were on the order of 1.2m basal diameter, with 3 to 5m rootwads, and 20m in length. Trees used included Sitka Spruce (*Picea sitchensis*), Western Red Cedar (*Thuja plicata*), Western Hemlock (*Tsuga heterophylla*), and Douglas Fir (*Psendotsuga mensizii*). More than 500 logs were incorporated into the project. Jam configurations were modeled after stable natural structures, and precautionary measures were incorporated into the design to increase the factor of safety against jam breakup. Channel bed material was excavated to create a footprint for the ELJs and an additional trench was dug to accommodate the rootwads of key members. This allowed for the placement of key members in orientations resembling those in natural debris accumulations. Stacked members were placed on top of the key members to add ballast and increase the structure's elevation to the height of the floodplain. Racked members were then placed in front of the ELJs to decrease permeability.

The remainder of this discussion will focus on the 3 upstream structures (numbered 3, 4, and 5 in Figure 1) that were designed to function together and provide reach-scale bank protection. In an effort to increase the factor of safety with respect to jam stability, trenches were dug into the left riverbank and stacked members were placed across the ELJ and into this trench. This tied the entire structure into the bank and inhibited mobility of the composite structure. Final log jam dimensions were approximately 11m in width, 20m in length, with a crest elevation at the level of the floodplain. The spacing of these ELJs was based on design practices for rock groins and spur-dikes (Copeland 1983, Klingeman 1984). The suggested spacing, expressed as the ratio of the length between structures to the width of the structure (L/W), ranged from 2.0 to 5.0 for similar river systems. However the unique roughness characteristics of ELJs as well as the length scales over which this roughness is induced, lead us to hypothesize that L/W ratios greater than those suggested for rock structures would be successful for ELJ projects. Conservatively implementing this hypothesis, the ELJs were placed with a design L/W ratio of 7.0.

Geomorphic Effects:

Placement of the ELJs initiated significant geomorphic effects local to the structures and induced reach scale channel alterations. Distinct zones of scour and deposition developed as a result of the altered flow patterns associated with each structure (*Figure 3*). Induced turbulence scoured large, deep pools both upstream and lateral to the ELJs, and deposition occurred in the quiescent zones in the lee of the structures.

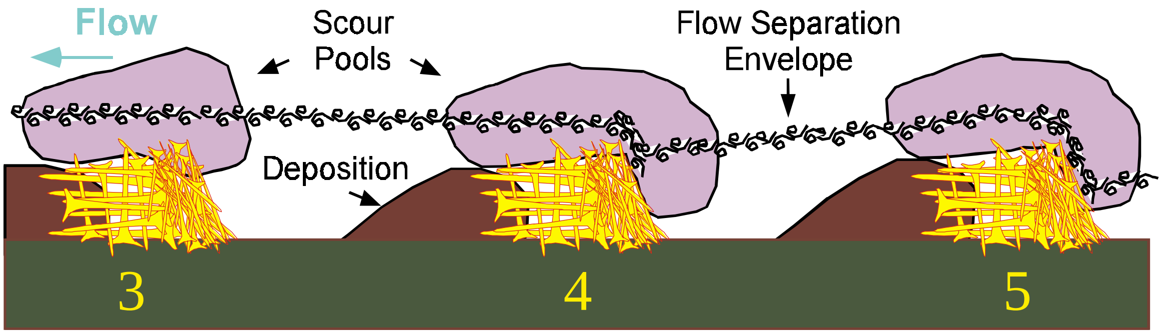

Figure 3: Qualitative description of geomorphic effects induced by placement of Engineered Log Jams # 3, 4, and 5.

The ELJs were placed directly in the thalweg of the river at low flow. During the ensuing high flow events, the thalweg was redirected away from the riverbank as reflected by the pattern of the flow separation zone (*Figure3*). Currently, one year after ELJ installation, the thalweg of the river impacts the first structure (#5) approximately 2m from the riverbank. It is deflected away from the bank and makes contact with the second structure (#4) approximately 8m from the riverbank. The thalweg is then located mid-channel and does not impact the third structure (#3). This translation of high velocity flow away from the left bank has halted channel migration, and sedimentation has occurred along the previously eroding bank. Topographic data was collected prior to and immediately after ELJ construction in the summer of 1998. Efforts are currently underway to re-survey this topography and document the channel alterations induced by ELJ placement. Preliminary data indicate that depths of pools formed by ELJs range from 2 to 3m below pre-project elevations. Initial snorkel surveys, July 1999, found 82% of adult Chinook identified within 2km of the project site holding in pools formed by ELJs.

Design Considerations:

As previously noted, the design spacing of these successive ELJs was determined after analysis of design practices for rock groins and spur-dikes. When spacing rock structures, designers have considered the width of the structure a necessary parameter in the determination of downstream spacing. Therefore the length to width ratio (L / W) has been documented and used in numerous designs (*Figure 4*). Little has been documented however, about the downstream length of the structure itself, the parameter λ as shown in Figure 4.

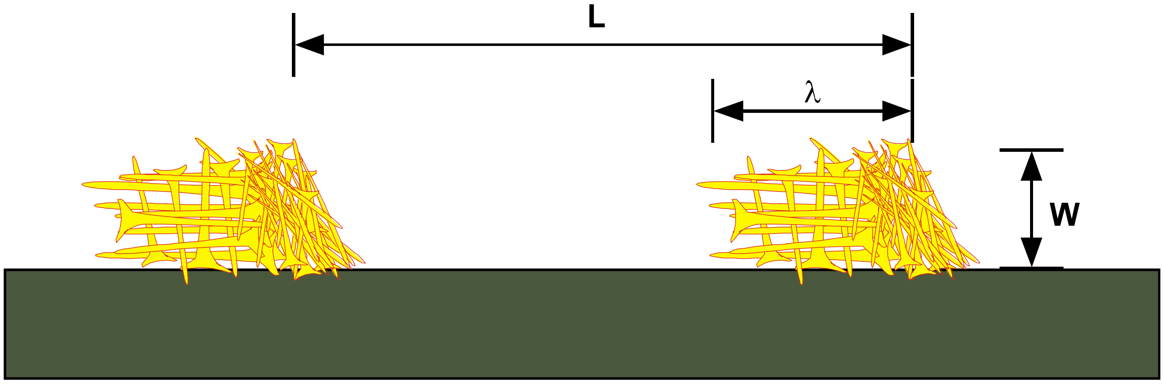

Figure 4

This parameter λ represents the length over which a flow deflection structure introduces roughness at the riverbank. For ELJs, the length scale λ is larger than the λ associated with traditional rock structures. In addition to roughness being induced over a longer length scale, the roughness characteristics of wood are quite different than those of rock materials. These roughness characteristics have a direct effect on the development of the flow separation zone around a given structure and the persistence of this separation downstream. Therefore affecting the optimal length (L) between structures when a series of them are designed to function as a unit.

The recognition of larger λ values for ELJs than for rock structures as well as the effect of woody debris roughness lead to a hypothesis that the L/W ratio for ELJs should be greater than that for traditional rock structures. The spacing ratio (L/W) of 7 to 1 for this ELJ application was designed to test this hypothesis. Recalling the thalweg translation depicted by the flow separation zone in Figure 3, one could conclude that spacing ELJs at L/W = 7 at this site was a successful means of protecting an eroding bank. Since the third structure is located completely within the flow separation envelope of the second, it is possible that these ELJs could have been successful if spaced even further apart. Alternatively, perhaps the ratio L/W can increase as one moves along a series of ELJs in a straight reach or one with a large radius of curvature.

In an effort to compare ELJ performance to that of traditional rock structures, design criteria for rock structures and ELJs are non-dimensionalized with respect to width (*Figure 5*). These data came from engineering plans and recommended design criteria for rock groins and spur dikes, and is limited due to many resources not providing the λ parameter. Non-dimensionalizing these data allows for the comparison of the design length between ELJ and rock structures (L) when the width of these structures (W) is equivalent and isolates the impact of the parameter λ.

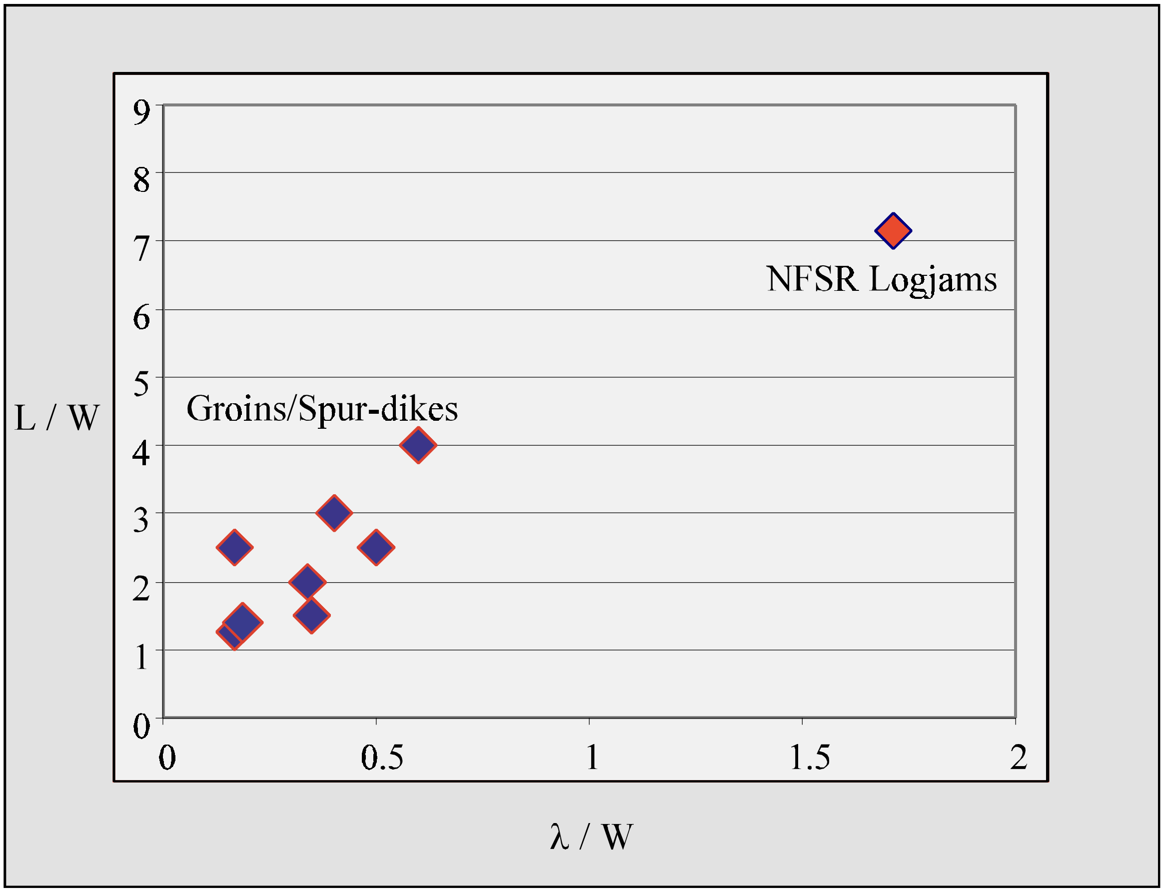

Figure 5: Dimensionless comparison of significant design parameters of Engineered Log Jams and traditional rock groins and spur-dikes: Length between structure (L), Width of structure (W), Length of individual structures λ. See Figure 4.

Figure 5 shows that the spacing length (L) for ELJs is greater than that for traditional rock structures of equal width (W). Therefore fewer structures can protect an equal length of bank. This reduces the cost associated with bank protection and decreases the environmental impact from placement of flow deflection structures.

Conclusions:

Perhaps the most fundamental conclusion that one can draw from this experimental application is that stable ELJs can be built in large river systems like the North Forth Stillaguamish. ELJs in the NFSR experienced 7 bank-full or greater events from fall 1998 through winter 1999. In addition, ELJs can be successful in halting bank erosion in actively migrating alluvial river systems. The North Fork Stillaguamish Project scoured large, deep pools in a reach that was lacking such features, and 4 of the 5 ELJs accumulated additional debris. Early returning Chinook Salmon have been identified holding in pools formed by ELJs, and this expansion of available habitat directly addresses one of the identified limiting factors to recovery of Chinook populations in the NFSR: the development and maintenance of holding pool habitat. Preliminary results suggest that spacing of ELJs can be greater than for rock groins and spur-dikes. Therefore protecting a specific length of riverbank would require fewer ELJs than rock structures. Decreasing the number of structures installed can reduce environmental impacts and potentially reduce overall project costs. The ability of the North Fork Stillaguamish ELJs to alter channel migration patterns establishes ELJs as a viable alternative to traditional bank protection practices such as rock rip-rap, groins, and spur-dikes. The success of ELJs meeting engineering objectives while simultaneously enhancing salmon habitat implies that ELJ technology has the potential to provide a more ecologically sound method of river engineering than traditional practices.

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