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DESIGN OF STABLE IN-CHANNEL WOOD DEBRIS STRUCTURES FOR BANK PROTECTION AND HABITAT RESTORATION: AN EXAMPLE FROM THE COWLITZ RIVER, WA

Tim B. Abbe[1], David R. Montgomery[2], and Catherine Petroff[3]

ABSTRACT

Most river bank protection structures are not designed to improve aquatic or riparian habitat and restoration projects often lack sufficient engineering and geomorphic analysis. Recognition of the ecological importance of in-stream wood debris (WD) has led to its extensive re-introduction in many parts of the United States, but limited understanding of the WD stability hampered these efforts. After appropriate analysis to determine the appropriate size, position, frequency, and type of WD, engineered log jams (ELJs) can restore riverine habitat and in some situations provide effective bank protection. Although WD is often considered a hazard because of its apparent mobility, our research in Olympic National Park has documented that stable WD jams can occur throughout a drainage basin. Even in large alluvial channels that migrate at rates of 10 m yr^{-1}, jams can persist for centuries, creating a mosaic of stable sites that in-turn host the large trees necessary to initiate stable jams. Based on the stability of these natural jams, three unanchored ELJs were designed to halt erosion along 427 m of the upper Cowlitz River, Washington. The channel at the site is 195 m wide and had an average bank erosion rate of 15 m/yr from 1990 to 1995. Five weeks after construction, the project experienced a 20 year recurrence flow (850 m^3/s). Each ELJ remained intact and met design objectives by transforming an eroding shoreline into a local depositional environment. Approximately 93 tonnes of WD that was in transport during the flood was trapped by the ELJs, alleviating downstream hazards and enhancing structure stability. Improvements in physical habitat included creation of complex scour pools at each ELJ. In addition to the environmental benefits, cost was a fraction of comparable rock solutions. This experimental project demonstrates that ELJs can meet erosion control objectives while restoring riverine habitat in large alluvial rivers.

INTRODUCTION

The vast majority of river bank protection utilizes rock unrepresentative of the river's natural bank characteristics. In forested landscapes wood debris (WD) can comprise a significant portion of the sediment supply and sometimes form the principle roughness element. Structures such as log crib walls, weirs, and deflectors have been used effectively in stream channels for centuries. Yet WD is rarely considered a useful material in river engineering throughout parts of the world where it is readily available. Two common concerns expressed about using in-stream WD structures regard stability and life expectancy. Abbe and Montgomery (1996) show that WD accumulations that form in large alluvial channels can be extremely stable, with life expectancies equal or exceeding the design life of most river engineering projects (50-100 yrs). Utilizing the distinctive structural attributes of naturally occurring stable WD jams and fundamental engineering and geomorphic principles, engineered log jams (ELJs) can provide a viable alternative to existing techniques of controlling bank erosion. ELJs also incorporate many of the ecological characteristics that river professionals are increasingly being asked to either preserve or restore (e.g., Shields et al. 1995). The performance during a 20 year flood of three experimental ELJs along the meander bend of a large alluvial river demonstrates that such structures can meet erosion control objectives. The techniques introduced here can provide distinct advantages in meeting bank protection, environmental, and economic objectives.

PROJECT SITE

The project site is 330 m above sea level and is located along the right bank of the Cowlitz River, about 3 km north of Packwood, Washington. Mean annual precipitation at Packwood is 1479 mm, 50% of which falls from November to January. The 694.4 km^2 drainage area is characterized by steep mountain terrain with elevations up to

[1] Graduate student, Department of Geological Sciences, University of Washington, Seattle, WA 98195, USA.
[2] Associate Professor, Department of Geological Sciences of the same University.
[3] Assistant Professor, Department of Civil and Environmental Engineering, of the same University.

4267 m. The Upper Cowlitz River is a wide meandering gravel-bedded channel that actively migrates within the valley bottom and has a mean annual flow of 42 m^3/s. The flood plain adjacent to the site consists of timber lands that have been selectively harvested since the 1930's. Present forest cover is a dominated by 50-80 year old Grand fir (*Abies grandis*), Douglas-Fir (*Pseudotsuga menezii*), Western Red Cedar (*Thuja plicata*), Red Alder (*Alnus rubra*), and Black Cottonwood (*Populus trichocarpa*) with basal stem diameters up to 2.2 m, averaging about 0.4 m. Bank erosion along the Upper Cowlitz is common and several major bank revetment projects have been constructed since the 1960's. Northward channel migration and a progressive widening of the Cowlitz River at the site has occurred since 1935. The project site is located on 49.5 acres of privately owned pasture and forest land. Erosion along their 427 m shoreline from 1992 through 1995 resulted in the loss of over 2 acres of forest land and as much 50 m of bank retreat (Figure 1 A). After a 12 year recurrence peak flow 11/30/95 and an apparent acceleration in bank retreat, the landowners inquired into erosion control alternatives that could also retain as much of the habitat and aesthetic qualities of the site as possible.

DESIGN CONSIDERATIONS

Natural WD jams exhibit distinctive patterns in the position and orientation of logs of various sizes. Using variations in log orientations and the structural attributes of natural jams, Abbe et al. (1993) identified distinct types of WD accumulations. The ELJs built along the Upper Cowlitz were based on bar apex and meander jams, both common in large alluvial channels and naturally occurring in the Cowlitz River. Both jam types consist of large key member logs with rootwads facing upstream and boles aligned with bankfull flow. Key members anchor and stabilize a larger WD structure. Bar apex jams usually consist of 1 to 2 key members in the center of the channel while meander jams have 2 or more situated adjacent to the bank. If correctly sized and placed, key members can trigger jam formation.

The fundamental aspects of mechanics, hydraulics, and fluvial geomorphology applicable to river engineering are incorporated in the design of ELJs. The stability of a single log or complete WD structure can be evaluated by a force balance analysis. A structure is stable when the sum of resisting forces, F_R, exceeds the sum of driving forces associated with drag, F_D, and buoyancy, F_B. Log size, shape, and density all govern the opposing gravitational, F_G, and buoyant forces. The magnitude and moments of these forces depends on the center of mass or centroid position of the log and displaced volume of water corresponding to the log's submerged volume. For example, assume a log bole is aligned with the x-axis, that symmetry is maintained along the log's length in the plane (y, z) orthogonal to x, and the log has a homogeneous mass. Describing log geometry as a simple function $f(x) = r_0\,(x_i)^a$, where r_0 is the rootwad diameter defined at x = 1, bole taper is defined by the exponent a, and the log extends from $x_{i=1}$ to $x_{i=n}$, the location of a log's centroid along the x axis is derived by dividing the moment of volume with respect to x, M_z, by the volume, V:

$$x_{c_m} = \frac{M_z}{V} = \frac{\left[a\ x^{2(a+1)} - a + 0.5\left(x^{2(a+1)} - 1\right)\right]}{\left[a\ x^{2a+1} - a + x^{2a+1} - 1\right]} \tag{1}$$

where $$M_z = \pi \int_{x=1}^{n} x\,\left(r_o\ x^a\right)^2\,dx = \frac{\pi\, r_o^2}{2a+2}\left(n^{2a+2} - 1\right) \tag{2}$$

$$V = \pi \int_{x=1}^{n} \left(r_o\ x^a\right)^2\,dx = \frac{\pi\, r_o^2}{2a+1}\left(n^{2a+1} - 1\right) \tag{3}$$

Assuming the log is resting on a level surface its tilt will be a function of its length and radii at either end (rootwad, r_0, and crown, r_n), the centroid elevation for this simple model is:

$$z_{c_m} = \left\{ r_n \cdot \tan^{-1}\left(\frac{r_o - r_n}{x_n - 1}\right) + x_n - x_{c_m} \right\} \sin\left(\tan^{-1}\left(\frac{r_o - r_n}{x_n - 1}\right)\right) \tag{4}$$

Centroid locations of submerged portions of a log upon which buoyant forces act can be determined through a numerical integration of the volume defined by the log's intersection with the relevant water surface elevation. A basic hydrostatic analysis is the first step in evaluating WD and structure stability. The water depth at which a log becomes fully buoyant, $F_B=F_G$, is referred to as the buoyant depth, h_b, and commonly corresponds to the log's maximum draft, d_m. The draft of the log relative to a particular flow depth is critical since it will influence the frictional resistance the log encounters along the channel boundaries. A bedform or roughness element upon which a log comes in contact can provide a resisting force equal to the driving forces, thus stabilizing the log. Consider a tree bole with attached rootwad diameter that is equal or greater than the bole's total length. Because of the large cross-sectional area of the rootwad relative to the log, small increases in water depth submerge large portions of the log resulting in shallow buoyant depths. This is why many stumps are transported and deposited in their "growth" position. In addition, the relatively short widths inherent in stumps decrease the probability of deposition against channel obstructions, thus stumps have little value as a structural component of stable in-stream WD jams. We recommend that boles with attached rootwads should have lengths well in excess of the rootwad diameters.

The green density of wood is usually associated with a moisture content of 30% and for the tree species at the Cowlitz site varies between 350 to 560 kg m^{-3}. It is important to recognize the differences not only between species, but various conditions. Although the specific gravity of wood itself is consistently about 1.5 for all species, void space and fiber structure result in differences between species. Wood density and decay rates are functions of tree species and moisture content, with latter being the principle factor. Thus the position of logs within a stream channel will directly influence a structure's mechanics and it's potential life expectancy. Under aerobic conditions occurring when completely saturated, wood can remain almost perfectly preserved for thousands of years. Studies of in-stream WD indicate that decay takes considerably longer than in terrestrial environments, commonly lasting several hundred years. Even if one uses terrestrial decay coefficients for most of the local species, the half-life of WD meeting the appropriate size requirements will can commonly exceed the 50 or 100 year design life of most projects. It is important to consider species as well as size in design analysis. Species with lower decay coefficients (e.g., *Thuja plicata*) are preferable and more appropriate for pieces elevated higher in a jam structure, while it is best to avoid using faster decaying species (e.g., *Alnus rubra*) as critical structural members.

Stability analysis must account for potential driving forces imposed by flowing water impinging on individual logs and the structure. Drag will depend on the cross-sectional area of a flow obstruction, the square of the incident flow velocity, a coefficient describing the relative form of the obstruction, and a blockage coefficient equal to the ratio of its total cross-sectional area to the channel cross-sectional area orthogonal to flow (e.g., Gippel et al. 1992, Abbe and Montgomery 1996). When introducing a flow obstruction there are several indirect consequences related to the drag a structure imposes on the flow. Because a flow obstruction results in a stagnation point where the velocity is essentially zero, the flow depth at that point is equivalent to the specific energy or $U^2(2g)^{-1}$, where U is the incident flow velocity and g the acceleration of gravity. An increase in the entire cross-sectional flow depth upstream of an obstruction can result from backwater effects. Gippel et al. (1992) provide a solution for estimating the increase in the water surface elevation or the afflux upstream of WD accumulations given the water depth and Froude number downstream of the flow obstruction, $Fr = U(g\,h)^{-0.5}$, and the blockage and drag coefficients of the obstruction. An additional factor influencing water surface elevation upstream of meander jams is super-elevation along the outside margin of the channel due to centrifugal acceleration through the bend, $\Delta h = w\,U^2\,(r_c\,g)^{-1}$, where r_c is the radius of curvature. Data from the Queets River shows that meander jams often reduce r_c of the thalweg by a factor of 10, increasing local water elevation (Δh) upstream of the jams and potentially leading to a channel avulsion. This process is an important factor in designing ELJs. Force balance and hydraulic calculations were done for each of the ELJs at the Cowlitz site.

Surcharge provided by overlying debris, sediments, or rock increases the cumulative F_G and thus stability. Hydraulic conditions associated with natural WD jams can result in substantial sedimentation on the downstream side of the structure (e.g., Abbe and Montgomery 1996), thereby burying much of the wood and significantly increasing the effective weight of the entire structure. This process is integrated into our design analysis by either letting sedimentation proceed naturally at a project or accelerating the process artificially by using sediments excavated during initial construction or rock to bury the key member boles. The racked members and upstream portion of an ELJ should be left exposed. The addition of sediment or rock surcharge can be used to increase a structure's factor of safety, but the wood should be sized and arranged to assure stability for the design peak flow independent of additional sediment or rock. In situations such as we faced at the Cowlitz site where the key members were of marginal size, an additional component to the jam structure was introduced. Additional key members were stacked above the basal end of the key member boles. Stacked-member rootwads were placed snugly over the outer key members on either side of the structure.

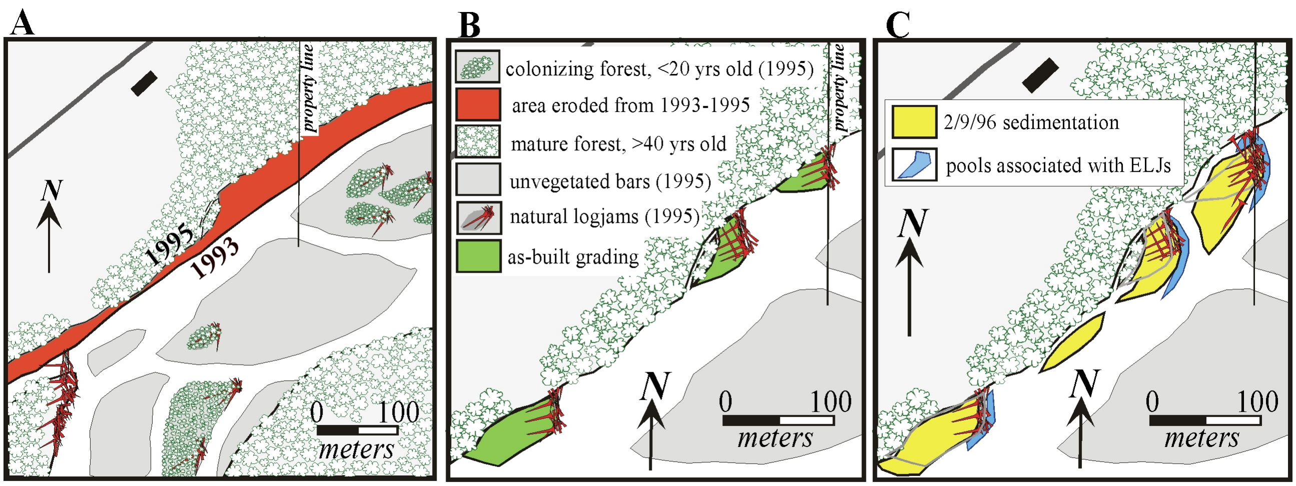

Figure 1 Project site 1993-1995 (A), enlarged planview of ELJ structures in 1/95 (B) and 3/96 (c).

Log and channel dimensions in rivers throughout western Washington provide an empirical model of WD stability using dimensionless variables of log size: the ratio of mean log diameter to mean bankfull depth, D/h_{bkf}, and the ratio of log length to mean channel width, L/w_{bkf}. Stable logs referred to as "key members" form the critical components holding loose debris in WD jams. In large alluvial channels stable logs had minimum values of L/w_{bkf} equal to 0.25 and values of D/h_{bkf} rarely below 0.8. In channels exceeding 40 m in bankfull width all key members consisted of a bole and rootwad and ratios of minimum rootwad diameters to depth, $D_0/h_{bkf} > 1$. The buttressing or taper of a tree's bole results in concentration of a substantial portion of a tree's mass near its base, which significantly effect the log's mass and buoyant depth. A rootwad can raise the enter of mass or centroid over 5 times the tree's diameter breast height. Hence, we recommend finding key members with large rootwads. In addition to their mass and greater buoyant depths, the lower surface area to volume of larger logs will result in significantly longer half-lives.

TABLE I Bank Retreat at Site	
Time Interval	Erosion Rate, m/yr
1959 - 67	0.75
1967 - 73	4.0
1973 - 74	24.0
1974 - 76	17.0
1976 - 78	1.0
1978 - 83	0.8
1983 - 90	1.71
1990 - 93	2.67
1959 - 93	3.35

Technical guidelines for revetment designs frequently recommend caution in considering rigid solutions: "Flexible linings are generally less expensive to install than rigid linings and have self-healing qualities which reduce maintenance costs" (WDOT 1995, p. 4-17). Well designed ELJs offer distinct advantages in regard to both of these considerations. One of the most common failure mechanisms of rock rip-rap is scour and subsequent collapse of the revetment's toe which then compromises the overlying rock lining. In contrast, ELJs have strength and elastic properties not associated with most rock structures. When scour undercuts the toe of a ELJ, the interlocking nature of ELJs allow them to settle. Plastic deformation of the structure seals areas of severe undercutting while retaining the structure's integrity. Used in combination with rock or even alluvial sediments, WD can be used to retain the material and add strength to the structure. Estimating the toe depth for ELJs follows a methodology applicable to revetment design. Empirical and analytical models to predict scour around dikes and groins are presented by Klingeman et al. (1984) and Raudkivi (1990). For revetments along channel bends, Thorne et al. (1995), present an empirical model predicting scour depth to within +/-25% observed values. Appropriate

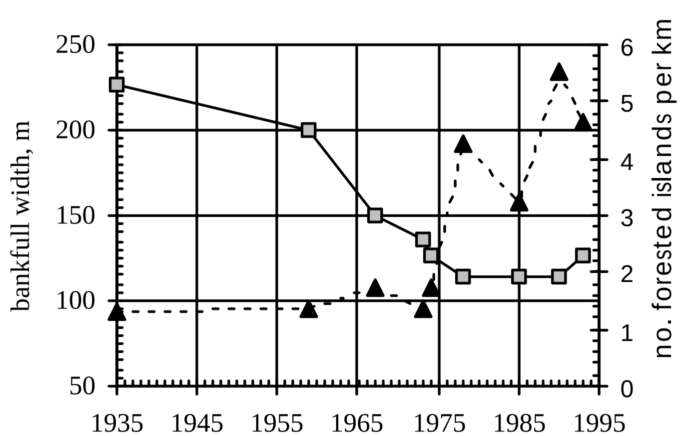

Figure 2 Bankfull widths (triangles) and forested island (squares), 1935 - 1993, Upper Cowlitz River, RK 205-209

predictive models (e.g., Abbe and Montgomery 1996), can be combined with simple reach surveys of maximum scour depths to establish realistic design criteria.

SITE ASSESSEMENT

During initial design planning for the project a 2704 m channel reach encompassing the project was surveyed on the ground and channel position through time was mapped using historical maps and aerial photographs. Average bankfull width for the reach was 195 m based on the most recent aerial photographs in 1993. Channel surveys in 1996 resulted in similar widths, an average bankfull depth of 1.1 m, and a reach average gradient of 0.0035. Pebble counts of the channel bed reveal D_{50} = 51 mm, D_{84} = 98 mm, and standard deviation = 2.2 mm. The 1, 2, and 20 year interval recurrence peak flows are 130, 350, and 860 m^3/s, respectively, based on a gauging station 3 km downstream from the site and a drainage area-discharge analysis of gauging records throughout the upper Cowlitz River basin. Channel cross-sections, bed textures, bedform roughness, and discharge can be used to estimate a range of design values for velocity, drag, scour, and backwater effects. Average meander wavelength, amplitude, and radius of curvature for a 4 km reach bracketing the project site are of 922, 160, and 387 meters, respectively. Examination of channel changes through time provides an effective means of evaluating a range of likely conditions the project will be subjected to.

TABLE II
Structure Changes After Subjected to a 20-year Recurrence Interval Flood, 2/9/96

Jam Site	As-built area (m^2)	Post-flood area (m^2)	Percent Change	As-built wood mass (kg)	Post-flood wood mass (kg)	Percent Change
1	1274	3312	260	36729	85977	234
2	1785	3200	179	45775	89560	196
3	1272	1272	0	42093	42093	0

Average bank erosion rates for the project area were computed by planimetering the area eroded and dividing by the channel length. Average erosion at the site was 2.67 m/yr between 1990 and 1993 to 6.81 m/yr between 1993 and 1995. These rates are within the variance of erosion rates determined along a single transect at the site (Table I). Channel width increased from 127 to 184 m based on aerial photographs and maps dating back to 1935 (Figure 2). Downstream migration of the channel's meander apex at the site averaged 17.4 m/yr from 1959 to 1993. A distinct reduction in the number of forested islands (bordered by channels ≥ 20 m wide) also occurred since 1935 (Figure 2). Using historical aerial photos the majority of islands appear to nucleate around stable WD jams, as discussed by Abbe and Montgomery (1996). Islands and WD jams have substantial ecological consequences, increasing the land-water interface, shade, cover, topographic and textural complexity of the channel, and concentrating flow in several deep channels instead of a wide shallow channel. Possible mechanisms to explain the increase in width and loss of islands include: (i) active removal of in-stream debris since the 1970's removed island nucleation sites; (ii) increased shoreline length treated with rock revetments and an increase in residential landuse has cut-off the recruitment of trees to the channel; (iii) timber removal in the region has significantly reduced recruitment of the largest trees. Secondary effects such as increased runoff and sediment yield from the basin could also contribute to the channel changes.

After design analysis indicated the supply of WD within the project area was adequate, the landowner applied for the appropriate regulatory permission to proceed. Because of the critical role in-stream debris has on fisheries habitat, any alteration of this material is closely regulated by the State of Washington. Project guidelines therefore clearly delineated that the largest and best trees were to be used in the structures, existing in-stream debris would be re-arranged, and in-stream grading would be limited.

The majority of large tree boles in the river and on bars adjacent to the project originated from an upstream portion of the property, many were deposited during the November 1995 flood (slightly less, but similar in magnitude to the 2/9/96 flood). Several boles with attached rootwads deposited along the length of the project shoreline, but the majority of debris had accumulated in a large naturally occurring meander jam at the downstream margin of the project. Evaluation of this structure indicated it was unlikely to protect more than just the downstream portion of the property and its integrity could be maintained while utilizing some of its debris in the upstream structures. Also, a buried WD jam appeared to be protecting a mature patch of *Thuja plicata* downstream of jam no. 2 (Figure 1 B). We chose to utilize this buried jam by constructing one of the structures directly above it.

The number and position of ELJs is based on their size, the predicted change in channel thalweg direction, and the probability that the WD moving through the system will be trapped by the structures (further enhancing their performance). Designs can incorporate empirical guidelines presented by Klingeman et al. (1984) for estimating the downstream flow deflection and length of protected bank that rock groins provide based on their blockage coefficient and the angle within the flow. Stress on the upstream ELJ of an array can be reduced if the first structure is situated at the upstream margins of the meander. Design recommendations for the Cowlitz site were for at least one and preferably two additional ELJs upstream of the existing three structures. But a lack of cooperation by the adjoining landowner constrained the project and the upstream ELJ was positioned at the upstream property boundary (jam no.1, Figure 1 A). The upstream structure is most susceptible to a channel avulsion in which flood flows can incise the bank adjacent to an ELJ. This process can severely compromise the project's performance and is an important factor in design. Where there is some flexibility in accommodating additional short-term erosion, modifications of the upstream portions of the structure to prevent over-flow and incision may not be necessary if the bank has a mature riparian forest. If the forest stand is of sufficient density and tree size, further erosion will recruit additional debris that will add to the original structure further armoring the bank and limiting or even reversing erosion. This scenario occurred at jam no.1 (Figure 1 C) and has already begun to seal the avulsion and further expand the large bar that formed downstream of jam no. 1 during the 2/9/96 flood event. Other channel changes include an increase in thalweg depth and up to 1.4 m in sedimentation in the lee of the key member rootwads along a cross-section at jam no.2 (Figure 3). The large peak flow (20 year recurrence interval) that occurred only 5 weeks after construction enhanced ELJ stability by the deposition of additional WD and sediment (Figures 1 C and 2, Table II). Prior to the project the site had only one shallow free-formed pool < 1m in depth. After the 2/9/96 flood, deep pools (i.e., > 2 m depths) with complex cover formed along each of the ELJs.

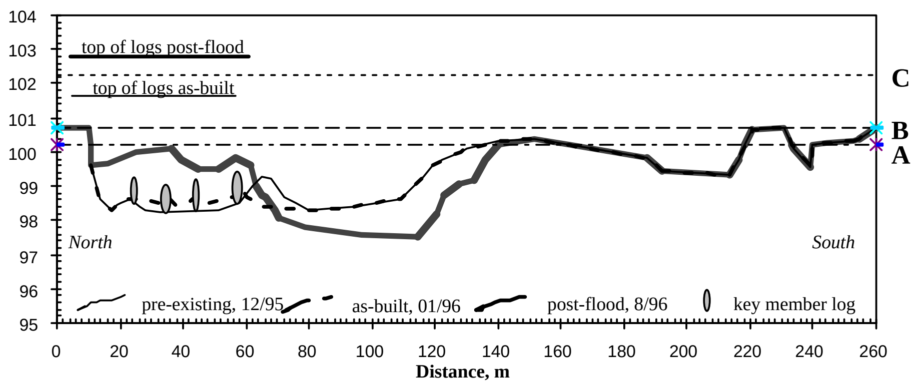

Figure 3 Channel changes at cross-section 2-1, structure no. 2. A, B, and C are estimated bankfull, floodplain, and 2/9/96 flood elevations, respectively.

COMPARISON TO TRADITIONAL BANK PROTECTION

There is a wide range of engineering alternatives available to professionals responsible for limiting river bank erosion (e.g. Klingeman et al. 1984, WDOT 1995). It is widely recognized that some level of geomorphological analysis is fundamental to successful river engineering by providing insight into both spatial and temporal variables limiting project performance. Simple geomorphic observations can answer fundamental questions from defining project objectives to delineating an adequate level of analysis and identifying appropriate hydraulic models. The most under-recognized design alternative in river engineering appears to be modifying human behavior through relocation or adapting landuse and structures compatible to natural fluvial processes. The chaotic appearence of ELJs strongly contrasts the rigid, clean attributes of traditional river engineering, but is more reflective of the forested fluvial systems.

To meet their principle objective of controlling further erosion of their shoreline, the landowners' considered a variety of bank protection strategies, such as a traditional rock revetment, rock groins, and submerged rock barbs (e.g., WDOT 1995). Estimates construct rock barbs or a minimal rock revetment were $50,000 to $225,000. The landowners' also expressed serious concern about the environmental and aesthetic consequences of these and other alternatives presented by county engineers and consultants. When the landowners' inquired about using on-site WD for bank protection, consultants repeatedly presented rock as the only solution. We consider this curious advice as even traditional log structures such as crib-walls, deflectors, barbs, weirs, and pile dikes can often match or exceed the hydraulic, environmental, and economic performance of rock structures.

Construction of a bank revetment about 2.5 km upstream of the project site offers a comparison to traditional rock rip-rap. The upstream site is located along a channel meander on the same side of the river that experienced similar rates of erosion. A rock rip-rap revetment extending over 400 m along this bank was completely destroyed during the November 1995 and February 1996 flood events. A "Emergency Watershed Protection" response by the U.S. Natural Resources Conservation Service involved construction of a larger rock revetment along the present shoreline. Funding was provided by the Federal Emergency Management Administration. The project involved a continuous rock revetment along 683 meters of bank and the construction of several low-crested rock barbs apparently as habitat mitigation. Each of the barbs had a single log oriented about 90^o to the barb axis, the upper portion of the bole buried in the barb, and the rootwad facing downstream. Project construction costs were about one million dollars (Table III). In contrast, the ELJs described here involved a similar situation and scale, but had a total construction cost of about $10,000 paid by the landowner. The cost of the ELJs would have been greater if it had been necessary to purchase and import the WD, however, the cost of rock for the rip-rap project was less than half the typical rate due to inter-agency cooperation. ELJs also offer desirable ecological attributes such as complex bed topography and texture, deep pools, and abundant cover, factors critical to anadromous fish (Lonzarich and Quinn 1995). Complete restoration of many large rivers may be unrealistic, but significant reach-scale improvements can be made.

TABLE III
Cost Comparison of Adjacent Cowlitz River Bank Protection Projects

Project	Shoreline length, m	Project Cost, $ US	Cost per meter	Date
Cowlitz RK 210.0 NRCS High Valley #11, Skate Creek EWP	683	$ 999,253*	$ 1,464	11/96
Cowlitz RK 207.7 (this project)	430	$ 10,000**	$ 23	1/96

* cost does not include design, administration, or oversight and material (rock) cost was $3.50/ton, well below typical cost of $6-10/ton.
** landowner contracting costs; no material cost since on-site logs were used, otherwise the 57 primary logs used would have been about $10,000.

CONCLUSIONS

The results presented here demonstrate that non-traditional structures based on natural analogs, modern river engineering, and fluvial geomorphology, can provide effective river bank protection while also offering significant environmental and economic benefits. Our initial success is encouraging, but the experimental nature of our techniques warrants further research and development. This approach is not ideal for all situations (i.e., high energy confined channel reaches). Nonetheless, we can identify general guidelines regarding ELJs: (i) $D_0/h_{bkf} > 2$, $D/h_{bkf} > 0.8$, $L > 3D_0$, (ii) installation at or below maximum predicted scour depth, (iii) top of ELJ > bankfull elevation, (iv) key member boles at or below channel bed (v) intact rootwads on key and stacked members, and (vi) wood with low decay coefficients. This experimental approach illustrates the potential for integrating natural processes into river engineering in ways that can meet human objectives to limit bank erosion while maintaining or even enhancing aquatic and riparian habitat. The objectives of traditional river bank protection are simply to modify the river's behavior, whereas river professionals are increasingly asked to preserve many of the river's attributes. The best solutions to river engineering often involve not only influencing flow conditions, but human behavior and expectations in these environments.

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