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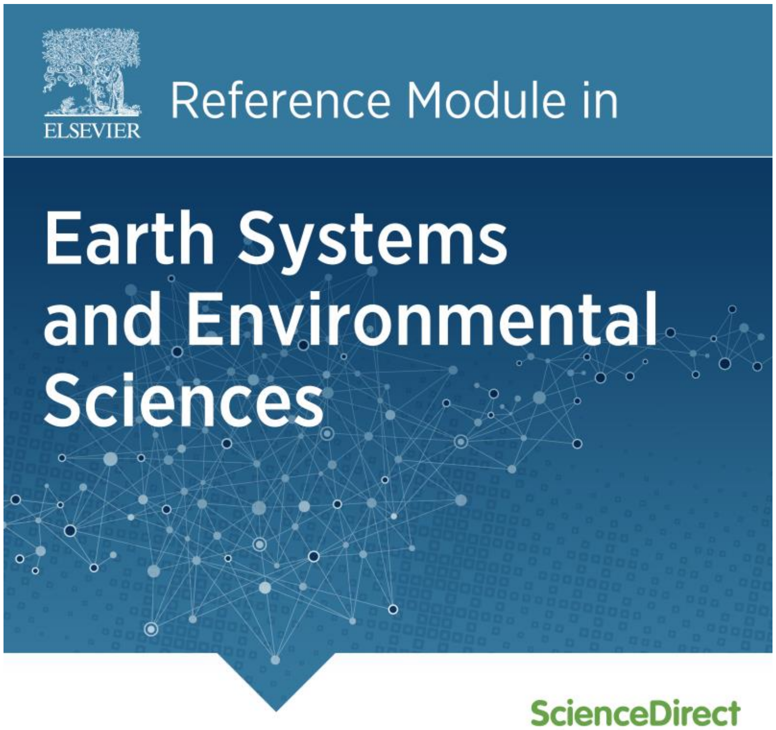

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Abbe Tim, Hrachovec Mike and Winter Steve, Engineered Log Jams: Recent Developments in Their Design and Placement, with examples from the Pacific Northwest, U.S.A., Reference Module in Earth Systems and Environmental Sciences, Elsevier, 2018. 30-Oct-18 doi: 10.1016/B978-0-12-409548-9.11031-0.

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Engineered Log Jams: Recent Developments in Their Design and Placement, with examples from the Pacific Northwest, U.S.A.

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Abbreviations

CFS Cubic feet per second
ELJ Engineered log jam
LWM Large woody material
Q100 Flow with 100-year recurrence interval

Introduction

Wood has been well-established as a material constituent of fluvial systems capable of altering channel morphology and fluvial processes. The published literature partially reflects humanity's relationship with wood. It was widely acknowledged that in-stream wood, even in large rivers, was a serious threat to navigation and capable of influencing fluvial systems. In his treatise on geology, Thomas Lyell (1830) describes logjams creating impoundments 50 km long in the Red River in the southern United States. Several major human activities were largely responsible for the disappearance of wood from fluvial systems of North America, beginning with the decimation of beaver populations. This was followed by massive efforts to clear snags and logjams from large rivers to allow navigation for land development (e.g., Guardia, 1933). Channel clearing and splash damming were widespread practices to transport the immense quantities of timber harvested during the industrial revolution. Homesteading and land development channelized and cleared channels to improve drainage. Wood was even removed under perceptions that it impeded fish passage. Dam construction has reduced downstream wood supply and altered flow regimes can reduce wood recruitment by reducing peak flows capable of erosion. The clearing of riparian and floodplain forests had a lasting impact on in-stream wood by eliminating the sources of functional wood. In many areas, it will take centuries to recover the natural quantities of wood that once existed.

With the disappearance of wood, so went the evidence of its key role influencing fluvial geomorphology and ecology. It wasn't until late in the 20th century that the influence of wood began to be studied in more detail, and over the last three decades wood research grew exponentially (Wohl, 2013; Montgomery et al., 2003). Evidence of wood's role in creating salmonid habitat became a major element of stream restoration programs (USBR and ERDC, 2016). Research has demonstrated that in-stream wood in many montane drainages was singularly responsible to gravel retention and limiting incision (e.g., Montgomery et al., 1996). By partitioning basal shear stress, wood reduces the sediment transport capacity of a stream (e,g., Manga and Kirchner, 2000). Wood removal increases sediment transport capacity which can lead to evacuation of alluvium and channel incision e.g., (Stock et al., 2005; USBR and ERDC, 2016).

Origin and Development of Engineered Logjam Technology

Wood can be a dominant control for fluvial processes and landscape evolution over a wide range of scales from headwaters to large rivers (Lyell, 1830; Russell, 1898; Veatch, 1906; Wolff, 1916; Dacy, 1921; Guardia, 1933; Clay, 1949; Keller and Swanson, 1979;

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Keller and Tally, 1979; Bilby and Likens, 1980; Sedell and Frogatt, 1984; Triska, 1984; Bisson, 1987; Harvey et al., 1988; Hartopo, 1991; Ralph et al., 1991; Lisle, 1995; Abbe and Montgomery, 1996, 2003; Gippel, 1995; Montgomery et al., 1995; Gippel et al., 1996; Montgomery and Buffington, 1997; Manga and Kirchner, 2000; Baillie and Davies, 2002; Brooks and Brierly, 2002; Montgomery et al., 2003; Wallerstein and Thorne, 2004; Brummer et al., 2006; Comiti et al., 2006; Montgomery and Abbe, 2006; Cordova et al., 2007; Magilligan et al., 2007; Mutz et al., 2007; Sear et al., 2010; Collins et al., 2012; USBR and ERDC, 2016). Abbe and Montgomery (1996) showed how natural logjams form "hard points" capable of redirecting flow and changing channel planform. This led to the idea that logjams could offer a natural alternative to traditional bank protection. After giving a presentation on natural logjams at the Randle Ranger Station in Gifford Pinchot National Forest in the summer of 1995, Tim Abbe was approached by a local landowner who was dealing with bank erosion on the Upper Cowlitz River. In December 1995 two logjams were constructed using local materials. Several weeks later there was a major flood in the Cowlitz (January 1996) and the logjams were effective in deflecting the river away from the property. The project initiated development of Engineered Log Jam (ELJ) technology, engineering based on mimicking natural structures and processes (Abbe et al., 1997; Abbe et al., 2003; Abbe and Brooks, 2011; USBR and ERDC, 2016). The reintroduction of wood to streams began before engineered logjams and most projects didn't involve calculations on wood stability and function. It is estimated that over 6000 wood placement projects were constructed in the United States between 1980 and 2005 (Bernhardt et al., 2005). Since the first ELJs were built in 1995, thousands have been constructed around the world and extensive research and improvements have been made.

ELJ technology presented a paradigm change of working with nature versus controlling nature with regards to river management. An ELJ is an attempt to emulate natural structures and processes. Natural logjams directly affect fluvial processes such as flow paths, flow conveyance and water levels, channel morphology and planform, sediment transport and deposition, pool formation, and riparian vegetation (Collins et al., 2012). Understanding these affects, ELJs can used to accomplish human goals such as bank protection in a way that can deliver ecological benefits as opposed to the impacts associated with traditional river engineering. ELJs can also be used to protect infrastructure. For example, ELJs can be an effective means of capturing and managing mobile wood which is often perceived as hazard to bridges and properties during flood events. Properly designed and applied, ELJs offer a valuable tool in sustainable river management.

An ELJ is a human designed and constructed log structure that emulates the functions of historic naturally-occurring logjams to restore riverine geomorphic, hydraulic and sediment transport processes.

The vast majority of ELJs have been used for habitat restoration where they create and sustain pools, form forested islands and anabranching channels, stabilize landslides, locally raise water elevations to improve connectivity to floodplain channels and wetlands, and to trap alluvial sediments. Protect buried pipelines (Abbe et al., 2009), provide bridge protection (Abbe et al., 2003) and reverse channel incision (Abbe et al., 2009). Current work is being to show the value of engineered wood placements in large scale treatment of channel incision and increasing water storage in channel networks.

The most recent guideline on the science and function wood in rivers is the Bureau of Reclamation's National Large Wood Manual (USBR and ERDC, 2016), which presents the science and engineering behind the use of wood for river restoration, including some sections on design and construction of ELJs. This paper presents the development and functional outcomes of ELJ installations with examples of the most recent applications of ELJ technology in the Northwest United States.

ELJ Applications

Bank Protection

In 1999, the first road protection project using ELJs was done for Gifford Pinchot Natinoal Forest in southwest Washington State. The project is located on the Cispus River (fifth order channel Q100 = 27,100 cfs) with goal to to protect a major highway after a rock revetment had failed. The ELJs were built as a series of discrete structures spaced along the edge of the highways road fill and acted to deflect flow away from the highway. The ELJs were constructed of a log crib design and backfilled with alluvium, topped with soil and planted with native trees (Abbe et al., 1997). The structures have acted as an analog to rock groins for their bank protection function, but with significantly greater in-stream habitat value by creating deep pools with complex overhead cover which support rearing and refuge for fish. The structures have remained stable and allowed a riparian buffer to become established between the roadway edge and the river, providing overhanging vegetation for shade and food production (Fig. 1).

Building on the success of this initial work, pile-stabilized ELJs were installed to protect State Route 101 along the Hoh River in 2004, including a series of 4 ELJs upstream from the erosion site to re-direct some of the river's flow prior to reaching the road embankment (sixth order channel, Q100 = 73,600 cfs) away from Highway 101. This flow re-direction successfully restored a single-thread channel into its historic anabranching morphology, resulting in several deep, narrow channel threads and a much more complex pool-riffle sequence, which also resulted in significantly reduced shear stress along the river's edge at the road fill (Abbe and Brooks, 2011) (Fig. 2).

This approach to installing ELJs upstream and out from the river bank was advanced further in the Quinault River (sixth order channel Q100 = 55,800 cfs) beginning in 2008, with the development of a tiered conceptual model to ELJ spacing (QIN, 2008) as shown below in Fig. 3. Closest to the edge of the historic valley margin, ELJs are tightly spaced, preferably within a zone of historic

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Fig. 1 Postconstruction conditions for ELJs installed along the Cispus River, Lewis County, WA.

channel migration and located to re-engage relict channels. This tight spacing functions to disperse incoming flows and reducing shear stress at the valley margins, thereby allowing for re-establishment of a riparian corridor interspersed with side channels, and creating extremely complex habitat conditions and slow, shaded water for salmonid rearing. Stepping out from this edge habitat, ELJs are spaced more widely apart to encourage anabranch conditions and establishment of perennial side channels separated by forested islands. In the center of the river corridor, ELJs are spaced more broadly apart, allowing development of wider central channels. In this zone, the spacing is dictated by accommodating the valley trends in directions and ELJs are located wherever possible at historic island heads. In zones of broad open gravel plains caused by human actions, locations are determined by a geomorphologist, primarily by reviewing historic channel locations as determined by air photos and/or relative elevation mapping.

This approach to restoring anabranching morphology in large rivers was first put into practice in 2008 on the Quinault River as shown in Fig. 4 (Shields et al., 2016). These log pile-stabilized ELJs were installed to provide perennial flow to the inlet of the Alder Creek side channel inlet and prevent the mainstem channel from eroding its connection with the mainstem. The general design layout of the ELJs is illustrated in Fig. 4. This side channel is particularly important as a fisheries resource by providing critical refugia and rearing habitat for juvenile blueback sockeye salmon. The sequence of images first represents a LIDAR image of the post-construction condition, showing the relative height of the ELJs above the surrounding surface. Array of ELJs constructed on large point bar in 2008. (depicted in LiDAR DEM at top). Main channel is in upper right and flowing to right to left (west). The 2009 image shows the initial collection of incoming LWM on the upstream faces of the ELJs and the flow splits occurring around each of the structures on the otherwise-planar gravel bar. By 2012 the river migrated into ELJ 08-10, forming a new pool, added more than 100 ft. of racked wood, initiated new side channels, two new logjams formed, the side channels are more pronounced and ELJs had begun forming forested islands. The final 2013 image illustrates a perennial side-channel which has established to provide steady flows to the head of the Alder Creek side channel; this side-channel has continued to receive a stable inflow due to the riverine response initiated and sustained by the ELJs.

This approach was advanced further in 2012 on the Upper Quinault River with the need to protect the South Shore Road and riverfront residential properties from continuing erosion down-valley of the original 2008 installation. Fig. 5 shows the conditions at and upstream from the South Shore road, with the mainstem channel impinging on the road and private residences. Local efforts had obtained little success in stabilizing the bank with logs tethered to the bank with steel cables. The river continued to erode laterally and down-valley, threatening the continued function of the South Shore road.

The After image (Fig. 5) shows the ELJs having successfully restored anabranch morphology to this reach, with tightly-clustered ELJs along the edge of the valley margins and resulting multiple small channels. These channels have high habitat benefit as they provide a wide range of hydraulic conditions (fast/shallow riffles as well as slow/deep pools) and resulting benefits of gravel sorting to provide stable spawning areas which are critical to the local blueback salmon.

Another major advancement in the use of ELJs to provide bank protection was initiated in 2010 on the South Fork Nooksack river (fourth order channel, Q100 = 24,600 cfs). In this case, a complex timber revetment was installed as an alternative to conventional riprap bank armoring. At this site, a previously-installed riprap bank had continued to fail due to the excessive scour at the toe undermining the riprap. The complex timber revetment was constructed starting with piles driven a minimum of 10 ft. into the river bed. Large rootwad logs were interlaced between the piles, and the logs were ballasted in place with rock sets connected by cables and draped over the log junctions. Additional log members were bolted between the piles to provide lateral interconnectivity in the structure. All bank vegetation removed during construction was incorporated into the structure as well as additional small logs and slash to provide addition cover for fish. This structure has settled into place on the river bank and continues to protect the bank, as trees planted within and upslope of the structure continue to grow and anchor the structure together with root mass and develop a riparian buffer at the river bank (Fig. 6).

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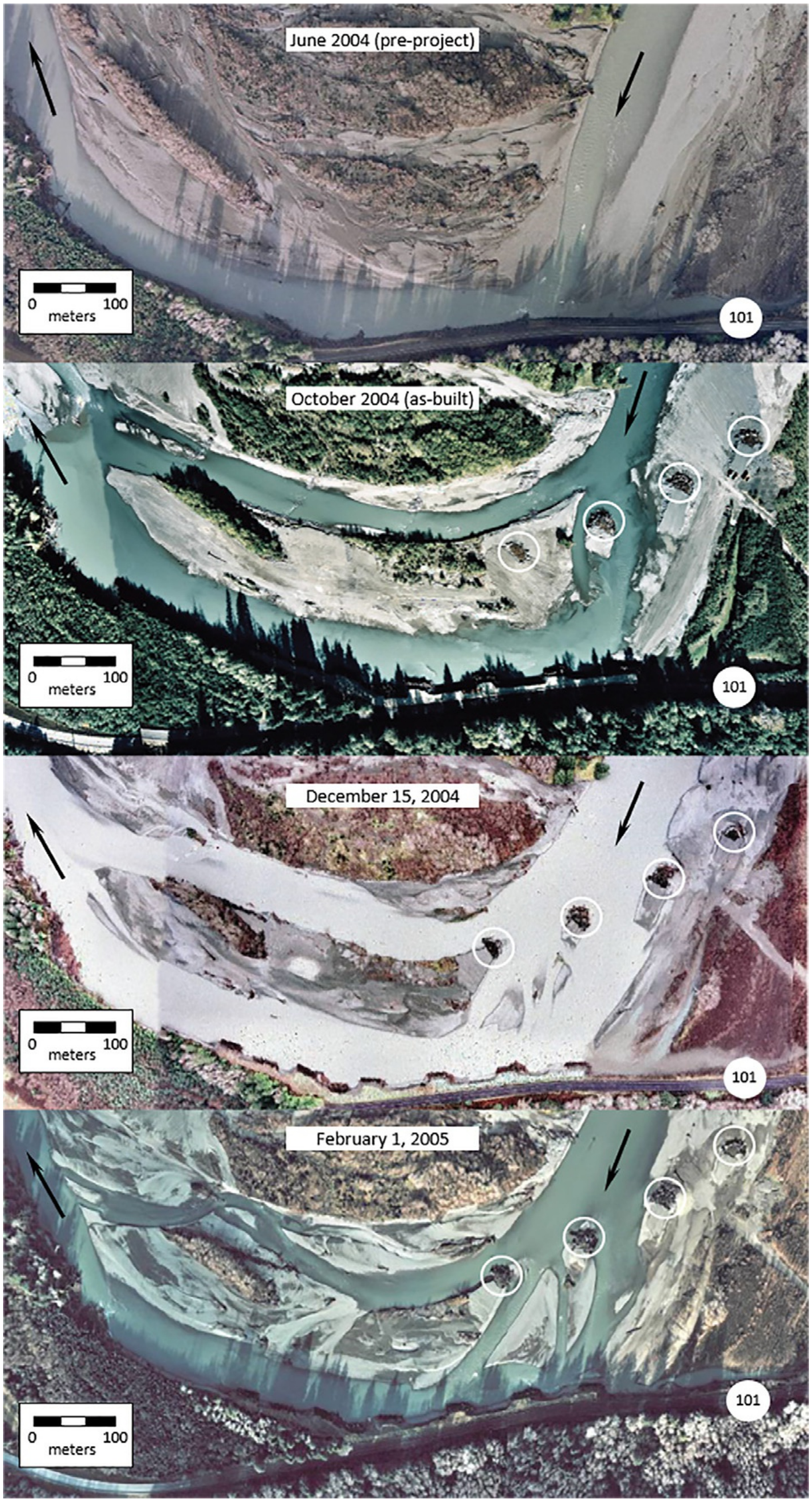

Fig. 2 Time sequence photos of pre-and post-project conditions for ELJs re-directing flows on the Hoh River, Jefferson County, WA.

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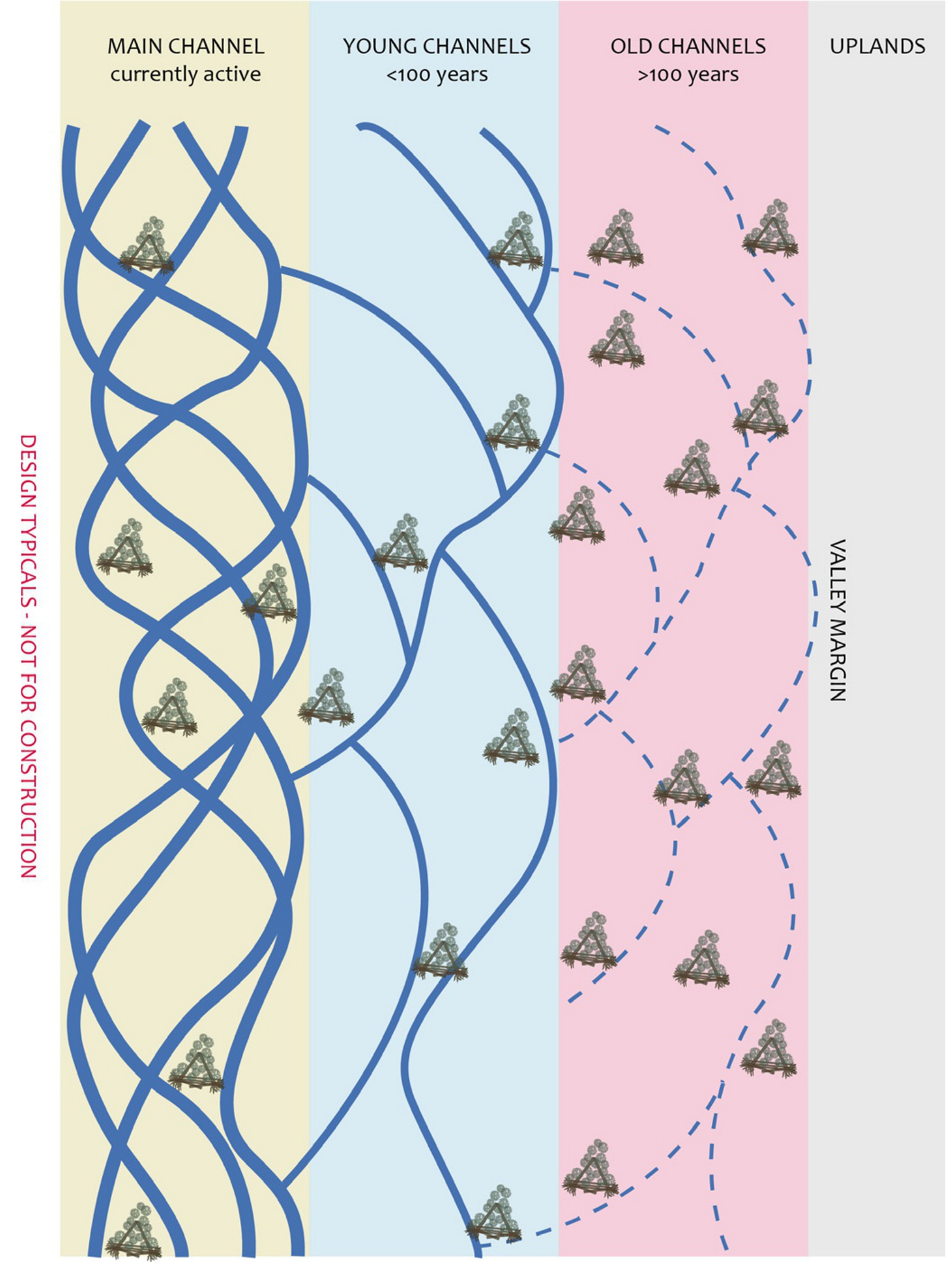

Fig. 3 Conceptual approach to development of anabranching morphology with ELJs in large rivers.

Reversing Incision

ELJs were first used to address channel incision in on Woodward Creek (Abbe et al., 2009). In this instance an existing gas pipeline had been installed five feet below the channel bed, but in subsequent years, channel incision exposed the entire gas line. To protect the gas line from damage a complex ELJ incorporating both interlaced rootwad logs and boulders was designed into a reinforced riffle to provide sufficient protective cover over the gas line and ensure fish passage that had been previously been inhibited by the exposed pipeline. This structure partitioned shear stress through hydraulic complexity at the bed of the channel and has remained stable over time.

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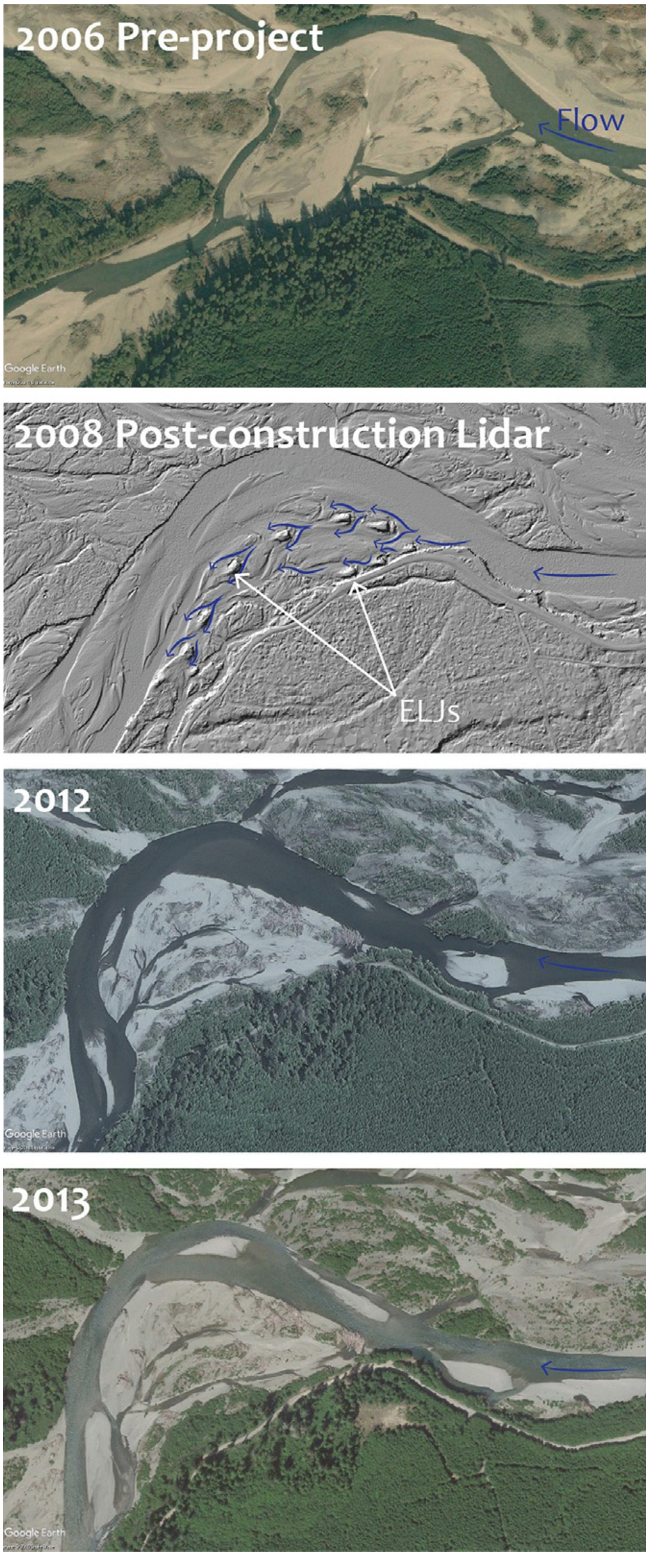

Fig. 4 Development of anabranching channel morphology using ELJs on the Upper Quinault River, Jefferson County, WA.

In 2014 a major advancement in reversing historic channel incision was undertaken on the South Fork Nooksack River fourth. This reach of the river had suffered from extensive ongoing channel degradation resulting from human-caused removal of wood from the channel (Abbe et al., 2009). For this project, full-spanning ELJs were installed as far as 120 ft. across the bed of the channel. These structures have raised the upstream water surface over 3 ft., triggering upstream bed fining which has transformed the reach

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Fig. 5 Preproject (before) and postproject (after) conditions at south shore road Upper Quinault River, Grays Harbor County, WA (this site is downstream of site in Figure 4 and in different county).

Fig. 6 ELJ installed as large wood revetment for bank protection along South Fork Nooksack River, Whatcom County, WA.

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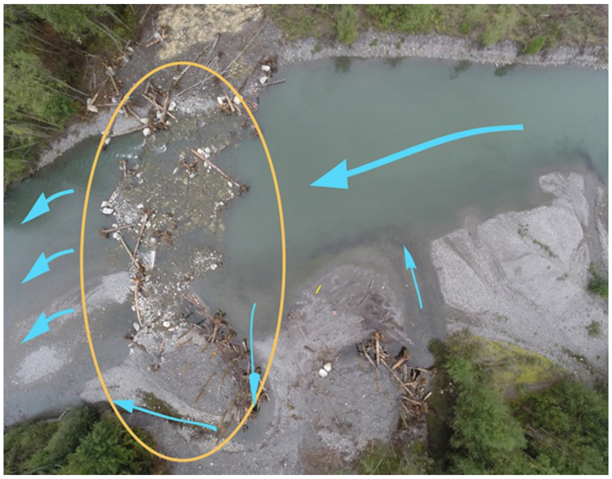

Fig. 7 Channel-spanning ELJs in Upper South Fork Nooksack river, Skagit County, WA.

from a boulder/cobble bed into a small-gravel bed suitable for spawning. In concert with the channel spanning structures, numerous ELJs were installed to direct flows into relict side-channels (Fig. 7).

In 2016, this approach of reversing channel incision with the use of channel spanning ELJs was advanced for Toppenish Creek in Yakima County, Washington (fourth order channel, Q100–4600 cfs). In this case, the design called for using pile-supported collections of partially channel-spanning log structures alternating from different banks and designed to collect and retain incoming fine sediment and gravels. This project was intended to not only reverse recent human-caused incision and reconnect relict channels, but also to increase water storage both instream and within the adjacent soils. This was done with the intent to raise groundwater levels and allow restoration of the historical riparian corridors which had died to due to loss of groundwater associated with incision. Fig. 8 below illustrates before and after conditions, where the groundwater has been elevated approximately three feet and satisfying project goals for arresting bank erosion. Fig. 8 shows pre-project conditions of an entrenched channel and failing stream banks which result in significant sediment inputs as the channel attempts to re-create and inset floodplain. The post-project image illustrates the ELJs shortly after construction, and the 1-year post project photo illustrates the ability of the ELJs to collect and retain incoming sediment, thereby elevating adjacent surface water and groundwater elevations.

Not all project sites can be accessed using ground-based excavators as were used for the examples above. The Ellsworth Creek (second order channel, Q100=340 cfs) restoration project was accomplished concurrent with logging using structures installed using cable logging equipment operating from adjacent ridgetops. The project intent was to reverse historic human-caused incision by installing whole trees in a self-ballasting matrix design that was intended to sufficiently slow incoming flows to trigger deposition of sediments and re-engage flows with adjacent relict floodplains and wetlands. This project advanced the science of ELJ design by incorporating large amounts of slash and racking into a valley-spanning ELJ. As shown in Fig. 9 the segment of channel without ELJs is fast and shallow during winter base flows, with velocities exceeding seven ft/s, a wetted width of approximately 30 ft. and a bedrock channel. The segment of channel with an ELJ has instream velocities less than one ft/s, a wetted width over 15 ft. and a channel of fine sediments.

Building on this success, full-spanning ELJs were installed by hand crews in a -second order headwater channel, Poison Creek (Q100 = 57 cfs), to reverse incision by collecting and retaining incoming fine sediments and re-connecting this deeply incised channel with its historic floodplain. In addition, the project is reducing downstream sediment loads and has caused a rebound in the adjacent groundwater elevations by several feet. It is anticipated that this design may be capable of providing sufficient groundwater storage to increase summer low flows.

Restoring Riverine Physical Processes

In 2010 ELJs paired with strategic excavations were first used to restore and sustain side channels on the Cle Elum River (fifth order channel, Q100 = 19,600 cfs for predam, historic conditions). At this site, the historic side channels have been vertically isolated due to human-caused activities, including bulldozing the channel and cutting off sediment inputs due to an upstream dam. The pair of ELJs succeeded in raising local water surfaces 1 ft. during low flow conditions; this, coupled with local grading at the historic side channel inlet re-connected over 1.4 miles of side channels. In 2014, a second phase of work was performed using a combination of helicopter and ground-based efforts to install 9 ELJs and 25 stabilized snags along 1.5 river miles of the mainstem Cle Elum River. These structures acting in combination to raise local water surface elevations and steer flows into excavated historic side channel inlets have restored over 4 miles of perennial side-channel habitat.

Fig. 10 shows before and after conditions at Side Channel B, where two ELJs working in concert to steer flows towards river left and split out a portion of the mainstem flow into the side channel inlet. Structure locations and flow splits were determined with

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Fig. 8 ELJs installed in Toppenish Creek in 2016 to raise bed level, water levels and stabilize high banks lacking riparian trees. Yakima County, WA.

Fig. 9 Ellsworth Creek with and without ELJs during storm. Pacific County, WA.

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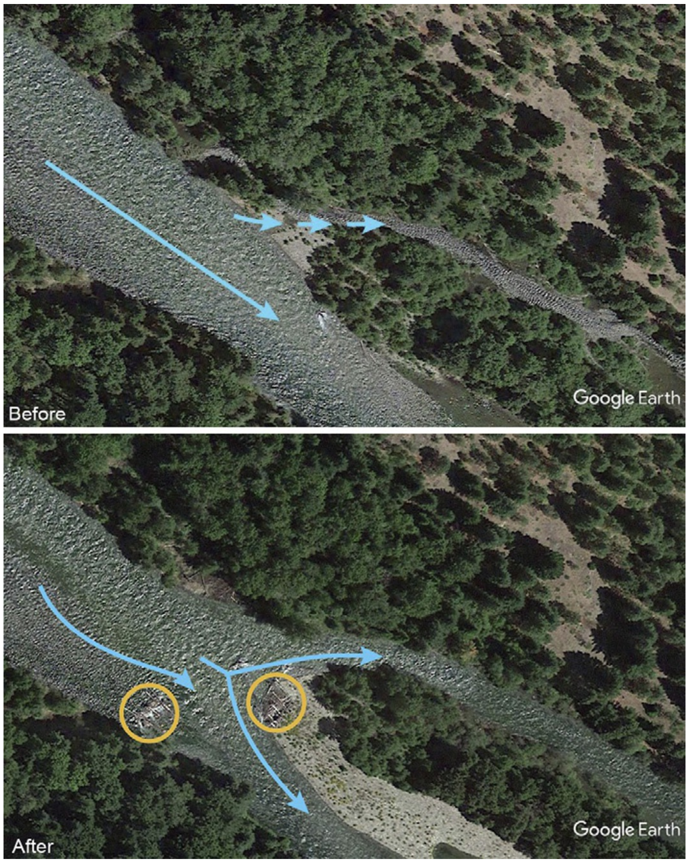

Fig. 10 Two ELJs directing flows into the upper side channel on the Cle Elum River, before and after conditions. Kittitas County, WA.

2-dimensional hydraulic modeling and iterative solutions to attain the desired hydraulic outcome, with predictions for velocity and shear stress on the bed.

In this second example, 2-dimensional hydraulic modeling of this reach identified the need for installation of four ELJs to work together to raise local water surface elevations, direct some portion of the flow river right to restore perennial flow into a historic side channel (Fig. 11).

For over 100 years prior to recent dam removal, the lower Elwha River (forth order, Q100–42,000 cfs) suffered from a lack of incoming sediment, as the natural sediment transport regime was interrupted by the upstream dams. That, coupled with human removal of large native wood resulted in a simplified channel with large aggregate and few deep pools, providing little rearing habitat for juvenile salmonids. To create additional pool habitat, ELJs were installed in 2000, 2002, and 2006; pool depth was found to consistently increase on an annual basis as shown in Fig. 12A, (data from Mike McHenry, Elwha Tribe, in Abbe et al. 2016). Median grain size (D50) (Fig. 12B) was found to decrease from 90 to 19 mm (3.5 to 0.8 in.) over the same time period. This represents a 79% decrease in grain size, which is a result of the stress partitioning caused by the ELJs.

ELJs can be placed to constrict the channel cross-section, causing a backwater condition with decreased average channel velocity. This lowers shear stress at bed level and can cause deposition of smaller-grained materials on the upstream side of the structures. In the case of paired ELJs on Deep Creek (third order channel, Q100 = 2900 cfs), 67% of the channel cross-section was obstructed by ELJs. Fig. 13 shows images of conditions upstream and downstream of the ELJs. Downstream, the bed grain size is in the cobble/boulder size range and unsuitable for spawning. Following ELJ installation, aggradation has occurred and the upstream bed grain size has reduced to a gravel substrate which is suitable for spawning.

Fig. 14 shows conditions prior to the project, immediately postproject and one year postproject for a helicopter-installed ELJ on Big Beef Creek (third order channel, Q100 = 2300 cfs). Twenty ELJS were installed in a single day and were intended to slow flows and increase channel sinuosity sufficiently to transform the reach from a degrading condition to an aggrading condition. One year after construction approximately three feet of gravel have been deposited within and around the ELJ, which not only creates stable spawning for salmonids, but has improved floodplain connectivity. These structures are collecting and retaining incoming small woody material, increasing bed texture and hydraulic diversity and storing excess sediment within the reach. The larger gravel bars, coupled with embedded logs and hydraulic gradient from upstream to downstream ends of the ELJs, have been found to improve hyporheic exchange and result in decreasing instream temperatures.

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Fig. 11 Four ELJs directing flows into a side channel on the Cle Elum River, before and after conditions.

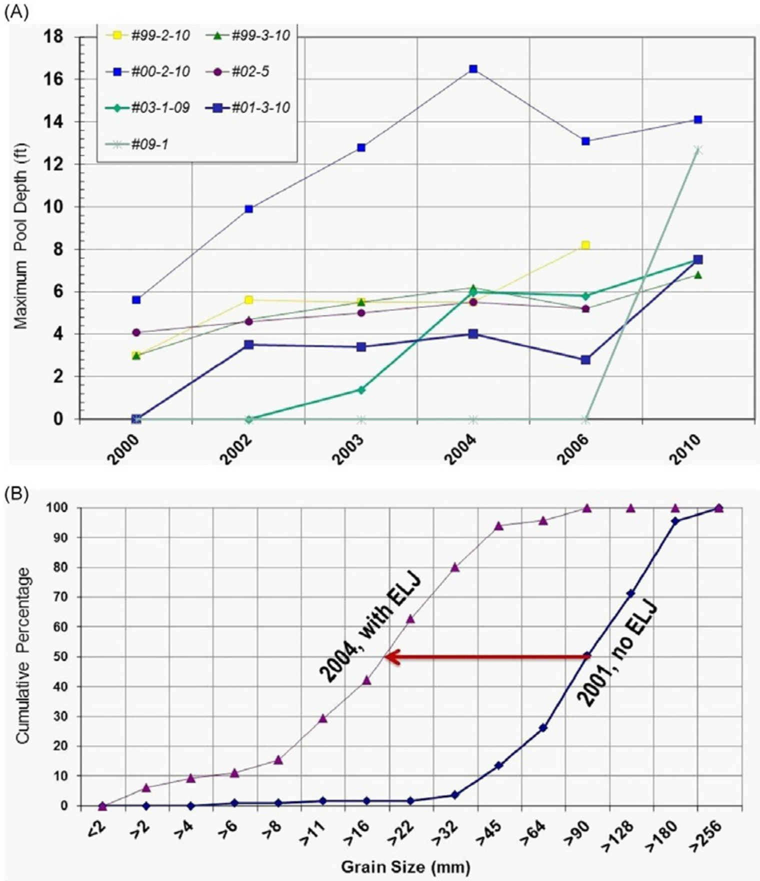

Fig. 12 Increasing pool depth (A) and decreasing grain size (B) following ELJ installation on Elwha River.

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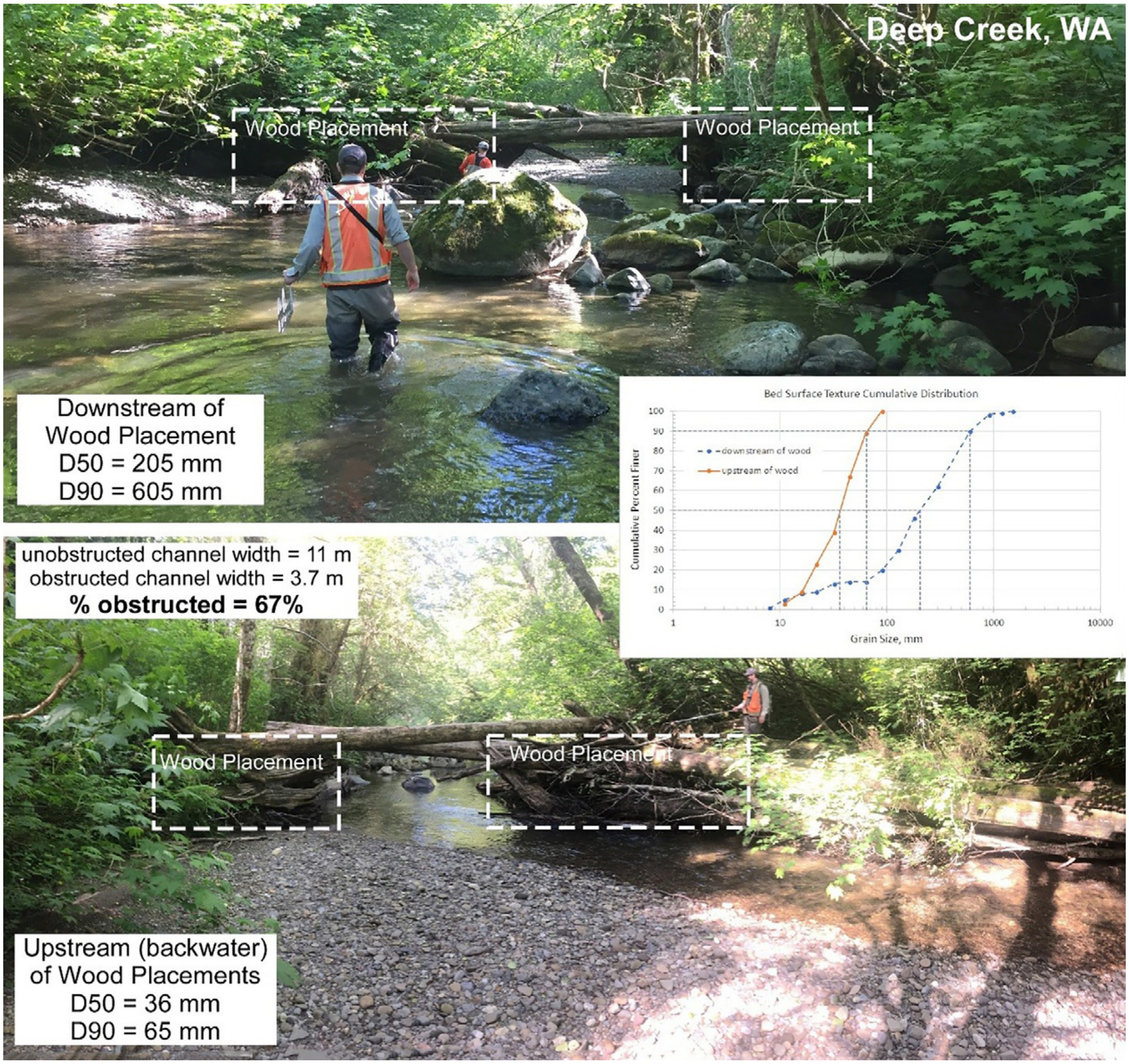

Fig. 13 Decreased upstream channel grain size resulting from ELJ placements on Deep Creek, Clallam County, WA.

ELJ Influence on Stream Evolution

Streams adjust to their boundary conditions, and when boundary conditions change, the stream responds by adjusting its shape. Channel Evolution Models have been developed and refined to establish the types of likely response to perturbations and include implications for habitat (Schumm et al., 1984; Simon and Hupp, 1986; Simon and Thorne, 1996; Cluer and Thorne, 2013). Streams that are adjusting to changes in boundary condition no longer provide the same types of instream habitats that native species have adjusted to, and the pace of geomorphic change can outstrip species ability to adapt. Large wood has also been shown to influence stream morphology and type, even shifting the channel form to a lower energy type (Montgomery and Buffington, 1997; Wohl, 2013).

Using the Quinault River example described above, the channel had been altered in a way that fundamentally shifted the channel type and geomorphic trajectory. Forest harvest and instream wood removal changed an anastomosing channel plan form with vegetated islands to a broad, unvegetated, braided form. The lack of key pieces of wood result in only transitory accumulations of wood and sediment that are easily mobilized by high flows. As a result, forested islands cannot form and the braided channel form persists, increasing the frequency of bed mobilization and altering instream habitats to conditions that do not favor native salmonids adapted to anastomosing systems. The channel is not able to evolve, locked in a lateral migration pattern and is trapped in a loop similar to the Stage 3–4 short circuit in Cluer and Thorne's Stream Evolution Model (2013). The regeneration of forest on

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Fig. 14 Pre- and postproject conditions and 1-year post project conditions for ELJ retaining sediment in Big Beef Creek, Kitsap County, WA. View looking downstream.

the valley margins will eventually result in forest growth to generate key pieces of Large Wood on the valley margins, but the pace of this recovery is likely on the scale of more than 100 years.

Engineered Log Jams provide a mechanism to alter the stream evolution trajectory and allow for aggradation of persistent landforms that would allow for sustainable riparian vegetation establishment-vegetation to speed recovery of the system. Natural log jams have been shown to persist for 100 s of years and can represent some of the oldest forest on the valley bottom (Collins et al., 2012). Engineered Log Jams provide a mechanism to install hard points within the active channel using smaller pieces of wood constructed as stable structures to emulate the function of key pieces to allow riparian forest to regenerate and persist. Installing ELJs can therefore push the system back onto a recovery trajectory in well below the natural time to recovery. By allowing aggradation and persistent vegetation establishment, the system can escape the Stage 3–4 loop and move to Stage 5 and beyond in Cluer and Thorne's Stream Evolution Model.

ELJ Design

The primary question to initiate ELJ design is to determine the appropriate type, size and function of structure that is required to achieve the design objective. Abbe and Montgomery (2003) identified a hierarchy of types and functions of natural logjams that

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vary both by recruitment mechanism and stream order, as well as the degree of effect each type has on the resulting morphology as shown in Fig. 15. For smaller (first–second order) streams, it is common to utilize less formal design methodology and smaller structures. Frequently, these structures are found in nature as having originated from landsliding mechanism and result in log steps or as post-flood debris-deposited structures particularly where the surrounding riparian zone is sufficiently developed to contribute mature trees into the channel that are sufficiently taller than the stream is wide to promote anchoring via entanglement.

As the stream order increases, so do the associated forces of stream power as well as flow depth and velocity. In most settings, the native trees have been removed and the riparian corridor consists of trees substantially shorter and smaller diameter than old-growth. With larger river systems (third order and greater) the riparian forests cannot contribute wood that is stable against flood forces. In this situation, ELJs can provide a structure of sufficient size and stability to resist the flood forces and restore channel physical processes. Flow deflection and apex structures are common design objectives that ELJs intend to emulate as they are frequently found to be capable of altering channel conditions in natural settings. Valley-spanning ELJs are less commonly used due to size and complexity of construction, but can provide significant ecological benefits for reducing flood velocities, developing pools, retaining gravels, and engaging lateral floodplain areas.

Fig. 16 illustrates a flow deflection ELJ installed on the Yakima River (fifth order channel, Q100–24,000 cfs). This pile-supported structure was designed to be sufficiently small in order to have no effect on the opposite bank due to landowner concerns. Rather, it was built to resist forces of flood flows and provide localized fisheries benefits by creating slow-water conditions in the lee of the structure, as well as complex overhead cover and pool formation for rearing of salmonids. In this reach, this series of structures are providing critical slow-water refugia, which is a key limiting factor for juvenile steelhead salmon in this reach. Flow deflection ELJs are likely the most common structure type.

The second-most common ELJ is the apex structure as shown in Fig. 17. The first example is a pile-supported ELJ installed using an excavator on the mainstem Yakima River. The photo illustrates several key attributes of an apex ELJ, including a crescentic pool at

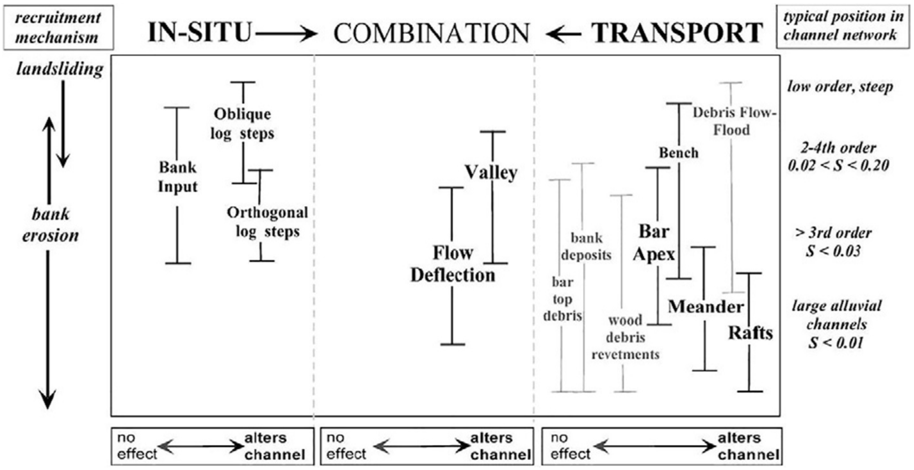

Fig. 15 Type and effect of naturally-occurring log jams (Abbe and Montgomery 2003).

Fig. 16 Flow-deflection ELJ in Yakima River, Kittitas County, WA.

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Fig. 17 Two examples of apex ELJs, Cle Elum River, Kittitas County, WA.

Fig. 18 Naturally-occurring valley log jam, Sullivan Creek, Pend Oreille County, WA.

the upstream face, indicative of flow splitting. This structure is splitting a portion of the mainstem flow into the side channel (photo left) to route flows into a series of bank structures and increase rearing and refuge along the channel margin. A matrix of root wad logs, slash and racking is placed at the upstream face, and the structure is backfilled with alluvium for ballast and to generate eddies in the lee of the structure for additional low-velocity refugia. The pool provides deep water habitat for low-flow refuge and feeding. During storm flows, slack water develops along the structure margins which serves as refugia for juvenile and adult salmonids, and the resulting pool tail-out provides riffle conditions suitable for salmonid spawning.

The second image is of a ballast-stabilized Apex ELJ that was installed via helicopter, then backfilled with local material using an excavator. The flow split into a side channel on river left is clearly visible and is made possible due to locally elevated hydraulics caused by two ELJs placed in conjunction as shown in Fig. 10.

In many cases existing channels have degraded extensively and have become disconnected from their historic floodplain. The natural analog of a valley-spanning log jam has been found to have successfully restored incised channels by reducing velocities and transforming degraded reaches into aggrading reaches. Fig. 18 shows a naturally-occurring valley log jam composed of a broad

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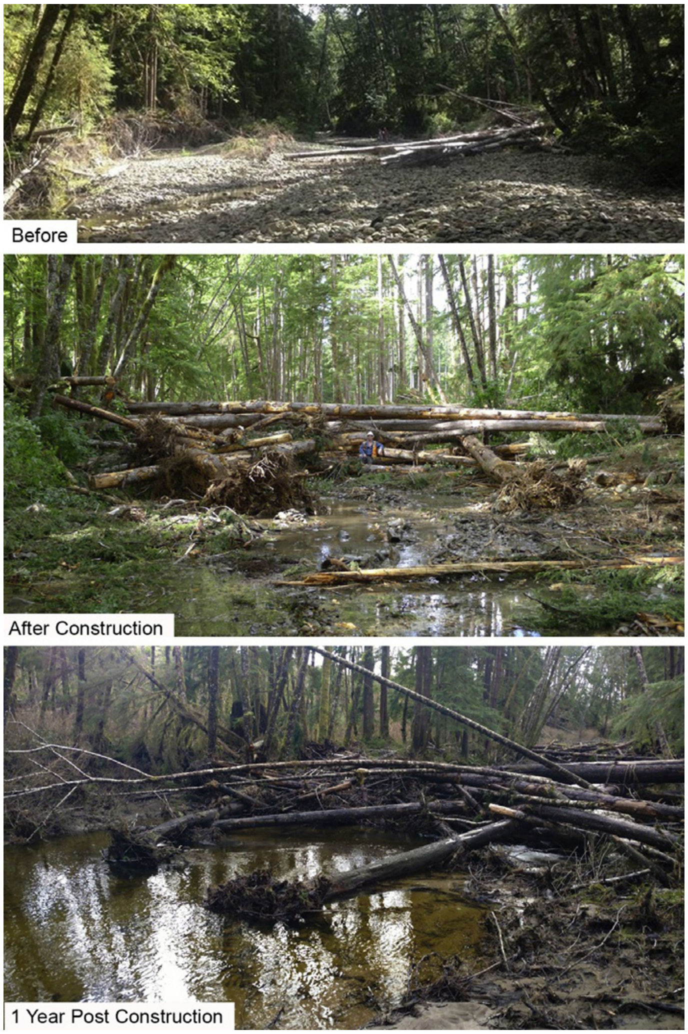

Fig. 19 Valley scale ELJ, pre-construction, post construction and 1 year afterwards. Hurst Creek, Jefferson County, WA.

collection of whole trees and smaller wood, which has achieved a vertical bed rise of over 6 ft. along the 200 ft. structure length. Downstream, the channel is predominantly cobble/boulder while upstream the bed is dominated by small to medium gravels. This structure is located on Sullivan Creek (third order stream, Q100 = 2200 cfs).

Design and installation of a valley-spanning ELJ is an emerging application with initial pilot installations installed beginning in 2015. Fig. 19 shows pre- and postproject conditions at the site where a valley-scale ELJ installed in Hurst Creek (second order stream, Q100 = 2300 cfs) intended to promote aggradation of the channel bed through retaining incoming sediment. This reach had entrenched approximately 4 ft. to bedrock, as a result of logging activities and changing hydrology as well as human removal of the historically-extensive collections of large wood from the channel. This structure was constructed of whole trees using trackhoes, and stabilized by entangling many of the trees into the surrounding riparian corridor.

Ongoing monitoring of the six valley-scale ELJs installed in series has found that sediment is beginning to accumulate in the channel, transitioning the bed from bedrock to small gravels. The 2-year storm is now re-engaged with the historic floodplain, which prior to structure installation had been elevated above the 100-year flow.

ELJ Anatomy

The primary elements of a simple mid-sized ELJ are illustrated in Fig. 20 in isometric and profile views as well as a photo of the installed structure. This ELJ was designed and successfully installed in the Lemhi River (fifth order river, Q100–3200 cfs) to activate a relict side channel and create local pool habitat. Structure stability is provided by six vertical posts driven a minimum of 12 ft. below thalweg. Structural members include four rootwad logs and three cross logs to secure the rootwad logs within the pile array via

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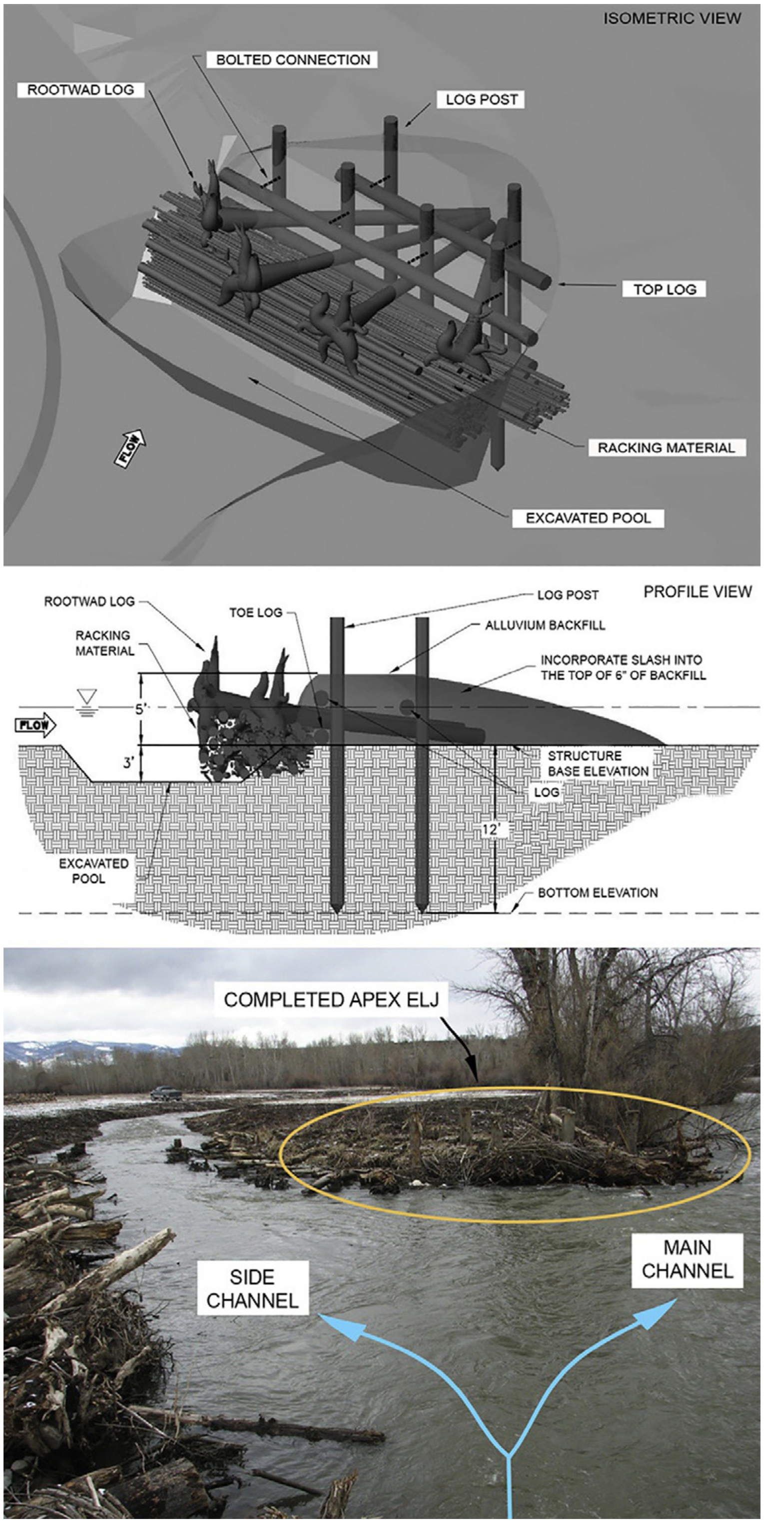

Fig. 20 Design layout and completed apex ELJ at side inlet to perennial side channel, Lemhi River, Lemhi County, ID.

bolted connections. Backfill of native aggregate is placed on the downstream end of the structure for additional ballast and to provide a higher floodplain surface for trees to be planted and create a forested island head (Abbe and Montgomery, 1996). Slash can be installed within the alluvium backfill to provide some structural stability to the fill as well as retain moisture to promote plant growth.

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A key element of successful structure function is to install significant amounts of racking material in the upstream face of the structure. In this instance this racking material is held in place by the overhead trapping rootwads. The racking creates diverse refuge habitat, particularly for juvenile salmonids.

ELJ Regulatory Considerations

Installing large wood in streams in the US typically requires a number of approvals at federal, state, and local levels of jurisdiction. The level of effort to obtain all required permits can vary greatly, often depending of the presence or absence of listed species in the waterway, and the degree of disturbance, and the potential for water surface impacts that extend beyond the property. At the federal level, Section 404 of the Clean Water Act regulates placement of dredged or fill materials, and while the actual wood is not necessarily regulated, the excavation and backfill for many structure types will require approvals by the US Army Corps of Engineers. The federal Section 404 permit then requires Endangered Species Act consultations. The EPA or State will also administer Clean Water Act Section 401 Water Quality Certifications, often focusing on sedimentation impacts to the waterway during construction. State and local regulations vary widely, but typically have a similar process as the CWA 404 that requires review and approval of in-water work. Design of ELJs often needs to be adjusted to meet local regulations that can restrict the type and extent of mechanical connections, timing to minimize impacts to habitat, and the amount of disturbance for access and in water work.

Federal, state, and local floodplain management regulations also will influence ELJ design and installation. The installation of ELJs will need to be integrated into floodplain management schemes. In the United States, FEMA and other floodplain managers typically focus on maintaining or lowering the stage of the 1% annual flood or 100 year recurrence event, termed the base flood elevation (BFE). The installation of ELJs typically has the intent and function of increasing stage for a particular event to change hydraulic conditions so there is the potential for conflict for floodplain regulations. Existing floodplain management procedures have been implicated in habitat losses, as noted by the findings of the Biological Opinions for Washington and Oregon that required changes to existing management to avoid take of salmonids listed under the Endangered Species Act. Therefore, updating floodplain management approaches that recognize that increasing flood stage can be beneficial, and that moving development away from flood hazard zones is the best way to minimize risk and loss in the future.

Discussion

Installation of ELJs in forested drainages is intended to mimic conditions that occurred when large trees were recruited into streams, fundamentally altering how fluvial energy is partitioned and expended down the length of the drainage. Before forests, streams on earth appear to have been broad channels with no bank strength to limit lateral migration (Davies and Gibling, 2011). After tree-like plants evolved, river morphology developed into forms we see today, characterized with generally lower width to depth ratios as vegetation increases bank strength and limits channel width. The removal of wood from forested drainages in the United States is pervasive, so much so that there is little direct evidence of the historical influence of wood on stream morphology (e.g., Wohl, 2014).

The historical influence of wood was predicated on mature forests that could generate large wood available for recruitment to stream channels. In the vast majority of cases in the United States, forest recovery is decades or centuries away from generating large wood at the sizes and rates suggested by the literature (e.g., Fox and Bolton, 2007). ELJs provide a structural method of constructing elements in the fluvial landscape that approach the functioning of the wood loading of the past, so provide a mechanism to accelerate geomorphic recovery of fluvial systems to states that provide in-stream habitat approaching historical conditions to which many aquatic species are adapted for, such as anadromous salmonids.

The design and implementation of ELJs has advanced as practitioners gain experience with this approach. Designs must address the primary forces applied to the structure, as well as systemic changes to the stream bed such as scour induced by flow constrictions. Designs must also fit the landscape context, as large wood will have had different degrees and types of influence in different geologic, geomorphic, and ecological settings. Thoughtful ELJ designs that consider the historic size, placement and structure type have the ability to restore riverine health through restoring the fundamental hydraulic and geomorphic processes that form and maintain a healthy river corridor.

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