3730

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# Trends in Using Wood to Restore Aquatic Habitats and Fish Communities in Western North American Rivers

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*Abstract.*—Advances in understanding wood dynamics in rivers of western North America have led to several important management trends. First, there is a trend away from using "hard" engineering approaches to anchoring wood in streams toward using "soft" placement techniques that allow some wood movement. Second, wood is being placed in locations where channel form and hydraulics favor stability and where wood is likely to accumulate. Third, there is an increased emphasis on passive recruitment of wood from natural source areas (instead of active placement) where the likelihood that it will enter streams through channel migration, windthrow, and landslides is high. Fourth, restoration targets for wood loads are incorporating landscape-scale objectives; thus, managing wood to emulate the spatial and temporal variability produced by natural disturbances is replacing fixed prescriptions for wood in individual reaches. Predicting the effects of wood restoration on individual fish populations in western North America is problematic because local biophysical conditions generate so much experimental noise that it is rarely possible to partition the effects of wood restoration from other sources of variation. Development of appropriate monitoring techniques, combined with a regional network of experimental catchments that include restored and unrestored streams, would help track changes in population status and gauge the effectiveness of wood restoration efforts.

## Introduction

Why use wood? Wood has been used to improve aquatic habitat in rivers for a long time, perhaps longer than any other restoration material. Because wood is an important component of habitat and is widely available, managers have often considered it the material of choice for restoration projects (Hunt 1993). Wood provides habitat structure at relatively little cost compared to many alternatives. It floats, which aids in placement. Wood looks and functions more naturally than artificial structures, and it is an important element of the natural habitat of many fishes.

A common restoration tactic has been to add wood to aquatic ecosystems to initiate habitat recovery until natural processes recruit new material. Frissell (1997) and Frissell and Ralph (1998) provided useful discussions of aquatic restoration in western North America that include reviews of wood placement in rivers. In most cases, wood has been used to enhance habitat for one or two target fish species, not entire communities. Wood has also been used to protect property by armoring streambanks and prevent lateral channel migration, but the majority of wood placement projects in western North America have been meant to create habitat for fish.

There has been a widespread belief among managers of fish habitat that when it comes to using wood to improve habitat, more is better. The following quotes from the National Research Council's report *Restoration of Aquatic Ecosystems* (NRC 1992) is critical of the strategy of adding structure to streams solely to improve fish habitat without understanding fluvial processes.

> Efforts to improve fishing by structural means sometimes also introduce into the ecosystem undesirable, nonbiodegradable materials (e.g., rebar, wire mesh, wire rope, planks, polypropylene, hardware cloth, rubber matting, cyclone fencing, corrugated steel, or fiberglass)...Most structural efforts to enhance fish habitat rely on stone or wood dams, current deflectors and camouflaged wooden bank coverings... Some fisheries biologists believe that "water and space are going to waste" if they are not used by trout and that "...even the best streams could be made better..." by producing more trout in them. To the ecologist interested in stream or river restoration, maximizing the ecosystem for trout, or any single species, is not the same as restoring the biotic structure and function of the stream [p. 229] ...When this work is done without a profound understanding of the interactions among stream hydrology, fluvial geomorphology, and fish, the least detrimental consequence may be that mechanical structures emplaced in the stream at con- siderable expense and trouble could be of limited durability and longevity [p. 223].

Over the last 3 decades, new information on the role and dynamics of wood in aquatic ecosystems has forced a reexamination of the ways in which managers think about the value of wood for habitat and its use in stream restoration (Gregory et al. 1991; Sedell and Beschta 1991; Naiman et al. 2000; Roni et al. 2002). Wood is now generally recognized as an integral part of a restoration strategy that emphasizes natural processes (Bryant 1983; NRC 1996; Frissell and Ralph 1998; Slaney and Zaldokas 1998). The NRC (1992) report suggests broad objectives that are at the core of many habitat recovery plans:

- Restore the natural sediment and water regime. Regime refers to at least two time scales: the daily-to-seasonal variation in water and sediment loads, and the annual to decadal patterns of floods and droughts....
- Restore a natural channel geometry, if restoration of the water and sediment regime alone does not.
- Restore the natural riparian plant community, which becomes a functioning part of the channel geometry and floodplain/riparian hydrology. This step is necessary only if the plant community does not restore itself upon achievement of objectives 1 and 2.
- Restore native aquatic plants and animals, if they do not recolonize on their own. [p. 207]

These objectives, generally accepted by ecologists, have shaped emerging trends in the way wood is being used for aquatic restoration. The goal of this paper is to summarize how these trends are changing wood management in river systems of western North America. We call for increased effort in developing monitoring protocols for wood restoration projects, especially in monitoring the direct impact on targeted populations of the species of interest, to better measure the relative success of restoration efforts and to improve future restoration efforts.

## Trend 1: Soft Engineering Methods Are Becoming More Common in Disturbance-Prone Systems

Until fairly recently, the approach to wood restoration has been to engineer wood structures and anchor them solidly in stream channels. The size, location, and configuration of wood structures have been engineered to provide habitat for game fishes, especially to enhance deep pools and overhanging cover. R. L. Hunt's *Trout Stream Therapy* (Hunt 1993) provides excellent illustrations of well-anchored structures designed to enhance trout habitat in North American streams in the upper Midwest, where spring-fed brooks have relatively stable flow regimes. The U.S. Forest Service's *Stream Habitat Improvement Handbook* (Seehorn 1992) discusses a similar approach in which solidly engineered wood structures have been used in streams in the southeastern United States (Figure 1). Procedures used to locate and anchor wood involve burial using heavy equipment, tethering the wood to the streambed or bank with stainless steel cable and waterproof glue, anchoring logs with metal reinforcement rods (rebar), and building clusters of logs and boulders held together by decay-resistant materials such as cable or steel mesh fence. These procedures are termed "hard" engineering because the goal is to maintain structures exactly as installed and prevent them from moving during high flow.

There are numerous examples of wood restoration projects in which individual pieces or clusters of pieces have been securely anchored to the bed, streambanks, or rock outcroppings in an attempt to keep them from moving during freshets (British Columbia Ministry of Environment 1980; Duff and Wydoski 1988). Anchoring wood structures has been based on a combination of concerns about maintaining good fish habitat in the area targeted for restoration and potential liability caused by materials floating downstream and damaging property or endangering life (Rosgen and Fittante 1986). In some instances, solidly anchored wood structures have been both durable and successful at emulating the effects of natural wood in channels. For example, the log weirs studied by Riley and Fausch (1995) and Gowan and Fausch (1996) produced a pool frequency that resembled the frequency of log-formed pools in streams flowing through old-growth forests in the Rocky Mountains of northern Colorado (Richmond and Fausch 1995).

However, there are also examples of restoration projects that were damaged or failed because structures moved, broke apart, or otherwise did not function in the way they were intended (Frissell 1997). Most projects have not been monitored, but one well-known study of habitat restoration in Oregon and Washington (Frissell and Nawa 1992) documented a relatively high loss rate of structures over a 5–10-year period that included several large floods (Figure 2). The principal causes of damage included anchor bolt and cable failures, scour underneath the structure, streambank erosion and lateral channel migration, and burial by sediment. Damage rates were highest in streams of the southern Oregon coast where intense freshets were common. The most durable structures were cabled natural large wood and logjams; the least successful structures were log weirs and log deflectors.

Concerns about project longevity and the failure of certain types of hard engineered structures to persist over time have led to new approaches in which placement of wood and methods of attachment better emulate the natural location of wood in channels (also see Reich et al. 2003, this volume). New methods are less reliant on cables, bolts, and rebar, and greater attention is given to utilizing wood of the appropriate size and species for the site. There is evidence that this "soft" engineering approach has led to project improvements. In one recent survey (Roper et al. 1998), persistence of habitat restoration structures, many of which were emplaced using soft engineering methods, during floods increased. Of 3,946 structures surveyed in 94 streams in Oregon and Washington, they found that fewer than 20% had been removed from sites experiencing floods ranging from 5- to 150-year return intervals (Table 1). Habitat structures were installed with heavy equipment and usually involved large logs greater than 30-cm diameter. Many structures were secured to the stream by cables or partial burial, so in effect, they combined soft and hard engineering techniques. However, logs were placed in such a way as to resemble natural wood location and to withstand heavy flooding characteristic of the Pacific coastal ecoregion. Most did not employ design specifications typical of wood restoration projects in eastern North America. Habitat structures made of partially buried logs or boulders proved to be more durable than structures made of clusters of logs and boulders cabled together. Logs with one or both ends anchored to or buried in streambanks were more durable than logs tethered to the middle of the channel. There was a decrease in durability as stream size increased, and structures in drainages with high landslide frequency were less durable than those in areas with stable valley walls.

The question of whether to cable or otherwise anchor logs to the streambed or streambank is addressed by several authors elsewhere in this book (for example, Gregory 2003; Abbe et al. 2003; Montgomery et al. 2003; and Reich et al. 2003; all this volume). Proponents of cabling argue that preventing movement of wood placed in the channel is needed to safeguard lives and property downstream and that habitat may be lost on site if structures are displaced. Opponents of cabling argue that wood movements are a natural feature of channel dynamics and that floated wood will assume locations within the stream that are fa-

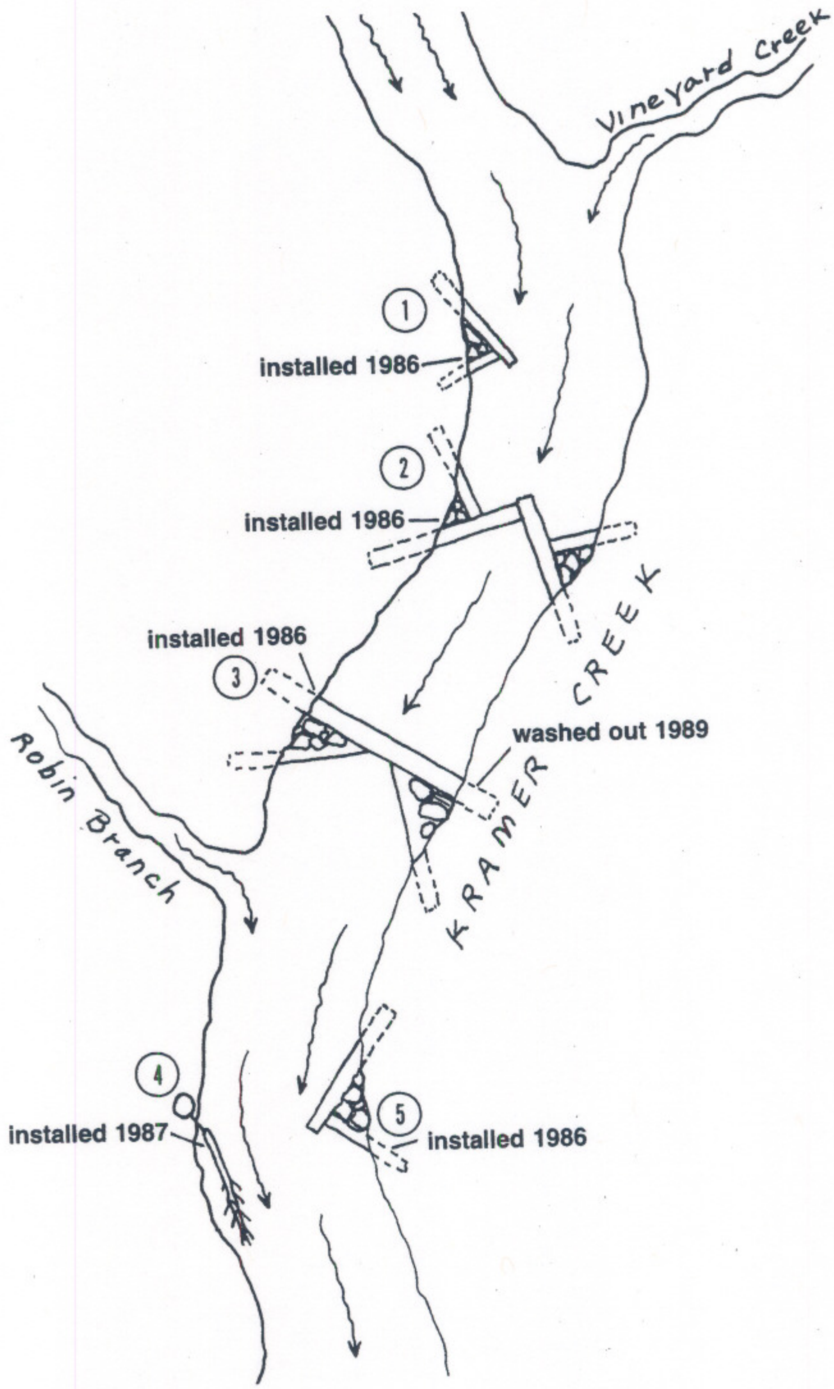


FIGURE 1. Examples of stream habitat restoration structures utilizing hard engineering techniques and relatively uniform spacing (from USDA 1992).

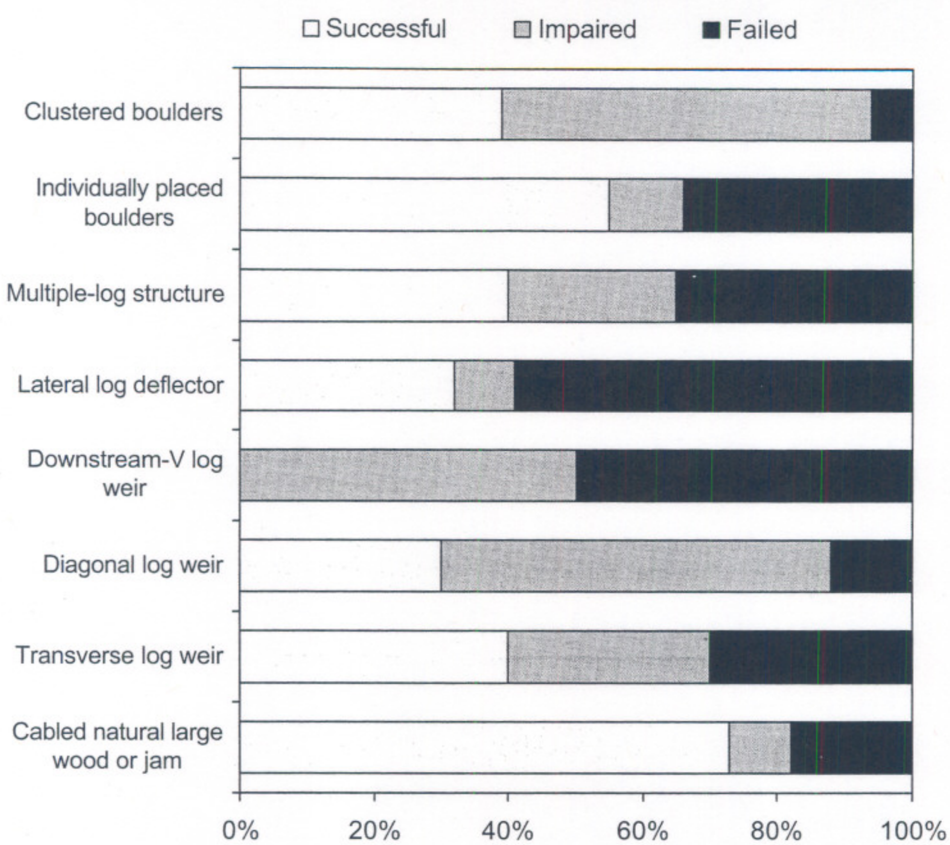


FIGURE 2. Rates of impairment and failure for 161 structures in western Oregon and Washington streams 1–5 years after emplacement (after Frissell and Nawa 1992).

TABLE 1. The persistence of 3,839 habitat restoration structures in streams of Oregon and Washington following severe flooding in 1995 and 1996, based on Roper et al. (1998). Sample size refers to the number of individual structures surveyed. "In place," "shifted on site," and "removed" structure categories approximate the "successful," "impaired," and "failed" categories, respectively, in Frissell and Nawa (1992).

| Stream order | Sample size | Flood frequency (years) | Structure movement category In place (%) | Shifted on site (%) | Removed (%) |
|---|---|---|---|---|---|
| 2 | 176 | <40 | 83 | 8 | 9 |
| 2 | 157 | ≥40 | 70 | 20 | 10 |
| 3 | 794 | <40 | 70 | 21 | 9 |
| 3 | 702 | ≥40 | 64 | 19 | 17 |
| 4 | 711 | <40 | 76 | 15 | 9 |
| 4 | 847 | ≥40 | 51 | 31 | 18 |
| 5 | 118 | <40 | 60 | 20 | 20 |
| 5 | 334 | ≥40 | 41 | 17 | 42 |
| | | Average[a] | 64 | 21 | 16 |

[a] Averages were weighted for sample size.

vorable for the full spectrum of ecological functions it provides. Because the question involves both ecological and social considerations, there is no categorically correct or incorrect answer. However, there is general agreement that engineered structures have a higher probability of remaining in place if they are positioned in such a way that they can withstand high flows, and this may or may not require the use of artificial materials to increase stability. The vast majority of recent improvements in project durability have been made possible by placing wood in locations where channel form and hydraulics naturally favor stability.

## Trend 2: Wood Placement Is Guided by Fluvial Patterns

Attempts to use wood to improve fish habitat have sometimes involved placing structures at more or less fixed intervals with little regard for natural patterns or even the appropriateness of placing wood in a particular stream reach (Heede and Rinne 1990; NRC 1992). More attention is now being given to placing wood in areas of the stream and its floodplain where it is likely to occur naturally and where it can provide for a more complete range of ecological functions (Sedell and Beschta 1991). An illustration is seen in the design of a large river restoration project in western Washington (Abbe et al. 1997). The location and structure of wood accumulations in a comparatively pristine system, the Queets River on Washington's Olympic Peninsula, were thoroughly studied and stable logjams mapped relative to channel and floodplain features (Figure 3). Insights into naturally stable accumulations of wood (Abbe and Montgomery 1996) were used to design logjams in the Cowlitz River (Figure 4) that created deep pools, provided protection against continued streambank erosion, and anchored the formation of vegetated gravel bars. The cost of the project was less than 2% of the cost of comparable streambank protection involving rock groins and revetments (Abbe et al. 1997).

Mobility of wood pieces and the degree of clumping along streambanks is strongly influenced by stream size and the intensity of high flows (Bilby and Ward 1989, 1991; Gurnell 2003, this volume). In small streams, large wood moves only short distances before it is trapped by channel or bank roughness elements (other logs, large boulders, confined valley walls). In larger streams, fluvial transport of wood typically moves pieces longer distances and results in jams along the channel edge (Richmond and Fausch 1995; Bilby and Bisson 1998). Understanding the transport characteristics of wood as a function of stream size aids resource managers in placing wood to mimic natural processes.

Many projects enhance both durability and ecological function by using very large logs and rootwads, either individually or in combination with smaller logs, to provide a secure foundation for the structure. These logs, termed "key pieces," are often larger than needed simply to resist movement in the channel. They act as a nucleus of accumulation, trapping smaller logs and branches, coarse sediment, and particulate organic matter. Habitat structures anchored by large key pieces better resemble those found in natural accumulations than those found in single small to medium-sized logs or simple clusters. In addition to providing pool habitat, complex cover exists within the jam. A low-gradient riffle is often created where sediment accumulates above the jam, and the entire wood-sediment complex serves as a site for organic matter processing and nutrient regeneration (Bilby and Bisson 1998; Bilby 2003; Wondzell and Bisson 2003; both this volume). Wood-sediment complexes also promote development of complex hyporheic water pathways that serve a variety of ecological functions (Triska et al. 1989; Duff and Triska 1990; Haggerty et al. 2002). Use of key pieces is central to many wood restoration project designs (Doppelt et al. 1993), and project managers are finding that the increased cost of large logs is offset by their long-term durability and improved ecological function. Managers are recognizing the detrimental outcomes when wood is installed in channels where it would not normally be abundant (Dominguez and Cederholm 2000). Certain types of channels (for example, those in low gradient meadows, high gradient cascades, and narrowly constrained canyons) are not appropriate candidates for wood restoration projects.

It can be very difficult to restore wood to levels that approximate the range of conditions occurring before human disturbance at the scale of an entire catchment. Reeves et al. (1997) describe a case study in western Oregon in which habitat restoration was attempted throughout a 171-$km^2$ drainage system that had been extensively logged and had experienced a major flood in 1964. Fish Creek, a fifth-order tributary of the Clackamas River, had abundant wood and pool habitat prior to timber harvest and a 100-year flood (pools were estimated at 45% of the stream area in 1959). Im-

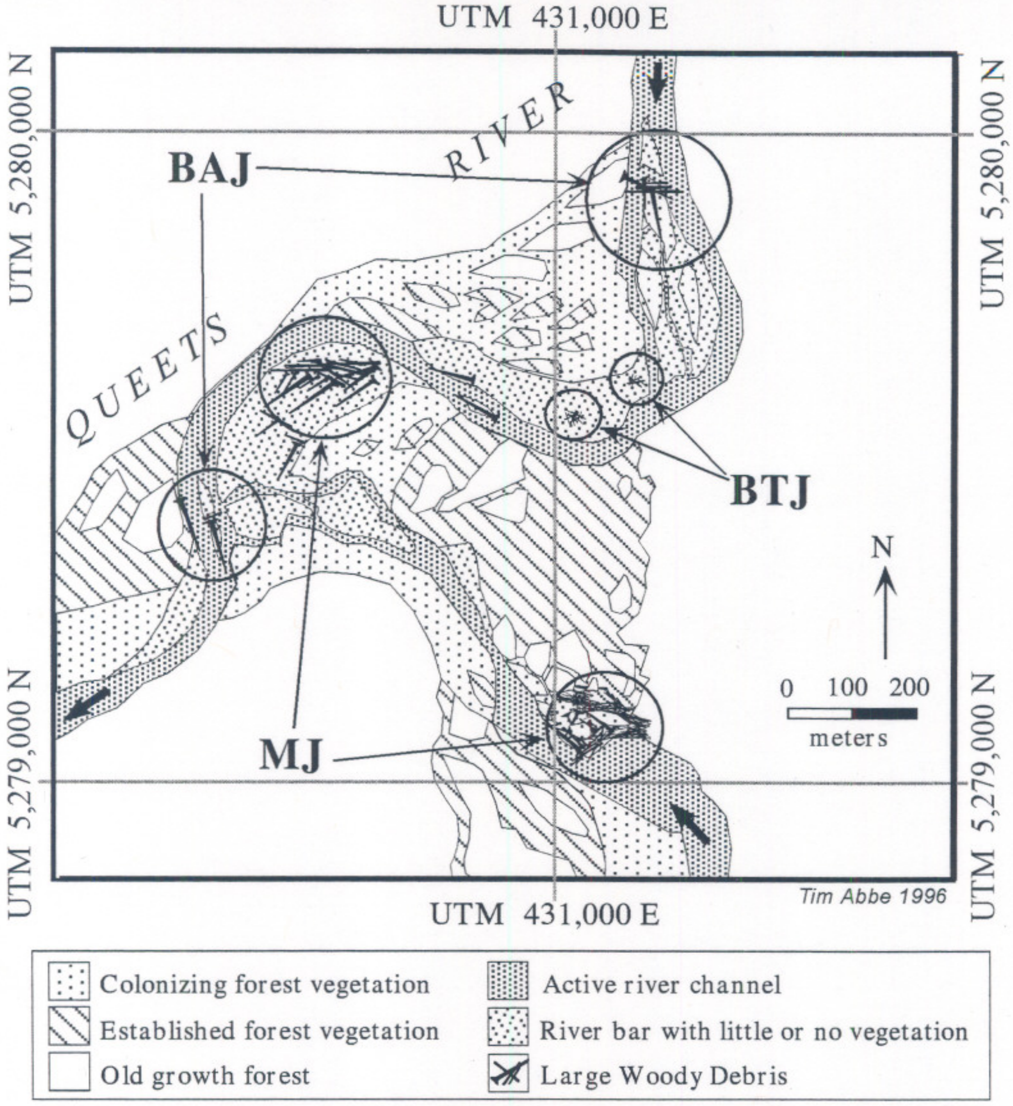


FIGURE 3. Distribution of natural wood accumulations in or near the channel of a large, relatively pristine river (Queets River) in western Washington. BAJ refers to bar apex jam, BTJ refers to bar transverse jam, and MJ refers to meander jam. From Abbe and Montgomery (1996) with permission from Regulated Rivers: Research and Management and John Wiley and Sons Limited.

mediately after the flood, pools comprised only 27% of the channel area, and by 1982, they constituted only 11% of the stream area as a consequence of wood removed from the channel during salvage logging operations. From 1982 to 1988, approximately 1,400 large wood and boulder structures were placed in Fish Creek at a cost of several hundred thousand dollars to create rearing habitat for salmon and trout. Many of the structures were solidly cabled to the streambed to prevent movement during high flow, and most were designed to withstand the hydrologic rigors of the region. During the period when structures were installed (1982–1988), pools ranged from 8 to 21% of the channel area; from 1989 to 1995, after completion of the restoration project, pools increased to 19–39%. Large storms in November 1995 and February 1996 resulted in major flooding and 236 landslides in the

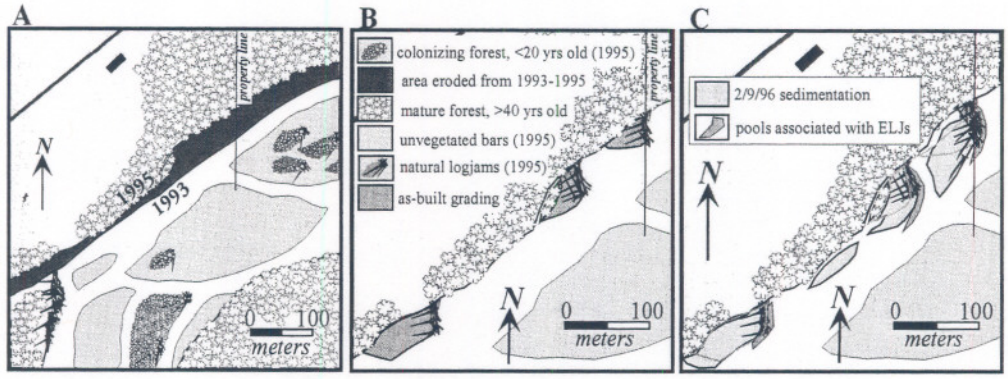


FIGURE 4. Plan view of a wood restoration project modeled after the location and structure of wood accumulations in a natural river (see Figure 3). Panel A shows the reach between 1993 and 1995; panel B shows the channel after the installation of three engineered log jams; panel C shows the channel after a major flood in February 1996. ELJs refer to engineered log jams. From Abbe et al. (1997) with permission.

watershed. Reeves et al. (1997) estimated that 49% of the structures were removed from the drainage by high discharge and debris flows. Following these two large storms, pool area declined to 33%, a percentage similar to that observed before the restoration period.

The high cost of restoration and the limited durability of wood structures in Fish Creek illustrate the difficulty of re-establishing wood in a relatively high-energy catchment. Much of Fish Creek consists of geomorphically constrained, high gradient (>4%) channels, and the large boulder and bedrock dominated substrate is typical of streams draining the Cascade Mountains. Previously wood was abundant but dominated by pieces from old-growth forests with partially intact rootwads and branches—characteristics needed for durability in high-energy systems but very difficult to replace. The study shows that even securely anchored structures have high failure rates during large floods and debris flows. Faced with this dilemma, managers are placing a higher priority on protecting and restoring natural source areas for future wood recruitment rather than on expensive, high maintenance, in-channel structures. This has resulted in the third general trend in wood management.

## Trend 3: Emphasis Is Shifting from Active Intervention to Passive Restoration

Except for extensive restoration efforts such as in Fish Creek, projects involving deliberate placement of wood usually affect only a small percentage of the channel network. Provisions for long-term wood recruitment are likely to be more important than short-term wood placement (Sedell and Beschta 1991). Large natural disturbances (fires, floods, and insect and disease outbreaks) create a landscape mosaic of different forest ages and species. Individual streams cycle from low to high wood loads as channels fill with, and flush, accumulated sediment and wood over periods that may span centuries (Benda et al. 1998). At any point in time, some streams will be highly loaded with wood, while in others, large wood will be relatively scarce. In montane landscapes, aquatic productivity changes from low to high to low levels again as streams accumulate wood and coarse sediment gradually through windthrow or channel meandering or rapidly through landslides and then lose this material gradually through decomposition or rapidly during brief but intense disturbances such as debris flows (Benda and Dunne 1997). From a management standpoint, the outcome of natural disturbance and recovery cycles is that some areas are highly productive for fishes and other aquatic species, while others remain relatively unproductive until erosion and fluvial transport restores structure and complexity to stream channels (Reeves et al. 1995). Viewed in this way, protection of wood source areas—riparian zones and landslide-prone hillslopes—and the processes that deliver wood to streams—windthrow, lateral channel movements, mass wasting—become important landscape goals (Reeves et al. 1995; Gregory and

Bisson 1997; Connolly and Hall 1999; Beechie et al. 2000; Benda et al. 2002; Boyer et al. 2003, this volume).

Passive restoration approaches that rely on natural processes to improve streams are recommended by the National Research Council to recover aquatic habitats where anthropogenic damage has not caused irreversible loss (NRC 1996). This is not to say that deliberate addition of wood has no place in habitat restoration, but rather that decisions about wood placement should be grounded in the context of the overall condition of the watershed and focused primarily on streams in which recruitment of new wood from adjacent riparian areas and hillslopes, if it occurred historically, is no longer possible. Wood restoration may be desirable to rapidly improve habitat while trees grow in source areas and are recruited to the stream, but with the understanding that the longevity of wood structures in river basins prone to flow extremes and high rate of erosion is limited.

Some landscape management plans allow future disturbances to deliver wood to channels by leaving protected riparian zones and headwater areas in locations likely to deliver wood to the stream network over time (Sedell et al. 1994; Cissel et al. 1998). Concerns are often raised that extreme natural disturbances, such as very large floods or wildfires, cause such damage to aquatic habitats that ecosystem recovery is unacceptably delayed or even rendered impossible without aggressive restoration. Certainly, western North America has experienced large natural disturbances over the last century, including floods, extensive wildfires, prolonged droughts, and volcanic eruptions. Yet the resiliency of native flora and fauna has been widely documented (for example, Franklin et al. 1985; Minshall et al. 1989; Swanson et al. 1998), and studies of ecological recovery after disturbances affecting wood abundance suggest that long-term restoration effectiveness is strongly influenced by the re-establishment of wood source areas that may include areas immediately adjacent to the stream as well as upslope sources (Benda and Cundy 1990; Reeves et al., in press). Depending on the extent of human disturbance and the potential for recovery, passive restoration may not require commitment to extensive instream structure addition as long as natural wood recruitment processes are preserved. (Boyer et al. 2003) The need to balance active and passive wood restoration approaches over entire drainage networks has resulted in a fourth trend.

## Trend 4: Wood Restoration Goals Are Being Defined at Larger Scales

Fixed restoration targets for wood abundance, usually expressed as numbers of pieces of large wood per unit length of channel, tend to be based on expected reference conditions, usually counts of wood within a relatively pristine river reach. However, fixed wood abundance targets do not easily account for natural variation among reaches or the habitat requirements of different aquatic species. When management plans set fixed standards, spatial and temporal variation in wood abundance is likely to be considered a "sampling problem." One consequence is that the differences in habitat requirements among species are often ignored. A more recent trend is for management plans to recognize that variation in wood abundance is an important part of the spatial and temporal variation present within landscapes and to include that variability in restoration planning.

Natural disturbances generating habitat variation are part of the environmental template for the evolution of aquatic species. The maintenance of genetic and phenotypic variation needed to cope with environmental change allows populations to persist in the face of habitat disruption (Scudder 1989; Poff and Ward 1990; Reice et al. 1990). Complex mosaics of aquatic and floodplain habitats are necessary to fulfill different fish life history requirements and for a full range of environmental conditions needed to maintain regional biodiversity. Fixed reach-level wood targets have the effect of homogenizing wood loads across a drainage network. Attempting to maintain constant levels of wood in all streams at all times may be unrealistic and contrary to natural patterns and processes.

Alternative approaches to restoring wood in river systems consider how disturbance processes affect wood distribution and abundance throughout the fluvial network. Roni et al. (2002) present a hierarchical strategy for prioritizing habitat restoration for salmon in the Pacific Northwest. The strategy begins with identification of those parts of a watershed that remain ecologically healthy or nearly so (that is, that contain high quality habitats and support the range of ecological functions needed to maintain them). After such areas have been located, corridors of good habitat are established between them that facilitate movements of fishes and other organisms in response to life cycle requirements. Often, re-establishing connectivity can be as simple as removing artificial obstructions to migration. Once these essential connections are restored, emphasis is placed on recovering aquatic ecosystems by eliminating or reducing anthropogenic stresses and by facilitating the beneficial effects of natural disturbances. Only after the preceding steps occur are deliberate short-term habitat improvements such as wood additions considered. Not all stream reaches will be productive for target species such as salmon; some settings will be far more productive than others (Reeves et al. 1995; Pess et al. 2002). The strategy proposed by Roni et al. (2002) forces a view of habitat improvement that goes beyond restoring wood to individual reaches and instead considers conditions and processes at much larger scales. Landscape management plans based on natural disturbance regimes (for example, Cissel et al. 1998) are likely to be successful over time because they accommodate watershed-scale features and broaden our perspective beyond the simple restoration of large wood in channels.

## Monitoring

Accountability for restoration effectiveness requires that wood restoration projects be monitored. In many cases, monitoring has focused on measuring the durability of structures and how the structures influenced the development of aquatic habitats (Crispin et al. 1993). Far fewer studies have examined the effects of stream restoration on target species (Botkin et al. 2000), and results from these investigations have been somewhat equivocal. Monitoring efforts have usually demonstrated an increase in fish utilization of the stream reach to which wood has been added (House and Boehne 1986), but very few studies have documented a sustained increase in fish populations over an entire drainage system.

A number of monitoring efforts have documented that fish do indeed utilize wood structures (House and Boehne 1985; Crispin et al. 1993; Cederholm et al. 1997; Roni and Quinn 2001). Of those studies where attempts to measure the response of entire populations to wood additions have taken place (for example, Gowan and Fausch 1996; Solazzi et al. 2000), monitoring may be limited to less than 10 years. This time period may be insufficient to detect treatment-related changes at the population level, especially for long-lived anadromous species (Hall and Knight 1981; Hilborn and Winton 1993). Power analyses based on estimates of interannual population variability of Pacific salmon have shown that decades of monitoring will be needed to detect treatment effects on some populations, even at relatively coarse statistical confidence levels (Bisson et al. 1997; Ham and Pearsons 2000). For resident freshwater fishes that are not subject to the environmental extremes faced by Pacific salmon, monitoring requirements may be less daunting. Gowan and Fausch (1996) found that an 8-year monitoring period was sufficient to detect a 44% increase in cutthroat trout *Oncorhyn-chus clarki* abundance after wood enhancement of several northern Colorado streams.

Other environmental factors often obscure the effects of wood restoration. For example, abrupt changes in freshwater and marine survival of anadromous salmonids may accompany climate changes that persist for decades (Ward 2000). If such a change occurs during a post-treatment monitoring period, results are easily misinterpreted. The Keogh River study in British Columbia provides a case in point. The Keogh River is a medium size drainage system on Vancouver Island draining a catchment of 130 km$^2$ (Ward and Slaney 1979). Populations of steelhead *O. mykiss*, coho salmon *O. kisutch*, and char have been monitored there since 1976, making the Keogh River system one of the longest continuously monitored catchments in western North America. Attempts to improve steelhead and coho salmon production have involved physical habitat improvements with logs and boulders, and during the 1980s, inorganic nutrients were added to the river to stimulate primary and secondary production. An increase in adult steelhead was observed in the Keogh River after these measures had been implemented. Analyses of long-term monitoring data have suggested that physical habitat manipulations have not improved smolt production as much as nutrient additions, but the overall productivity of anadromous salmonids in the system has been driven primarily by climate shifts influencing freshwater and marine survival (Ward 2000). Furthermore, a sharp decline after 1990 in returning adult steelhead, the dominant anadromous salmonid in the Keogh River, suggests that unfavorable climate shifts have masked restoration efforts and placed fish populations at risk of extirpation. Such a conclusion would not have been possible without decades of careful, time-consuming monitoring.

Long-term restoration monitoring studies, such as those at Keogh River, BC and Fish Creek, Oregon, are rare in western North America but have contributed greatly to our understanding the influence of climate shifts, floods, and other natural disturbances on fish populations. Because these studies have spanned decades, they have involved extraordinary commitment from their funding organizations and participating scientists. Likewise, other long-term studies of forestry operations on fish populations (for example, Alsea watershed study and Carnation Creek study) have produced invaluable information on the effects of logging on aquatic resources (Hartman and Scrivener 1990; Stednick and Hall, in press). Elsewhere, we have argued for the establishment of a regional network of experimental catchments in which habitat restoration and other management trials can be carried out at a landscape level appropriate to fish populations and with a commitment to long-term monitoring (Bisson et al. 1992). We repeat that call here.

Integrative indices of environmental quality (for example, community-based measures such as IBI, the Index of Biotic Integrity [Karr 1998]) usually combine data on physical habitat, water quality, and the abundance of certain indicator organisms. They are of limited value in determining the *specific* effects of wood restoration on fishes, although they may provide information on overall aquatic ecosystem condition relative to more pristine sites (Karr and Chu 1998). Wallace et al. (1996) successfully used the North Carolina Biotic Index (NCBI) and the Ephemeroptera + Plecoptera + Trichoptera (EPT) index to track the invertebrate community and ecosystem-level responses to experimental insecticide application in a headwater stream at the Coweeta Hydrologic Laboratory in North Carolina. Wallace et al. (1995) examined invertebrate community responses to wood addition and documented immediate changes in composition: abundances and biomass of scrapers and filterers decreased; collectors and predators increased; overall shredder biomass was unchanged, but biomass of trichopteran and dipteran shredders increased while most plecopteran shredders decreased; and plecopteran predators also decreased despite greater abundances of potential prey. These authors found shifts in functional group abundances, biomass, and production between control and wood-enriched sites, which emphasized the importance of wood in structuring invertebrate communities within mountain streams (see also Benke and Wallace 2003, this volume).

Additional biological performance measures of wood restoration effectiveness that incorporate natural variability are needed, particularly as related to the response of fishes. Promising areas for investigation include changes in the guild structure of fish communities, physiological responses to wood restoration such as changes in growth, and changes in the availability of prey related specifically to wood addition. One measure of performance that was formerly popular among aquatic scientists, but is now uncommon in most American investigations, is production—a measure that integrates population density and average individual growth rates (Chapman 1978). Estimates of fish production may be especially valuable in studies involving a before-after control-impact (BACI) experimental design. There have not been any studies of fish populations in western North America in which annual production has been estimated over long periods of time, so it is not known whether production is less variable than simple population censuses. Salmonid fishes often exhibit density-dependent growth in streams (Warren 1971), which may serve to dampen variation in annual production estimates. If so, production may be a less variable indicator of the habitat capacity of the stream than annual density estimates, and detection of population responses to wood restoration could be achieved with shorter monitoring intervals. But production estimates are costly and can be confounded by undetected movements of fish between streams (Fausch and Young 1995). Thus, a suite of performance measures, including growth, age and size structure, abundance, movement, and production would be helpful in obtaining an accurate picture of the effects of a wood restoration project.

Finally, it is useful to include some measures of the ecological response of a stream and its riparian zone to wood restoration that may not directly impact fish survival and growth but may influence fish communities through indirect pathways. For example, it is well known that large wood traps salmon carcasses and facilitates the entry of marine-derived nutrients into aquatic food webs (Cederholm et al. 1989; Bilby and Bisson 1998). Other questions remain. For example, how does wood restoration affect the abundance of aquatic invertebrates (potential prey)? Also, how does wood restoration affect riparian vegetation, either by trapping carcasses and other organic matter or by changing the patterns of vegetated gravel bars? Additionally, the significance of wood restoration to the pattern and extent of hyporheic water and nutrient storage in small streams (Haggerty et al. 2002) deserves additional investigation because hyporheic flows influence stream temperature and nutrient availability.

## Summary

Today, more managers are viewing wood restoration as a component of ecosystem management rather than a simple, stand-alone mitigation tool. Greater efforts are being made to manage landscapes in a manner promoting or emulating natural processes that distribute wood throughout the channel network. Although most restoration projects focus on one or two fish species of commercial or recreational importance, the role of wood in creating complex habitats is better understood and the link between habitat complexity and fish populations is more widely appreciated.

As wood restoration projects increasingly resemble natural wood distribution patterns, aquatic communities as a whole will benefit. Landscape perspectives that recognize and allow for disturbance and recovery processes over space and time are gradually replacing prescriptions that set fixed targets for wood in rivers. Broader landscape perspectives draw our attention back from reach scales to entire drainage systems with the understanding that wood loads will naturally increase and decrease in different parts of the river basin over time. Provisions for long-term recruitment of wood are starting to receive higher priority than placement of wood structures in streams.

Monitoring the effects of wood restoration on fish populations presents many challenges, and refinement of alternative performance measures deserves greater attention. Highly variable fish populations and application of wood restoration to limited portions of the drainage system often prevent statistical detection of possible improvements at the population level. Several biological measures may be needed to detect the effects of stream habitat changes brought about by wood additions, including community structure, biomass and abundance, age and size structure, physiological performance, and production. Development of appropriate biological monitoring techniques remains a significant challenge to assessing wood restoration effects. A regional network of experimental catchments or network segments in which wood restoration can be studied would help scientists and managers address questions about restoration effectiveness that currently remain unanswered.

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# The Ecology and Management of Wood in World Rivers


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