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A Review of Stream Restoration Techniques and a Hierarchical Strategy for Prioritizing Restoration in Pacific Northwest Watersheds

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Abstract.—Millions of dollars are spent annually on watershed restoration and stream habitat improvement in the U.S. Pacific Northwest in an effort to increase fish populations. It is generally accepted that watershed restoration should focus on restoring natural processes that create and maintain habitat rather than manipulating instream habitats. However, most process-based restoration is site-specific, that is, conducted on a short stream reach. To synthesize site-specific techniques into a process-based watershed restoration strategy, we reviewed the effectiveness of various restoration techniques at improving fish habitat and developed a hierarchical strategy for prioritizing them. The hierarchical strategy we present is based on three elements: (1) principles of watershed processes, (2) protecting existing high-quality habitats, and (3) current knowledge of the effectiveness of specific techniques. Initially, efforts should focus on protecting areas with intact processes and high-quality habitat. Following a watershed assessment, we recommend that restoration focus on reconnecting isolated high-quality fish habitats, such as instream or off-channel habitats made inaccessible by culverts or other artificial obstructions. Once the connectivity of habitats within a basin has been restored, efforts should focus on restoring hydrologic, geologic (sediment delivery and routing), and riparian processes through road decommissioning and maintenance, exclusion of livestock, and restoration of riparian areas. Instream habitat enhancement (e.g., additions of wood, boulders, or nutrients) should be employed after restoring natural processes or where short-term improvements in habitat are needed (e.g., habitat for endangered species). Finally, existing research and monitoring is inadequate for all the techniques we reviewed, and additional, comprehensive physical and biological evaluations of most watershed restoration methods are needed.

Watershed restoration is a key component of many land management plans and endangered fish species recovery efforts on public and private lands. Millions of dollars are spent annually in individual river basins in an effort to enhance or restore habitat for salmonids and other fish species (NRC 1996). This increased interest and funding is, in part, due to increased listings of Pacific salmon *Oncorhynchus* spp. and steelhead *Oncorhynchus mykiss* stocks as threatened or endangered under the U.S. Endangered Species Act. The majority of this money is being allocated to local citizen watershed groups for watershed restoration and recovery. Unfortunately, local citizen groups often lack adequate guidance on which types of restoration or enhancement to conduct first or which techniques are most successful. More importantly, it is often unclear how individual site-specific actions might fit into a larger context of watershed restoration and recovery of salmon stocks.

I: TAYLOR

In part, the lack of guidance stems from limited information on the effectiveness of various habitat restoration and enhancement techniques (Reeves et al. 1991; Frissell and Nawa 1992; Chapman 1996). Unfortunately, few watershed and stream habitat restoration techniques (e.g., instream structure placement, riparian planting, road restoration, and reconnection of isolated habitats) have been thoroughly evaluated, and their effectiveness is highly debated within the scientific community (Reeves et al. 1991; Kondolf 1995; Kauffman et al. 1997). Most monitoring has focused on the physical response to various instream restoration techniques, leaving fish, invertebrates, and other biota inadequately assessed. Response of these biota are inherently more difficult to monitor than are physical conditions. However, the biological response to various restoration techniques is the

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ultimate measure of restoration effectiveness. Because of the large interannual variability in abundance of juvenile and adult salmonids, 10 years or more of monitoring is often required to detect a response to restoration (Bisson et al. 1992; Reeves et al. 1997). Some techniques, such as wood and boulder placement in streams, have produce highly varied results (Chapman 1996). Therefore, drawing conclusions about the biological effectiveness of various techniques has been difficult and has hampered efforts to provide scientific guidance on restoration activities.

However, we do have a reasonable understanding of the processes that affect channel morphology and create fish habitat. In the coastal Pacific Northwest, for example, the delivery of organic matter (e.g., woody debris and leaf litter), water, and sediment are some of the major processes dictating channel morphology and the formation of habitat (Montgomery and Buffington 1998). In the 1990s restoring watershed processes became widely accepted as the key to restoring watershed health and improving fish habitat. Beechie et al. (1996), Kauffman et al. (1997), and Beechie and Bolton (1999), among others, have described restoration strategies that place emphasis on restoring physical and biological processes that create healthy watersheds and high-quality habitats. Activities that restore processes (e.g., road removal and stream restoration, culvert removal, and riparian and upslope restoration) are often conducted at the site or reach level. A method is needed that places site-specific restoration within a watershed context. The objectives of this paper are to summarize the effectiveness of various restoration techniques and provide a hierarchical strategy for prioritizing site-specific restoration activities within a watershed.

KATIE II.

Identifying Restoration Needs Through Watershed Assessment

Traditional approaches to habitat management focus on repairing or augmenting specific habitat conditions, rather than on restoring landscape processes that form and sustain habitats. Habitat modifications, such as placing log structures or protecting stream banks, often fail to create expected habitat conditions because they are constructed without consideration of the causes of habitat degradation (Frissell and Nawa 1992; Beechie et al. 1996; Kauffman et al. 1997). Many authors have suggested that a more holistic approach to managing salmonid habitats would help avoid these problems (e.g., Chapman 1996; Reeves et al. 1997; Beechie and Bolton 1999).

Neglecting the biological context of a watershed often results in projects that do not address factors limiting fish production or that help one species but harm others (Reeves et al. 1991). Successful restoration requires that we understand how and when different aquatic species use different parts of a stream network (Beechie and Bolton 1999). Moreover, individual fish stocks are adapted to a range of local environmental conditions, which means that generic habitat targets (e.g., number of pools or pieces of wood per kilometer) should be avoided. More appropriate targets for restoration reflect the range of conditions that existed naturally in a watershed (Beechie and Bolton 1999) and presumably supported diverse biotic communities.

KATIE II.

Land use can effect habitat by disrupting the processes that form and sustain habitats, such as the supply and movement of sediment from hillslopes, woody debris recruitment, shading of the stream by the riparian forest, and delivery of water to the stream channel (Figure 1). Many processes that create habitat operate on time scales of decades or longer (e.g., channel migration and the formation of off-channel habitats). Interrupting these processes (e.g., by stabilizing banks or constructing roads and levees) can lead to loss of fish habitat over the long term (decades to centuries; Beechie and Bolton 1999).

The simplest way to avoid these problems is to focus on restoring processes that form, connect, and sustain habitats. Each reach within a stream network can produce a limited range of habitat characteristics depending upon its position within the drainage network and site-specific physical characteristics (e.g., valley slope, valley confinement, and proximity to sediment sources). Instream restoration techniques often attempt to create instream or floodplain features incompatible with the natural characteristics of the site. Focusing on the restoration of natural processes avoids the misapplication of restoration techniques by enabling the natural array of habitat types to form in all parts of a stream network. Moreover, this approach provides suitable habitats for all native aquatic species because it restores the conditions to which local fish stocks are adapted. Thus, it avoids the problem of building habitats that may improve habitat for one species yet degrade habitat for others.

Identifying habitat-forming processes that have been degraded and that need to be restored requires

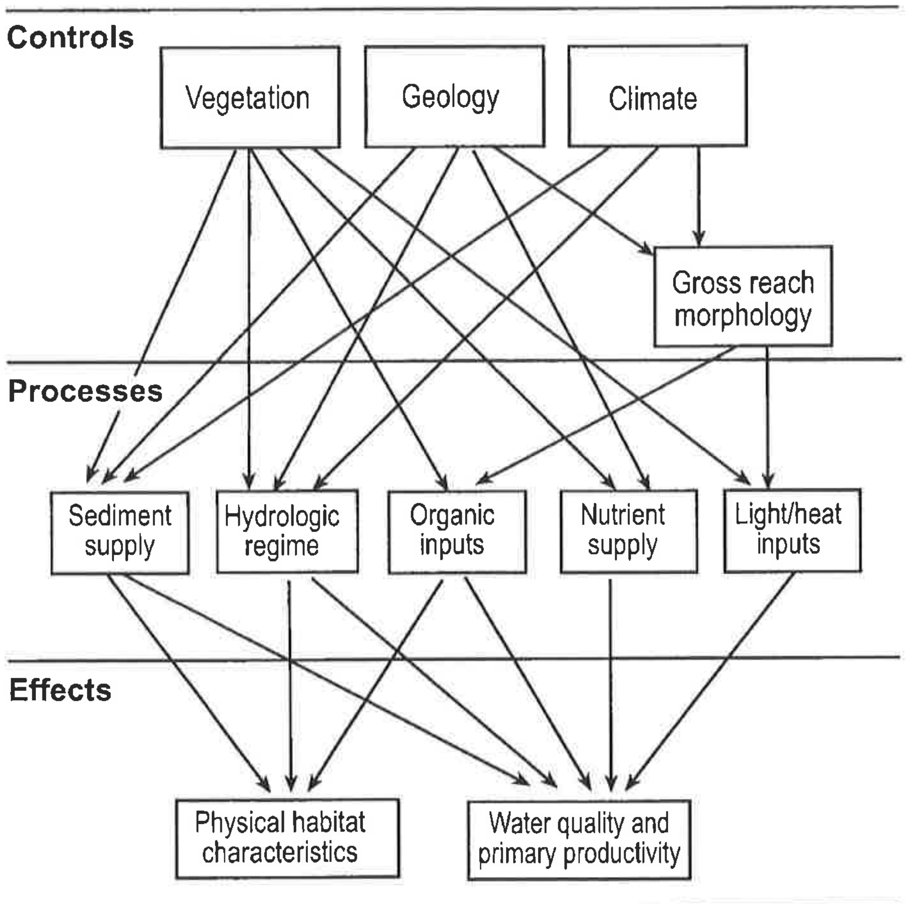

FIGURE 1.—Schematic diagram of linkages between landscape controls on habitat-forming processes and between habitat-forming processes and effects on habitat conditions.

three basic steps: (1) identifying the types and natural rates of habitat-forming processes, (2) determining where processes are altered and the factors responsible, and (3) deciding how to restore the disrupted processes. An appreciation of historical process rates (step 1) guides our understanding of the potential of the landscape to form salmonid habitats, and provides reasonable expectations of how a restored watershed or stream reach will function (e.g., expected rates of natural landslides or the types of riparian forests that are suited to a particular geomorphic setting). The historical assessment also provides a context for analyzing where watershed processes have been disrupted by land use (step 2). There are many techniques used to describe how processes functioned historically and how land uses have changed them (e.g., WDNR 1995; Skagit Watershed Council 1999; Watershed Professionals Network 1999). They include, but are not limited to, assessment of wildfire probabilities (Booth 1991), rates of sediment supply from landslides (Reid et al. 1981), dynamics of riparian forests (Featherston et al. 1995), and stream temperature regimes (WDNR 1995; Table 1). With this understanding, practices and actions required to restore processes and habitats for the long-term can be identified (step 3).

KATIE V.

Review of Effectiveness of Restoration Techniques

A watershed assessment is the first step in understanding watershed processes and identifying restoration needs within a watershed. However, before one can prioritize specific restoration actions, a thorough understanding of the physical and biological effectiveness of various restoration methods is also needed. We review and summarize the effectiveness of various restoration techniques to use as a basis for prioritizing restoration techniques and for identifying additional research and monitoring needs. Our review focuses on the response of salmonids to restoration because little

TABLE 1.—Examples of watershed processes and watershed assessment methods used to determine effects different processes have on stream morphology, instream habitat, and water quality.

Watershed process[a]	Examples of assessment methods
Sediment supply and erosion	Inventory landslides and calculate sediment budgets
	Inventory roads for landslide hazard; list sites requiring restoration work
	Map surface erosion hazards (road surfaces and soils)
Hydrology	Assess changes in hydrologic regime due to increased impervious surface areas
	Assess changes in peak flows resulting from rain-on-snow and extension of drainage networks by road ditches
	Assess connectivity of wetlands, sloughs, and stream channels
Riparian and organic inputs	Map riparian forest conditions to locate areas of low woody debris availability
	Assess historical riparian vegetation including land use and fire history to understand changes in woody debris and organic matter inputs
Nutrients	Assess inorganic nutrient inputs based on geologic mapping
	Assess current and historical salmon escapement to examine changes in marine-derived nutrients
Light and heat inputs	Assess current and historical shading to estimate changes in stream temperature

[a] Complete and detailed description of watershed assessment techniques for each process can be found in WDNR (1995), Skagit Watershed Council (1999), Watershed Professionals Network (1999), or other watershed assessment manuals.

information is available for nonsalmonid fishes. Restoration techniques fall into five general categories: (1) habitat reconnection, (2) road improvement, (3) riparian restoration, (4) instream habitat restoration, and (5) nutrient enrichment.

Isolated Habitats DYLAN III.

We classify isolated habitats into three general categories: (1) off-channel freshwater areas such as sloughs, wetlands, and oxbow lakes; (2) stream reaches isolated by culverts and other artificial obstructions; and (3) estuarine habitats such as isolated sloughs, distributary channels, and blind channels.

Off-channel restoration.—Off-channel habitats such as freshwater sloughs, alcoves, wall-based channels, ponds, wetlands, and other permanently or seasonally flooded areas are important rearing areas for juvenile salmonids. However, off-channel habitats normally associated with floodplains have been routinely isolated or altered by floodplain and hillslope activities such as agriculture, urbanization, flood control, and transportation. Beechie et al. (1994) concluded that the loss of side-channel and distributary sloughs off the main-stem Skagit River, Washington, was the major factor limiting smolt production of coho salmon *Oncorhynchus kisutch*.

Most research to date has focused on the use of off-channel habitats by juvenile coho salmon, which prefer pool habitats during summer and off-channel habitats and pools during winter (Nickelson et al. 1992). As stream flows increase in fall and winter, juvenile coho salmon and certain other salmonids seek refuge in off-channel habitats (Peterson 1982; Tschaplinski and Hartman 1983). Overwinter survival and growth of coho salmon are higher in off-channel ponds and low-gradient ephemeral tributaries than in main-stem habitats (Swales and Levings 1989). Use of off-channel habitats by chinook salmon *Oncorhynchus tshawytscha* is less certain, though juvenile spring (stream type) chinook salmon may use off-channel habitat for overwintering (Swales and Levings 1989). Coastal cutthroat trout *Oncorhynchus clarki clarki* may use off-channel habitat (channels and ponds) extensively in winter (Bustard and Narver 1975; Peterson 1982; Cederholm and Scarlett 1991). In contrast, steelhead do not use off-channel habitats extensively during winter (Swales and Levings 1989). Thus, most off-channel restoration efforts have focused on providing habitat for juvenile coho salmon and, to a lesser extent, cutthroat trout and chinook salmon. DYLAN III.

In addition to reconnecting isolated (e.g., by culvert modification or levee breaching) natural off-channel habitats, excavating new ponds and wetlands is also a common technique. Alcoves (i.e., small ponds excavated adjacent to the stream channel) increased juvenile coho salmon winter densities and overwinter survival in Oregon streams (Solazzi et al. 2000). Creation of new off-channel ponds has also shown promise for coho salmon (Cederholm and Scarlett 1991), but produced little response in chinook salmon (Richards et al. 1992) or other salmonids. DYLAN III.

The optimal depth, morphology, and design of off-channel habitats is unknown. Peterson (1982) found higher survival in deeper ponds (78% in deep versus 28% in shallow ponds). In contrast, Swales and Levings (1989) suggested that shoreline perimeter and shallow water areas were key factors determining juvenile coho salmonid survival in off-channel habitats. Lister and Finnigan (1997) suggested restricting pond area to 0.1–0.3 ha, providing ample woody debris for cover, and providing a variety of depths. Hydrology is another factor that may determine the effectiveness of off-channel habitats to provide habitat for juvenile fishes. V.A. Poulin and Associates (1991) blasted pools into side channel habitats, but channel connections with main-stem habitat ran dry and prevented fish from using the new pools. Generally, floodplain habitats can produce large numbers of coho salmon smolts (Peterson 1982), suggesting off-channel restoration may be more promising than many other habitat enhancement techniques for this species. Additional research is needed to determine the pond size, depth, morphology, and cover needed to maximize juvenile fish production.

RyAN IV.

Culverts and fish passage.—Fish passage through structures such as culverts and other artificial barriers in streams is critical to maintaining connectivity among habitats. In Washington State, over 7,700 river kilometers (rkm) of historical salmon habitat is currently blocked by impassible culverts, even though regulations that govern the design of water-crossing structures for roads normally include provisions for fish passage (Conroy 1997). Culverts designed for adult passage often create water velocities that exceed juvenile salmon swimming abilities and prevent juvenile fish from reaching important rearing areas (Furniss et al. 1991). Smooth culverts lacking roughness or baffles normally impair juvenile fish passage except at very low slopes (Robison 1999).

Culverts and other barriers can also degrade fish habitat by altering or limiting the downstream movement of sediment, woody debris, and organic materials, and may reduce the upstream extent of nutrient inputs by limiting the number of adult salmon that can move upstream (see *Carcass Placement and Nutrient Enrichment* section). Coho salmon can be particularly affected by culverts because they use small streams. In Washington State, for example, impassible culverts are estimated to have reduced potential coho salmon smolt production in the Stillaguamish and Skagit river basins by 30–58% (Beechie et al. 1994; Pess et al. 1998). In both basins, reconnecting isolated habitats appears to be one of the most important components of restoring salmonid populations.

RyAN IV.

Restoring fish passage is an effective way to increase the availability of habitat and can result in relatively large increases in potential fish production for a nominal cost. For example, Scully et al. (1990) examined the relative benefit of barrier removal, off-channel habitat development, instream structure placement, and sediment reduction projects in the Salmon River Basin, Idaho. They found that barrier removal projects accounted for 52% of steelhead and 72% of chinook salmon parr produced from these four project types between 1986 and 1988. Monitoring data from a fish passage improvement project on Little Park Creek, Washington indicated that more than 90% of the coho salmon spawning occurred above the fish passage improvement project 1 year after completion (Beamer et al. 1998). Pess et al. (1998) found similar results for juvenile and adult coho salmon after removal of impassible culverts in tributaries to the Stilliguamish River. Moreover, stream channels with high-quality habitat (e.g., low gradient, high pool frequency, and high wood loading), rather than stream length, produced greater benefits. Therefore, habitat quality above an impassible culvert should be one factor used in prioritizing culverts for removal or replacement and for determining whether other restoration techniques might be more cost-effective.

RyAN IV.

A variety of culverts and bridges provide adequate adult fish passage at road crossings, but not all provide passage for juvenile fishes or maintain sediment and wood transport, and many affect channel morphology (Table 2). Bridges often allow the passage of other materials and formation of a natural stream channel but are costly. Open-bottom culverts or embedded (e.g., countersunk) pipe-arch culverts allow a natural substrate to form within the channel and are effective at passing both juvenile and adult salmonids (Furniss et al. 1991; Clay 1995). However, such culverts may constrain the stream channel if the culvert size does not account for large flows or the volume of sediment and wood transported by the stream (Robison 1999). Other design options include backwatering culverts at the outlet or inlet and placing baffles within the culvert to reduce flow velocity. Clay (1995) provides a concise review of culvert designs and methods for retrofitting impassible culverts. However, most culverts are designed to pass adult fish and additional research is needed to confirm which types effectively pass juvenile fish at a variety of flows.

RyAN IV.

Fish passage projects should be prioritized after basinwide objectives are developed and fish passage impediments are identified throughout the watershed. The inventory should identify culvert and other artificial blockages, along with specific information on habitat quantity and quality and

TABLE 2.—Summary of various stream crossing structures and whether (Y = yes; N = no) they allow for juvenile and adult salmonids fish passage and the transport of sediment and large woody debris (LWD) or impact stream morphology by constraining the channel.

Stream crossing type	Provides fish passage for		Transports		Constrains channel[a]
	Adult	Juvenile	Sediment	LWD	
Bridge	Y	Y	Y	Y	N
Culverts					
Bottomless pipe arch	Y	Y	Y	N	Y
Squash pipe or countersunk	Y	Y	Y	N	Y
Round corregated, baffled	Y	Y	N	N	Y
Round corregated, no baffles	Y or N[b]	Y or N[b]	N	N	Y
Smooth (round or box)	N[b]	N[b]	N	N	Y

[a] Constrainment depends upon size of culvert or bridge relative to channel and floodplain width.
[b] Fish passage depends upon culvert slope and length.

fish presence and absence above and below each blockage. A prioritized list based on cost–benefit ~~analysis~~ can then be developed (Pess et al. 1998).

DYLAN II.

Estuarine habitats.—The loss and degradation of estuarine habitats in the Pacific Northwest since Euro-American settlement has been well documented. Simenstad and Thom (1992) estimated that 71% of the estuarine habitat in Puget Sound has been lost and 42% in the coastal Pacific Northwest. Estuaries are important foraging areas for juvenile fish, as well as physiological transition zones for adult and juvenile anadromous fish (Healey 1982; Simenstad et al. 1982). In particular, populations of juvenile chum salmon *Oncorhynchus keta*, pink salmon *Oncorhynchus gorbuscha*, and chinook salmon are highly dependent on estuaries, which they annually occupy for 4–29 weeks (Healey 1982; Simenstad et al. 1982); juvenile coho salmon populations may use estuaries for up to 15 weeks (Healey 1982; Simenstad et al. 1982).

Estuarine habitat manipulations can be segregated into three categories: restoration, enhancement, and creation. Restoration efforts attempt to create natural hydrologic, morphologic, and biotic conditions, and may include breaching dikes, removing fill, and planting emergent and submergent plants. Dike-breaching and other techniques that reconnect isolated habitats show particular promise. For instance, 11 years after dike breaching on the Salmon River, Oregon, a highly productive marsh habitat developed with complete tidal exchanges, rapid sedimentation, and new habitats for juvenile fish (Frenkel and Morlan 1991). However, they did not quantify fish or other biota. In general, where data on fish use are scant (which is generally the case), estuarine restoration is believed successful if salinity intrusion and sediment transport or sedimentation are restored (Simenstad and Thom 1992).

Restoration projects aim to return habitat to some predisturbance condition, and enhancement strategies attempt to augment a portion of a degraded habitat. Often, however, neither address the underlying processes. For example, adding sand and gravel to eroding beaches and stabilizing banks is an enhancement technique that may have to be repeated because some habitat-forming process such as hydrology or sediment transport is deficient (Simenstad and Thom 1992). Little information exists on the success of these projects at increasing fish production. Dylan III.

Creation projects construct or excavate new estuaries or wetlands along the coastal shoreline where they did not historically exist, usually to mitigate habitat degradation or loss elsewhere in the watershed. Some constructed projects appear to be successful in creating estuarine habitat for salmonids. For example, Shreffler et al. (1992) documented temporary residence and foraging of juvenile chum salmon and chinook salmon in a created estuarine wetland in the Chehalis River estuary. Moreover, Miller and Simenstad (1997) found no differences in juvenile coho salmon growth between a natural and created estuarine slough. Although these constructed habitats seem to provide functional fish habitat, creating new estuarine wetland habitat is generally discouraged because key processes that maintain them may not be present (Simenstad and Thom 1992). As with the other watershed restoration techniques, estuarine restoration strategies should focus on reconnecting isolated habitats and restoring natural processes rather than creating new habitats. However, where land-use conversion has virtually eliminated wetland and estuarine habitats, creation of new

TABLE 3.—Processes restored (×) by various road improvement techniques.

Road improvement technique	Hydrology	Sediment delivery	
		Fine	Coarse
Removal of roads	×	×	×
Culvert or stream crossing upgrades (correct unstable crossings)		×	×
Sidecast removal or reduction		×	×
Reduce road drainage to stream[a]	×	×	
Increase surface material thickness or hardness with crushed rock or paving		×	
Traffic reduction (unpaved roads)		×	

[a] Drainage reduced through increased crossings and by diverting water onto forest floor.

habitats will probably be necessary to provide anadromous salmonids and other fishes with the continuum of essential habitats.

Ryan IV.

Road Improvements

Roads can harm streams and salmon habitat through increased delivery of fine sediment, landslide frequency, and changes in stream hydrology (Furniss et al. 1991). In addition, stream-crossing structures (e.g., culverts) can impede the transport and delivery of sediment and woody debris to downstream reaches (see previous section on *Culverts and fish passage* and Table 2). Sediment delivery from roads affects fish habitat in two ways. First, fine sediment (sand and smaller particles) produced by surface erosion can infiltrate spawning gravels and reduce survival of salmonid eggs (Reid et al. 1981). Second, coarse sediments (gravel and larger particles) from road-related landslides contributes to increased bedload supply, which fills holding or rearing pools and decreases bed and bank stability by causing bed aggradation or lateral migration (Tripp and Poulin 1986).

Ryan IV.

Surface erosion and delivery of sediment to streams can be substantially reduced by good road design and maintenance (Table 3). Use of local soils for road surfacing typically creates an erodable road surface because soil particles are small and easily transported to ditches by rainsplash, sheetwash, or rilling of the road surface. Using crushed rock (7.6–15.2 cm in diameter) reduces surface erosion by protecting the more erodable local fill that forms the road prism (Burroughs and King 1989: WDNR 1995). Use of the hardest rock available for surfacing also reduces the generation of sediment. Ditches and cross-drain discharges should be directed onto the forest floor (Bilby et al. 1989) or away from streams wherever possible.

Reduction of landslide hazards from roads may include removal of roads or reconstruction of roads so that failures are less likely (Harr and Nichols 1993; Waters 1995). Methods for identifying potential landslide sites include initial inspection of aerial photographs to reduce field effort, followed by a field survey that identifies sites with high likelihood of road failure and delivery to a stream. Removal of roads typically includes removal of sidecast material and removal of culverts, cross drains, and fills (Harr and Nichols 1993). On active roads, stream crossings should be constructed so that they do not fail and initiate debris flows. The most reliable alternative is a bridge, although bridges are typically not cost-effective when many small streams must be crossed. Use of aligned rock fill over culverts reduces risk of erosion and failure if culverts become plugged and water spills over the top. Cross-drains should not discharge onto unstable slopes, and full-bench construction (no side-cast fill) should be used on steep slopes to avoid side-cast failures. Additional detail on various road removal, restoration, and improvement techniques can be found in Furniss et al. (1991) and Waters (1995).

Ryan IV.

While road restoration techniques are relatively straightforward, little physical or biological evaluation of road restoration has been published. Evaluations of road-surface erosion reduction techniques have been limited to comparisons of fine sediment concentrations in road runoff at different traffic levels and with different surfacing materials. Bilby et al. (1989) found a positive relationship between traffic levels and fine sediment delivery to stream channels. Reducing traffic levels in the Clearwater River watershed reduced surface erosion by a factor of 10 (Reid and Dunne 1984). Reid and Dunne (1984) and WDNR (1995) demonstrated that increasing the thickness of surfacing material to 15.2 cm reduces surface erosion by about 80%. Reducing the amount of road surface draining directly to streams can also reduce fine sediment delivery.

Ryan IV.

Very few evaluations of restoration techniques for landslide hazard reduction have been conducted. Harr and Nichols (1993) provided anecdotal evidence that road removal resulted in reduced landslide rates. However, the mechanisms by which roads cause landslides are well understood. Thus, common techniques for reducing landslides from roads, including removal, stream crossing upgrades, sidecast removal, and management of cross-drain discharges, should be very effective if done properly (Table 3).

To evaluate the effectiveness of road restoration techniques, monitoring programs, such as periodic updating of subbasin sediment budgets and classifying landslides by associated land use, are needed (Beamer et al. 1998). This would allow evaluation of the total sediment supply to streams from roads, as well as comparison to background sediment supply and sediment supply from other land-use activities. Additional, biological monitoring is needed to determine the effect of changes in sediment supply and hydrology on stream biota.

Riparian Restoration IAN V.

Riparian silviculture.—Timber harvest and other anthropogenic activities have transformed many riparian areas in the coastal Pacific Northwest from conifer-dominated to hardwood-dominated forests (Bisson et al. 1987; Beechie et al. 2000). Although hardwoods, such as red alder *Alnus rubra* and bigleaf maple *Acer macrophyllum*, may provide adequate shade and small woody debris to streams, they do not provide a long-term source of large woody debris (LWD) important for creating and maintaining instream fish habitat (Beechie et al. 2000). In the absence of disturbance, hardwoods and tall shrubs may dominate riparian zones and suppress conifer growth for decades (Emmingham et al. 2000). Silviculture techniques such as planting conifers or removing overstory or understory vegetation are frequently implemented in riparian areas to accelerate the growth of conifers and improve fish habitat.

IAN V.

Hundreds of conifer conversion projects have been implemented in hardwood-predominated riparian zones of the Pacific Northwest in the last few decades. However, little information is available on the effectiveness of these techniques because most conifers need 100 years or more to mature and the results of silviculture treatments will not be evident for several decades. We located only one publication summarizing the initial results of many riparian conversion projects (replanting and conifer release) in the Pacific Northwest. Emmingham et al. (2000) examined over 30 riparian conversion projects in coastal Oregon and suggested that initially riparian silviculture treatments show promise at establishing conifers in hardwood-predominated riparian zones. A common problem with many riparian conversion projects has been minimal reduction of overstory or understory vegetation. This results in slow conifer growth and shading by rapidly growing understory shrubs. In addition, the lack of follow-up maintenance appears to be a common problem for many riparian conversion projects. Competition from hardwoods and tall shrubs in the coastal Pacific Northwest is intense, and timely and repeated removal of shrubs is critical to survival and growth of young conifers (Emmingham et al. 2000). Planting larger trees and using mesh tubing or other material to protect against browsing of young seedlings from deer *Odocoileus* spp. and elk *Cervus elaphus* is needed in many areas. Conifers, such as western redcedar *Thuja plicata* and Douglas-fir *Pseudotsuga menziesii*, are particularly vulnerable to damage by deer and elk (Emmingham et al. 2000). Fencing conifers larger than 10 cm in diameter may also be needed to protect against damage from beavers *Castor canadensis* and mountain beavers *Aplodontia rufa*.

Berg (1995) and Beechie et al. (2000) developed models for determining growth of conifers under different riparian silviculture treatments. Beechie et al. (2000) provided guidance for determining when thinning is appropriate and when it will result in a loss of near-term recruitment of LWD that may create fish habitat. Their model predicts that thinning of the riparian forest does not increase recruitment of pool-forming LWD where the trees are already large enough to form pools in the adjacent channel and that thinning reduces the availability of adequately sized wood. Conversely, thinning increases LWD recruitment in riparian areas where trees are too small to form pools within the adjacent channel. The combination of short-term evaluation of riparian silviculture treatments and long-term models of tree growth suggests that, when applied appropriately, silviculture treatments can be effective at converting riparian zones from hardwoods to conifers and in providing long-term sources of LWD. Although little information exists on the growth and ecology of many conifers in riparian zones, research on upslope areas can be useful in determining the appropriate species for riparian replanting (Emmingham et al. 2000). However, continued research and monitoring for several decades is necessary to determine the overall effectiveness of various riparian silviculture treatments.

IAN V.

IAN V.

Grazing and fencing strategies.—Livestock grazing within stream riparian corridors can harm riparian ecosystems and stream channels (Platts 1991; Armour et al. 1994). Armour et al. (1994) conservatively estimated that livestock grazing has degraded 50% of all riparian ecosystems on federal rangelands in the western United States. Grazing may alter natural riparian and channel processes and cause upland and streambank erosion, channel sedimentation and widening, increased stream

IAN V.

temperatures, decreased water quality, and changes in the water table (Elmore and Beschta 1987; Platts 1991). Platts (1991) reviewed 19 studies, of which 15 reported either decreased fish abundance with livestock grazing or an increase in fish abundance with cessation of grazing.

IAN I.

Riparian and stream channel habitats affected by grazing are restored primarily by completely excluding livestock, or by implementing a grazing strategy that enables riparian vegetation to recover (Elmore 1992). Riparian vegetation functions such as shade, sediment storage, and hydrologic effects (e.g., water storage and aquifer recharge) often recover quickly (i.e., 5–10 years) with livestock exclusion or substantial reductions in grazing intensity (Elmore and Beschta 1987; Myers and Swanson 1995; Kauffman et al. 1997; Clary 1999). Bank stabilization, channel geometry, habitat complexity, and other channel characteristics also recover quickly but may take longer in deeply incised stream channels (Elmore and Beschta 1987; Myers and Swanson 1995). Various grazing management systems have been implemented throughout the western United States, but out of 17 riparian grazing systems described by Platts (1991), only light use and complete livestock exclusion provided adequate protection to riparian and fisheries resources. Historically, grazing systems have not differentiated between riparian and upland range areas (Clary and Webster 1989). However, specially designed riparian grazing systems that control the intensity and timing of use may be beneficial (Elmore 1992). Spring grazing, for example, can result in equal distribution of stock between riparian and upland areas, and maintain herbaceous stubble heights that can adequately protect erodable streambanks (Clary and Webster 1989). Rest-rotation and other seasonal grazing strategies have shown promise at protecting riparian and aquatic habitat when coupled with intensive monitoring (Myers and Swanson 1995), but these strategies need additional evaluation (Clary and Webster 1989). Nevertheless, considerable debate remains as to whether such management strategies enhance vegetation production, improve livestock production, or protect riparian resources (Platts 1991). Limitations of previous research and monitoring designs make drawing firm conclusions about the affects of grazing strategies on riparian habitat and fish populations difficult (Rinne 1999).

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Our understanding of the effects of grazing on fish populations has been developed primarily by examining effects of grazing on stream habitat characteristics (Platts 1991; Clary 1999). Thus, much of the recovery in riparian and channel characteristics is assumed to benefit fish populations; however, fish populations may or may not respond over the time frame investigated (Rinne 1999). This is partially due to the inherently large interannual variability in salmonid populations (Bisson et al. 1992). Clearly, additional research is necessary to determine adequate buffers on agricultural and grazing lands and to determine the response of fish populations to different grazing strategies.

Instream Habitat Restoration ESTEBAN VI.

Efforts to restore stream habitat using structures have increased greatly in the Pacific Northwest since the early 1980s, when the importance of woody debris in maintaining and creating fish habitat became widely accepted (Bisson et al. 1987). Large woody debris or boulder placement has become one of the most common techniques to improve fish habitat and compensate for the simplification (loss of habitat complexity) of stream habitat caused by decades of land-use practices (Kauffman et al. 1997). Instream restoration techniques were originally pioneered in the midwestern United States and have been modified for use in steeper, high-energy western streams (Reeves et al. 1991). Materials commonly placed in streams to enhance or restore habitat include individual logs, log jams, brush bundles, boulders, rock-filled wire gabions, and spawning gravel.

ESTEBAN VI.

Monitoring of instream restoration projects in western North America has focused primarily on whether LWD and artificial structures produce the desired physical response. Reported failure rates for various types of wood and boulder structures are highly variable, ranging from 0% to 76% (Table 4). The conflicting results of these studies are probably due to differences in definitions of "functioning," structure age and type, or placement method. More recent structure evaluations (e.g., Thom 1997; Roper et al. 1998) suggest that 85% percent of artificially placed wood remains in place and contributes to habitat formation. This may be due to an increased emphasis on replicating natural architecture of wood in streams (creating natural jams or pinning logs between riparian trees) rather than artificial structures (e.g., weirs, deflectors, etc.) or due to the short duration of these studies. The available evidence suggests that most instream structures persist for less than 20 years (e.g., Ehlers 1956; House 1996), though little long-term monitoring has occurred.

Increases in pool frequency, pool depth, and

TABLE 4.—Summary of studies evaluating structure durability and function in the Pacific Northwest. Note that most studies did not break down success rate by structure type (NA = data not available).

			Percent of structures functioning					
Study	*N*	Years after placement	Log weirs	Rock weirs	Deflectors	Natural logs or jams	Gabions	Total
Ehlers (1956)[a]	41	18	33	0	50	NA	0	24
Armantrout (1991)[b]	362	5	70	93	NA	88	90	85
Frissell and Nawa (1992)[c]	155	1–5	32	46	33	74		39
Roper et al. (1998)[d]	3,946	NA	NA		NA	NA		84
House et al. (1989)[a]	812	1–8	NA	NA	NA	NA	NA	86
Thom (1997)[e]	143	1	NA	NA	NA	86		86
Crispin et al. (1993)[a]	200	1–4	NA	NA	NA	NA	NA	98
House (1996)[a]	22	6–12	100	100	100	100	100	100

[a] Functioning defined as in place and functioning as intended.
[b] Functioning defined as improving habitat.
[c] Functioning defined as functioning as intended.
[d] Functioning defined as in place, or largely in place, but shifted.
[e] Functioning defined as no movement or movement less than one bankfull width.

woody debris and sediment retention following placement of instream structures have been well-documented (e.g., Crispin et al. 1993; Cederholm et al. 1997; Reeves et al. 1997). However, biological evaluations have produced variable results (Table 5), and few comprehensive biological evaluations of instream enhancement techniques exist. We located 11 papers summarizing biological evaluations of 29 instream restoration projects for anadromous fish in the Pacific Northwest. Of these evaluations, posttreatment juvenile abundance for at least one species or life stage increased significantly in 12 streams or was higher in treatment reaches than in control reaches; however, in only five of these studies (6 streams) were populations monitored beyond 5 years (House et al. 1989; House 1996; Cederholm et al. 1997; Reeves et al. 1997; Solazzi 2000). A few of those studies employed an extensive posttreatment design (see Chapman 1996), sampling many sites in 1 year. Among sites, only coho salmon densities appeared to be consistently higher following restoration, with increases in at least one season reported in 16 of 18 streams and significant results reported in 6 streams (Table 5). Significantly higher age-1 and older steelhead densities were reported in 7 of 22 streams in either summer or winter. Different placement techniques and structure and material types were used in various studies, but no pattern in fish response to structure type was apparent. The inconsistent results of these studies emphasize the need for continued biological evaluation of instream restoration efforts. Moreover, the majority of these evaluations occurred in summer months; only six projects evaluated during the fall, winter, or spring. Because winter is a critical time for juvenile salmonids (Roni and Fayram 2000), additional evaluation in winter and spring is needed.

A recent examination of 30 LWD-placement projects in western Washington and Oregon streams revealed significantly higher densities of juvenile coho salmon in treated reaches than in control reaches during summer and winter and significantly higher densities of juvenile cutthroat trout and steelhead during winter (Roni and Quinn 2001). The differences in seasonal response both within and among species appeared to be due to differences in species-specific seasonal habitat preferences. Additional comprehensive studies are needed for other regions, restoration techniques, and species.

Although several studies have examined the response of juvenile salmonids to instream habitat restoration, fewer studies have examined the response of adult salmonids. This partially stems from the multiple generations needed to detect an adult response. However, the restoration of spawning gravel has frequently been an objective of stream restoration projects (Reeves et al. 1991). Where spawning gravels are in low abundance or of low quality, habitat structures, such as channel-spanning LWD, boulder clusters, or gabions may recruit and store gravel. House (1996) reported that gravel trapped above and below channel-spanning gabions in Lobster Creek, Oregon, increased suitable spawning habitat by 115%. Following treatment, 60% of steelhead and 56% of coho salmon adults in East Fork Lobster Creek spawned within 5 m of structures, whereas before construction, 18% of coho salmon redds were located in

TABLE 5.—Summary of juvenile salmonid response (0 = no response, + = positive response, − = negative response) to instream habitat restoration from published studies in the Pacific Northwest; asterisks (*) indicate results were significant at $\alpha = 0.05$. Structure types were categorized as large woody debris structure (LS), naturally placed large woody debris (LN), gabion (G), and boulder clusters or structure (B). States or provinces include British Columbia (BC), California (CA), Idaho (ID), Oregon (OR), and Washington (WA). Trout fry were young-of-year cutthroat trout or steelhead; salmon species and other steelhead and cutthroat trout were age-0 parr, age-1, or older juveniles. Sources: Ward and Slaney (1981); Moreau (1984); House and Boehne (1986); House et al. (1989); V. A. Poulin and Associates (1991); Slaney et al. (1994); Chapman (1996); House (1996); Cederholm et al. (1997); Reeves et al. (1997); Solazzi et al. (2000).

Stream	Region	Years of monitoring	Structure type(s)	Coho salmon	Trout fry	Cutthroat trout	Steelhead	Chinook salmon
			Summer sampling					
Bonanza Creek	BC	2	LN	+*				
Keogh River	BC	3	LS, B	+*			+*	
MacMillan Creek	BC	3	LN	+				
Nechako River	BC	1	LN					+
Sachs Creek	BC	2	LN	+	−		+	
Southbay Creek	BC	3	LN		+			
Hurdygurdy Creek	CA	2	B				+	
Crooked Fork Lochsa River	ID	1	LS				0	0
Crooked River	ID	1	LS, LN, B				+*	0
East Fork Papoose Creek	ID	1	LS		0		+*	
Lolo Creek	ID	4	LS, B				0	+
Papoose Creek	ID	4	LS				+*	0
Red River	ID	1	LS, B				0	0
Squaw Creek	ID	4	LS				+*	+*
Alsea River	OR	8	LS, AL	+*	0	0	0	
East Beaver Creek	OR	6	G	+	+	+	0	
East Fork Lobster Creek	OR	9	B, G	+*	0	+*	0	
Fish Creek	OR	13	LS, B, G	−	−		+	
J-Line Creek	OR	5	LS, B	+		−	−	
Little Lobster Creek	OR	5	B	+	0	−	−	
Lobster Creek	OR	3	B, LS	+	+	+	−	
Lower Elk Creek	OR	4	LS, B	+		0	−	
Nestucca River	OR	8	LS, AL	+*	0	0	0	
South Fork Lobster Creek	OR	2	LS		+	+		
Steamboat Creek	OR	1	LS, B				+*	
Tobe Creek	OR	3	G	+	+	+	+	
Upper Lobster Creek–1	OR	3	G	+	+	+	+	
Upper Lobster Creek–2	OR	5	B, LS	0	0	0	0	
Porter Creek	WA	6	LS, LN	0	0		0	
			Winter sampling					
Steamboat Creek	OR	1	LS, B				+*	
Porter Creek	WA	6	LS, LN	+	0		0	
			Spring sampling					
Nechako River	BC	1	LN					+*
Porter Creek	WA	6	LS, LN	0	0		0	
			Spring smolt trapping					
Alsea River	OR	8	LS, AL	+*		+	+*	
Fish Creek	OR	13	LS, B, G	0	−*		+	
Nestucca River	OR	8	LS, AL	+*	0	+*	+*	
Porter Creek	WA	6	LS, LN	+*				

the treatment area (House 1996). Similarly, Anderson et al. (1984), Moreau (1984), and House et al. (1989) observed adults using newly recruited gravels associated with weir or deflector structures. Crispin et al. (1993) indicated that coho salmon spawner abundance in Elk Creek increased four-fold in the years following placement of instream structures, whereas spawner abundance elsewhere in the Nestucca River basin remained the same or decreased during the study.

The most effective structures for enhancing salmonid spawning areas in lower-gradient streams (<3%) appear to be "V" weirs or diagonal weirs (Anderson et al. 1984; House and Boehne 1985).

However, artificial structures such as weirs tend to have high failure rates and may not persist for more than 10–20 years. In a long-term evaluation, House (1996) noted that wire gabions began to deteriorate after 10 years and no longer performed as initially constructed. Kondolf et al. (1996) suggested that for spawning enhancement to be successful, the geomorphic context of the site must be considered during project design and implementation. Taking these considerations into account, artificial salmon spawning enhancement by placing structures or supplementing gravel should be undertaken as short-term measures until natural watershed processes are restored.

The majority of LWD placement and other instream restoration projects have been in small streams, but more recently, artificial log jams have been constructed in larger streams (>20 m bankfull width). Preliminary data from these log-jam projects in western Washington rivers indicated that densities of adult chinook salmon increased in treated areas (G. Pess, unpublished data), suggesting that this technique shows promise for creating or increasing spawning and holding habitat in large streams. In addition, this technique may increase riparian vegetation because riparian trees colonize bars forming behind log jams. Natural log jams may persist for decades or even centuries, providing long-term riparian and in-channel benefits (Abbe and Montgomery 1996). Nevertheless, it appears that creating artificial log jams is successful only if they are engineered properly and implemented in locations where log jams would naturally occur. Additional research and monitoring is needed to confirm initial findings.

Recent studies in western Oregon and Washington indicate that anthropogenically placed logs that remain stationary are more likely to scour and create pools than logs that move during high flows (Thom 1997; P. Roni, unpublished data). In addition, anchored pieces are less likely to move from an initial location than unanchored ones (Roper et al. 1998). Hence, limiting the mobility of anthropogenically placed wood is more likely to elicit a positive biological response. Anchoring devices are often used to limit wood movement, though the need for anchoring devices to keep the wood in place is eliminated if wood of sufficient dimensions relative to the channel size is used (Hilderbrand et al. 1998). Pinning channel-spanning logs between trees in the riparian zone has been shown to be an effective method for anchoring LWD (Thom 1997). In addition, LWD stability is enhanced by the presence of a rootwad (Abbe and Montgomery 1996). Regardless, traditional approaches to placing wood in streams are generally not appropriate for channels larger than approximately 12 m bankfull width or gradients in excess of 4–5%. Wood also appears to be most likely to have the desired effect on habitat conditions when placed in channels in a manner consistent with natural wood accumulations. For example, channel-spanning logs perpendicular to the flow (log weirs) are uncommon in low-gradient streams greater than 10 m bankfull width (Bilby and Ward 1989). Thus, constructing log weirs in larger channels is not consistent with natural wood positioning and is unlikely to be stable or produce the desired physical and biological response.

In summary, our review of the literature on instream habitat restoration techniques indicates that LWD projects are effective at creating juvenile coho salmon rearing habitat and increasing juvenile densities, but the response of other species is less clear. Although increased spawner densities have been reported in some studies, there are no thorough evaluations of the response of spawning adults to structure placement. The majority of evaluations for anadromous salmonids have been in coastal streams, particularly in Oregon, and comprehensive evaluation in other regions is necessary. Furthermore, artificial structures such as log weirs and deflectors appear to have moderate to high failure rates, and their benefits to fish may be temporary. Therefore, placement of LWD and other material in the stream channel should mimic natural processes by using and placing materials consistent in size, type, location, and orientation to that found in natural channels.

Carcass Placement and Nutrient Enrichment

Research conducted over the last decade has made it increasingly evident that salmon themselves represent an important attribute of the habitat where they spawn. Because Pacific salmon return to their natal streams to spawn and die after spawning, they provide a nutrient and organic matter subsidy to the vegetation bordering the channel and to various species of wildlife (Johnston et al. 1997; Larkin and Slaney 1997; Bilby et al. 1998). The recent application of stable isotope analysis, which has enabled direct quantification of marine-derived nutrients in streams, has helped elucidate the ecological significance of salmon carcasses in streams (Johnston et al. 1997; Bilby et al. 1998).

Salmon abundance has declined dramatically over much of the Pacific Northwest over the last century (Nehlsen et al. 1991; Gresh et al. 2000).

These declines have caused a corresponding decrease in the amount of nutrients and organic matter delivered to freshwater ecosystems. For example, abundance of salmon spawning in tributaries of Willapa Bay in southwestern Washington declined from about 475,000 fish annually in the early 20th century to about 40,000 fish by the early 1990s (NRC 1996). Deposition of carcass biomass in these streams declined from approximately 2,650 metric tons (mt) to 205 mt, and contributions of nitrogen (N) and phoshorus (P) from this source decreased by more than 90%. Even in regions where salmon have not declined, localized nutrient deficiencies due to decreases in specific salmon populations have been observed. An extensive survey of nutrient delivery by spawning salmon in British Columbia streams indicated large decreases of nutrients in watersheds where populations have not been enhanced by hatchery supplementation, fertilization, construction of spawning channels, or other mitigating action (Larkin and Slaney 1997).

Techniques to address nutrient deficits caused by reduced salmon populations have recently been developed. The primary techniques to increase nutrient availability are the addition of inorganic N and P to streams during summer and the distribution of hatchery-spawned salmon carcasses in streams. Both techniques have been associated with increases in biological productivity.

Addition of N and P to lakes used by sockeye salmon for rearing has been used for several decades to increase smolt production (LeBrasseur et al. 1978). This technique was not widely used to enhance stream productivity until recently. The addition of inorganic nutrients to streams increases autotrophic (Johnston et al. 1990) and invertebrate (Hershey et al. 1988) production and increases the growth rate of juvenile salmonids (Johnston et al. 1990). Late summer weights of coho salmon and steelhead fry in the Keough River, British Columbia, were 1.4–2.0-fold greater and smolt yield doubled during years when N and P were added to the river (Johnston et al. 1990; Ward 1996). In experimental applications, nutrients are usually added by slowly dripping a concentrated solution of nutrients into the stream. This technique requires considerable maintenance to replenish the nutrient solution and maintain the proper drip rate. A slow-release fertilizer pellet has been developed that greatly simplifies the process (Ashley and Slaney 1997). Addition of inorganic nutrients to streams is a technique that is currently used in British Columbia but has been used infrequently elsewhere.

Nutrient augmentation projects should consider the nutrient status of a system not only at the location of application, but also downstream (Stockner et al. 2000). In many Pacific Northwest watersheds excess nutrients occur in downstream reaches flowing through developed areas. The risk of further degrading conditions in these downstream reaches should be weighed against any benefits associated with increased nutrient levels in upstream reaches.

Artificially increasing nutrient availability by adding carcasses of hatchery salmon to streams is currently common in much of the Pacific Northwest. Biological responses to this method have also been documented. Elevated primary production and density of invertebrates have been associated with carcass additions (Wipfli et al. 1999). The addition of coho salmon carcasses to a small stream in southwestern Washington doubled the growth rate of juvenile coho salmon at this site compared with a nearby stream reach with a low density of carcasses (Bilby et al. 1998). Response by the juvenile fish in this experiment was largely from direct consumption of the carcass flesh and eggs rather than elevated nutrient levels. Fish residing at the treatment site contained nearly 20 times more material in their stomachs (60% to 95% of it salmon eggs and flesh) than did fish collected on the same date from an area without carcasses.

However, distributing hatchery salmon carcasses cannot replace all the ecological functions provided by naturally spawning fish. Spawning fish remove sediment from streambed gravel during redd construction, and this disturbance affects the composition and productivity of invertebrate communities (Minikawa 1997). Salmon also spawn over an extended period, especially in systems used by multiple salmon species. Therefore, carcass material would be present in the channel for a much longer time than would be the case with hatchery carcasses added on a single date. Adding hatchery carcasses to a site several times through the spawning season could alleviate this problem. However, this option is often infeasible because of the expense and logistical constraints of making multiple releases at numerous locations. Application of this technique also may be limited by carcass availability. Out-of-basin transport of carcasses is usually prohibited because of concerns about disease introduction. Thus, carcass addition is generally an option only in watersheds with a hatchery. Because of these difficulties, carcass placement should be considered as an enhancement technique primarily in situations where the

TABLE 6.—Typical response time, duration (plus sign means it could extend beyond the indicated duration), variability in success, and probability of success (low = L, moderate = M, high = H) of common restoration techniques.

Specific action	Years to achieve response	Longevity of action (years)	Variability of success among projects	Probability of success
Reconnect habitats				
Culverts	1–5	10–50+	L	H
Off-channel	1–5	10–50+	L	H
Estuarine	5–20	10–50+	M	M–H
Road improvement				
Removal	5–20	decades to centuries	L	H
Alteration	5–20	decades to centuries	M	M–H
Riparian vegetation				
Fencing	5–20	10–50+	L	M–H
Riparian replanting	5–20	10–50+	L	M–H
Rest-rotation or grazing strategy	5–20	10–50+	M	M
Conifer conversion	10–100	Centuries	H	L–M
Instream habitat restoration				
Artificial log structures	1–5	5–20	H	M[a]
Natural LWD[b] placement	1–5	5–20	H	M[a]
Artificial log jams	1–5	10–50+	M	M[a]
Boulder placement	1–5	5–20	M	M[a]
Gabions	1–5	10	M	M[a]
Nutrient enhancement				
Carcass placement	1–5	Unknown	L	M–H
Stream fertilization	1–5	Unknown	M	M–H
Habitat creation				
Off-channel	1–5	10–50+	H	M
Estuarine	5–10	10–50+	H	L
Instream	(See various instream restoration techniques above)			

[a] Low to high; depends upon species and project design.
[b] LWD = large woody debris.

abundance of spawning salmon cannot be increased sufficiently through restrictions on har~~vest.~~

KATIE I.

Prioritizing Site-Specific Restoration within a Watershed

Prioritizing restoration actions may be based on a number of factors, including the needs of individual species, locations of refugia, or cost-effectiveness (Beechie and Bolton 1999). It is also important to consider the response time, probability and variability of success, and the duration of a given restoration action (Table 6). Those techniques that have a high probability of success, low variability among projects, and relatively quick response time should be implemented before other techniques. For example, reconnecting isolated off-channel habitats or blocked tributaries provides a quick biological response, is likely to last many decades, and based on available evidence, has a high likelihood of success. Generally, these types of restoration activities should be undertaken before methods that produce less consistent results. Riparian restoration or road improvement may not produce results for many years or even decades for some functions (Table 6) and should be considered after reconnecting high-quality isolated habitats. Other techniques, such as instream LWD placement or other instream restoration, are generally effective at increasing coho salmon densities (see section on *Instream Habitat Restoration*). However, instream actions such as these are habitat manipulations or enhancements that should either be undertaken after or in conjunction with reconnection of isolated habitats and efforts to restore watershed processes. In addition, manipulation of instream habitat may be appropriate where short-term increases in fish production are needed for a threatened or endangered species (Beechie and Bolton 1999).

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We developed a hierarchical flow chart based on these principles that can be used to help guide selecting and prioritizing restoration projects (Figure 2). This flow chart combines the known ef-

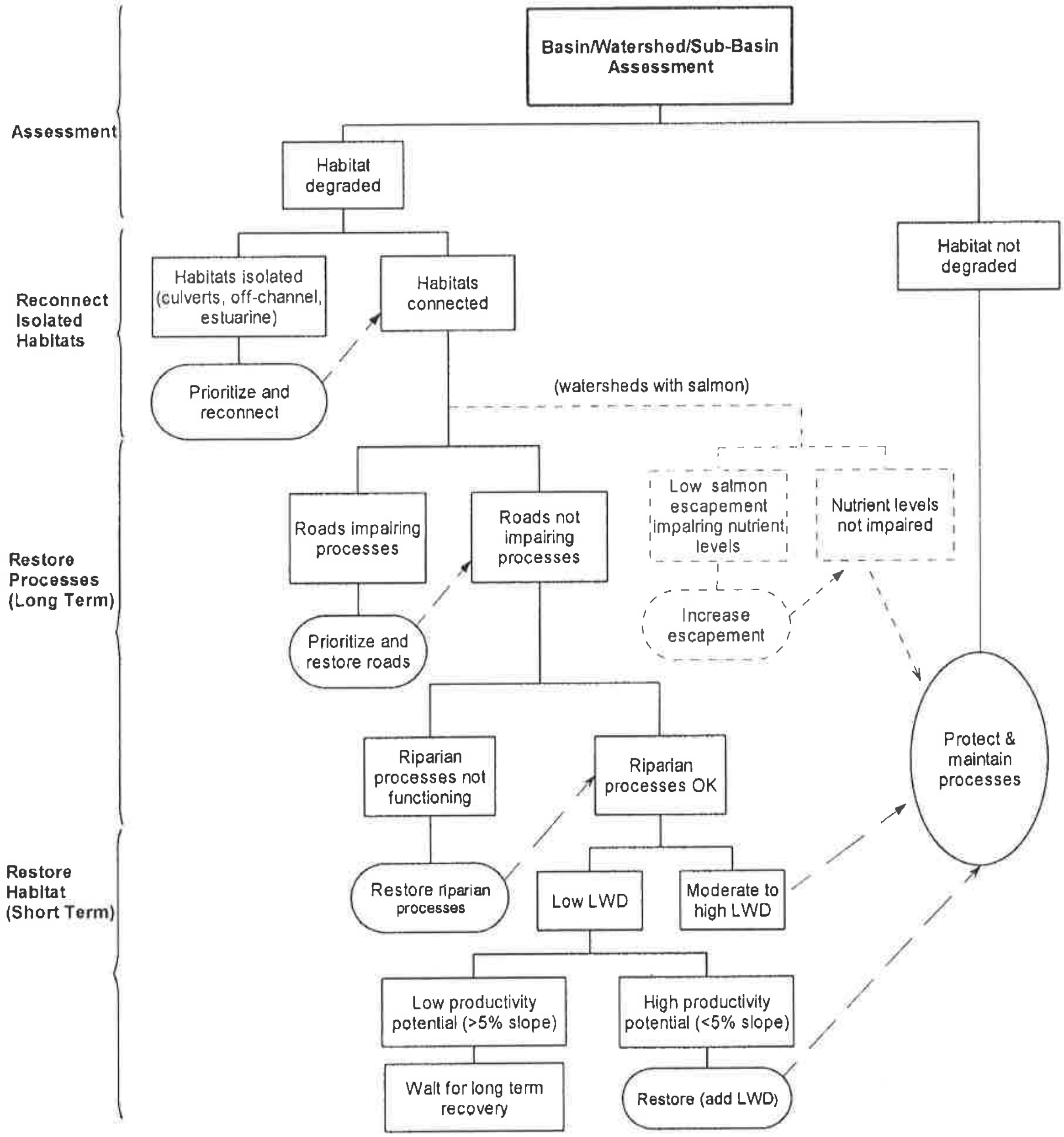

FIGURE 2.—Flow chart depicting hierarchical strategy for prioritizing specific restoration activities. Ovals indicate where restoration actions should take place. Addition of salmon carcasses or nutrients (small dashed lines) may be appropriate at various stages following reconnection of isolated habitats.

fectiveness of various techniques with the need to protect high-quality habitats and restore habitat-forming processes (Figure 1) identified by a watershed assessment. Ideally, habitat restoration requires reconnecting isolated habitats and restoring the disrupted habitat-forming processes (Beechie and Bolton 1999). Habitat manipulations (i.e., instream structures) are generally unnecessary except where adjacent land uses constrain restoration options. In such areas, instream projects that are consistent with the natural habitat characteristics of the site are an option.

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Although most techniques fit well into this hierarchy or framework, carcass placement and nutrient enhancement and estuarine restoration are new techniques, so their place in this hierarchy is uncertain. Little is known about the effectiveness of estuarine restoration. However, reconnecting isolated estuarine habitats such as distributary sloughs is similar to reconnecting isolated off-

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channel habitats, which has been shown to be effective (Table 6). Furthermore, given the importance of estuaries to anadromous fishes and the success of reconnecting isolated off-channel habitats, reconnecting estuarine habitat would probably be effective and should be considered at the same time as reconnecting other isolated habitats. The placement of salmon carcasses or other nutrients into streams may increase fish condition and production in the short term. This restoration technique is a form of habitat enhancement that can occur at any stage in the watershed restoration process. However, because it does not restore, but rather mitigates for a deficient process, we have suggested that it be considered at the same point as instream habitat manipulation. Similarly, the creation of new estuarine or off-channel habitats does not restore a process, and the effectiveness of these efforts is unclear.

I. KATIE

Within the broad restoration categories in Figure 2, some techniques are more effective than others or more applicable in some provinces than others. For example, we include riparian silviculture with fencing and reduced grazing under riparian restoration. Livestock exclusion is a form of riparian protection that has been shown to be effective on range and agricultural lands (Platts 1991). The long-term effectiveness of riparian replanting and conversion techniques, however, is largely unknown. Priorities for different types of riparian restoration will differ by region and watershed, as will other specific restoration techniques that fall into the broad categories we have defined. However, a watershed assessment is the important first step to determine the most effective type of restoration within a given restoration category for the watershed in question.

Placement of instream LWD or boulders into reaches we segregate into high production potential (low gradient) or low production potential (high gradient). Low-gradient channels (<5% slope) are the stream reaches most frequently used by Pacific salmon (Montgomery et al. 1999) and are the reaches where LWD additions are known to provide physical and biological benefits. Therefore, in the cases where instream restoration techniques are implemented, they should occur in reaches with gradients less than 5%. Placing wood or other structures in steeper channels is less likely to have the desired physical or biological benefits.

Summary

Our review of various restoration techniques indicates that knowledge about the effectiveness of most techniques is incomplete and comprehensive research and monitoring are needed. Even techniques that appear to be well studied, such as instream LWD placement, need more thorough evaluation and long-term monitoring. The methodology we present for prioritizing site-specific restoration strategies in a watershed context (Figure 2) is based on three key elements: (1) principles of watershed processes, as indicated in Figure 1, (2) protection of existing high-quality habitats, and (3) current knowledge of the effectiveness of specific techniques (Table 6). We view techniques that manipulate instream habitat as the final step in the hierarchical strategy because they tend to be short-lived, the results are highly variable among techniques and species, and because they do not seek to restore processes. Although we focus on restoration techniques in this paper, it is important not to overlook the need to protect high-quality habitats. Protection of high-quality habitat should be given priority over habitat restoration because it is far easier and more successful to maintain good habitat than to try and recreate or restore degraded habitat. Furthermore, our recommendations are dependent upon a watershed assessment and in no way negate the need for adequate assessment of processes and current conditions in a watershed.

Our approach was primarily designed for forest, range, and other moderately modified rural lands. In urban areas, hydrologic and sediment processes in streams are highly altered (e.g., increased high flows and channel down-cutting). Areas with intensive agriculture often have severe water quality problems, and stream channels in both urban and agricultural areas are often highly channelized and lack adequate riparian vegetation. A combination of urban and agricultural impacts may also inhibit restoration of estuarine habitats. Therefore, the framework we outline may need to be modified for use in these highly altered systems where some processes cannot be reliably restored or where water quality or hydrologic changes may compromise the effectiveness of many of the commonly employed restoration techniques. A more detailed watershed assessment and restoration prioritization technique, such as that outlined by the Skagit Watershed Council (1999), may be useful in these areas.

Finally, we view this paper as a first step in assisting with prioritizing site-specific restoration activities and for providing guidance for allocating monies spent on restoration of Pacific Northwest watersheds inhabited by anadromous salmonids.

Our approach is designed for watersheds where detailed information on processes and stream reaches is lacking and to provide general guidance for biologists and community groups conducting watershed restoration. Cost, site access, fish production potential, and other factors should also be considered when prioritizing restoration projects. We view watershed assessment and restoration as an iterative process. As more information becomes available on a specific watershed and on the effectiveness and cost of various techniques for salmonids and other fishes, our approach should be modified.

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