North American Journal of Fisheries Management 28:856–890, 2008
American Fisheries Society 2008
DOI: 10.1577/M06-169.1

[Article]

Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques

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Abstract.—The degradation of inland aquatic habitats caused by decades of human activities has led to worldwide efforts to rehabilitate freshwater habitats for fisheries and aquatic resources. We reviewed published evaluations of stream rehabilitation techniques from throughout the world, including studies on road improvement, riparian rehabilitation, floodplain connectivity and rehabilitation, instream habitat improvement, nutrient addition, and other, less-common techniques. We summarize current knowledge about the effectiveness of these techniques for improving physical habitat and water quality and increasing fish and biotic production. Despite locating 345 studies on effectiveness of stream rehabilitation, firm conclusions about many specific techniques were difficult to make because of the limited information provided on physical habitat, water quality, and biota and because of the short duration and limited scope of most published evaluations. Reconnection of isolated habitats, floodplain rehabilitation, and instream habitat improvement have, however, proven effective for improving habitat and increasing local fish abundance under many circumstances. Techniques such as riparian rehabilitation, road improvements (sediment reduction), dam removal, and restoration of natural flood regimes have shown promise for restoring natural processes that create and maintain habitats, but no long-term studies documenting their success have yet been published. Our review demonstrates that the failure of many rehabilitation projects to achieve objectives is attributable to inadequate assessment of historic conditions and factors limiting biotic production; poor understanding of watershed-scale processes that influence localized projects; and monitoring at inappropriate spatial and temporal scales. We suggest an interim approach to sequencing rehabilitation projects that partially addresses these needs through protecting high-quality habitats and restoring connectivity and watershed processes before implementing instream habitat improvement projects.

In response to aquatic habitat degradation from a variety of human activities, rehabilitation of these habitats has become commonplace throughout the world (NRC 1992; Cowx and Welcomme 1998). Rehabilitation efforts are often undertaken to restore or improve natural resources that are of economic, cultural, or spiritual importance. Rehabilitation typically occurs in a single reach or in reaches spread throughout a watershed; this includes both riparian and upland activities as well as activities in the lowlands, such as reconnection of floodplains and addition of habitat structures (e.g., logs, boulders, and weirs) to streams. The vast majority of such efforts have been undertaken to restore fisheries resources; in some cases, large sums of money are spent on a single species or group of species. For example, hundreds of millions of dollars are spent annually in western North America in an effort to increase runs of Pacific salmon *Oncorhynchus* spp. that once sustained large fisheries but are now threatened with extinction. Other ecosystem restoration programs have been initiated in the Florida Everglades; the Missouri, Mississippi, and Sacramento rivers; the Louisiana Delta; Chesapeake Bay; the Great Lakes; and other major basins (Northeast Midwest Institute, unpublished data). It is estimated that over US$1 billion are spent annually on various aquatic habitat rehabilitation activities (Bernhardt et al. 2005). Similar efforts are underway in Europe to rehabilitate and reconnect habitats throughout large systems, such as the Rhine and Danube River basins (Buijse et al. 2002). In many developing countries, interest in watershed rehabilitation is also increasing because of declines in fisheries resources, increased frequency of flooding due to poor land use practices, or desertification due to overappropriation of streamflows (Parish 2004). For example, large efforts are underway to reforest areas, restore floodplain wetlands, and reduce flooding in the Yangtze River basin, China, and to restore streamflows and wetlands and halt desertification and loss of biodiversity in the arid Timar River basin (Parish 2004). Similarly, reflooding of large portions of the Mesopotamian Marshes in Iraq, which almost disappeared after extensive draining in the 1990s, is currently underway (Richardson et al. 2005).

Restoration ecology is a relatively young interdisci-

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Received June 26, 2006; accepted August 8, 2007
Published online June 16, 2008

plinary field, and the literature on aquatic rehabilitation is extensive yet fragmented (Buijse et al. 2002). Several existing publications have discussed project design and techniques used for rehabilitation in North America (Hunter 1991; NRC 1992; Hunt 1993; Slaney and Zoldakas 1997; FISRWG 1998), Europe (Brookes and Shields 1996; Petts and Calow 1996; RSPB et al. 1994; Cowx and Welcomme 1998; Vivash 1999; O'Grady 2006), Australia (Rutherfurd et al. 2000), east Asia (Parish 2004), and globally (Roni et al. 2005). Other texts discuss the ecological basis for restoration (e.g., Calow and Petts 1994; Naiman and Bilby 1996; Perrow and Davy 2002), and some regional papers (or gray literature) discuss effectiveness of different techniques (e.g., Binns 1999; Roni et al. 2002; Avery 2004). Understanding the effectiveness of various habitat rehabilitation techniques is critical for project planning, directing future restoration efforts, and project design (Roni 2005). Unfortunately, no comprehensive review of the effectiveness of various rehabilitation techniques has been completed. In particular, examination of the effectiveness of these efforts at improving fish habitat, water quality, and nutrients and increasing fish and biota abundance is required (Roni et al. 2002).

To address the need for a comprehensive review of rehabilitation effectiveness, we synthesized the published information on various stream rehabilitation techniques, quantified the number of published studies, and determined which techniques were demonstrated to be effective. Here, we outline common shortcomings of previous studies, indicate which techniques require additional evaluation, and make recommendations for prioritizing and evaluating stream rehabilitation techniques.

Methods

Literature search.—To assess the effectiveness of stream and watershed rehabilitation techniques, we conducted an extensive review of the existing literature, focusing primarily on peer-reviewed literature and readily available gray literature. We acknowledge that the published literature may be biased towards reporting positive results; however, we had no way of quantifying this bias, and thus we interpreted the located literature as providing an accurate representation of evaluations that have occurred. We searched common scientific databases, including Aquatic Sciences and Fisheries Abstracts, Web of Science, and Google Scholar, to locate relevant papers, book chapters, and technical reports on evaluations of project effectiveness published through 2006. We also searched library catalogs of the United Nations Food and Agriculture Organization (FAO); the Northwest Fisheries Science Center (NWFSC), National Oceanic and Atmospheric Administration (NOAA); and the University of Washington. We conducted our search in English, which may have resulted in some bias; however, many journals in languages other than English contain English abstracts, and most scientific literature is reported in English. We used the following keywords in our online searches: habitat, stream, watershed, aquatic restoration, aquatic rehabilitation, aquatic enhancement, and improvement. We then examined each paper to determine whether the study included evaluation of a stream habitat rehabilitation project; those that did were included in our database. Each paper was examined to determine the type of technique used and whether physical, biological, or water quality responses were evaluated. Physical habitat included hydrology, channel geometry and morphology, channel units (i.e., pools and riffle units), and bank stability. Water quality included (but was not limited to) temperature, dissolved oxygen, nitrates, phosphorus, and conductivity. Biota included fish, macroinvertebrates, plants, aquatic vegetation, algae, and periphyton. Other factors, such as remediation of pollutants, toxicology, water quality, and water quantity, are important for successful watershed rehabilitation, but they are beyond the scope of this review; we focus strictly on freshwater habitats and habitat modifications.

There are many different definitions of restoration and rehabilitation, and practitioners and researchers are in disagreement about what constitutes restoration (Gore 1985; Cairns 1988; NRC 1992; Kauffman et al. 1997). The term restoration, which in the most formal sense is defined as returning an ecosystem to its original, predisturbance state, has commonly been used to refer to all types of habitat manipulations, including enhancement, improvement, mitigation, habitat creation, and other situations. These activities are more accurately termed rehabilitation, as most do not truly restore a system; in many areas where the land use is predominantly agricultural, residential, urban, or industrial, true restoration will be infeasible for the foreseeable future (Stanford et al. 1996). Therefore, we use the term habitat rehabilitation throughout this document to refer to the various activities and, where appropriate, we use more-specific terminology.

Techniques examined.—Dozens of methods and techniques have been developed to rehabilitate freshwater habitats, ranging from those that attempt to restore natural processes (e.g., riparian replanting and sediment reduction) to those intended to create immediate changes in physical habitat (e.g., placement of instream habitat structures) with the goal of creating rapid increases in target species. Typically, many types

TABLE 1.—Categories of stream habitat rehabilitation and examples of common techniques, typical goals of rehabilitation projects, and factors limiting project effectiveness.

Category	Examples of common techniques	Typical goals	Common factors limiting effectiveness
Road improvements	Removal or abandonment; resurfacing; stabilization; addition or removal of culverts	Reduce sediment supply; restore hydrology; improve water quality	Forest roads: surface material, soil treatment, replanting (road removal projects), number of cross drain structures, stream crossing type, traffic levels, tire pressure, soil treatment, and level of replanting (road removal projects) Urban roads: water quality, level of impervious surface area, size of area treated, riparian conditions
Riparian rehabilitation	Fencing to exclude livestock; removal of grazing; planting of trees and vegetation; thinning or removal of understory	Restore riparian vegetation and processes; improve bank stability and instream conditions	Grazing: livestock levels, width of buffer (fencing), upstream riparian shade and sediment, duration of grazing, season of grazing Riparian silviculture: soil treatment, herbivore control, plant species, hydrology and instream flows, floodplain connection, water quality, invasive species
Floodplain connectivity and rehabilitation	Levee removal; reconnection of sloughs and lakes; excavation of new floodplain habitats; remeandering a straightened stream; replacement of impassible culverts or other barriers; removal or breaching of dam; Increase instream flows; restoration of natural flood regime	Reconnect lateral habitats; allow natural migration of channel; reconnect migration corridors; restore longitudinal connectivity; allow natural transport of sediment and nutrients	Level of connectivity (perennial versus seasonal), water quality, instream flows, level of channel incision, restoration of natural flood regime, contaminants, upstream sediment, wood sources (riparian conditions), type of culvert or stream crossing
Instream habitat improvement	Placement of log or boulder structures; engineered log jams; placement of spawning gravel; placement of brush or other cover	Improve instream habitat conditions for fish	Instream flow, water quality, riparian shade, sediment sources, structure design, channel erosion, structure type, previous level of instream structure, upstream processes (wood, water, and sediment), intensity and magnitude of habitat improvement (number of structures and length of stream treated)
Nutrient enrichment	Addition of organic and inorganic nutrients	Boost productivity of system to improve biotic production; compensate for reduced nutrient levels from lack of anadromous fishes	Initial nutrient status, water quality, type and amount of nutrients added (organic versus inorganic), access, existing biotic community (e.g., plankton, invertebrate, or fish community structure)

of rehabilitation are undertaken at the same time at a given site or within a catchment. We categorize these rehabilitation activities into five general areas based on where they occur or the processes or habitats that are targeted for improvement, including (1) road improvement, (2) riparian rehabilitation, (3) floodplain connectivity and rehabilitation, (4) instream habitat improvement, and (5) nutrient enrichment (Table 1). A detailed list of specific techniques within the five categories and the goals of those techniques are outlined in Table 1. We focused on techniques that rehabilitate watersheds for fish; we did not examine techniques designed to protect human infrastructure, such as bank protection or removal of American beavers *Castor canadensis*. We also did not examine habitat protection strategies, such as land purchases, conservation easements, nutrient reduction programs, and regulations protecting habitat, but these are an important part of any habitat rehabilitation and protection strategy.

We summarize the number of studies for each type of rehabilitation, summarize the factors commonly examined, and then describe what is known about each rehabilitation type's effectiveness at improving phys-

TABLE 2.—Total number of reviewed studies that examined different types of stream rehabilitation and responses in water quality or nutrients (WQ), biota (fish, plants, or macroinvertebrates), or physical habitat (e.g., sediment, woody debris, bank stability, and habitat types).

Technique	Response			Number of papers
	WQ	Physical	Biota	
Road improvements				26
Abandon or remove	1	11	4	15
Culvert or hydrology	2	3	2	5
Resurface or sediment reduction	1	6	1	6
Riparian rehabilitation				48
Planting and thinning	2	1	9	10
Exotics and other	0	0	2	3
Fencing and exclusion	6	17	21	25
Rest–rotation grazing	1	9	9	10
Floodplain connectivity and rehabilitation				90
Levee removal or setback	2	4	6	7
Reconnect existing habitats	2	3	11	11
Meander creation	4	10	16	20
Beaver reintroduction	0	4	5	5
Constructed habitats	3	5	17	17
Dam removal	2	11	10	14
Flood flow or flow modification	1	7	14	15
Other	0	1	1	1
Instream habitat improvement				163
Logs, wood, or rock structures	1	109	118	142
Gravel additions	2	7	6	10
Other	0	9	9	11
Nutrient addition				18
Organic nutrients	1	0	9	9
Inorganic nutrients	2	0	9	9

ical habitat, water quality, and biota. For biotic responses, we focus primarily on fishes and to a lesser extent on macroinvertebrates, but we report on plants and other biota when such studies are available and appropriate. Because the studies were vastly different, even within one given category of rehabilitation, it was not possible to quantitatively compare or analyze studies. Therefore, we provide a written synthesis of the studies (papers or technical reports) and indicate the most effective techniques and factors limiting their effectiveness (though not all studies reported this); techniques that are in need of additional monitoring and evaluation are noted. For counts of the number of studies describing a given technique, if a study occurred in more than one country, state, or province it was counted more than once. We used a similar approach for tallying the number of studies that examined physical habitat, water quality, nutrients, and biological monitoring. However, if a paper reported the use of more than one category of rehabilitation, it was categorized based on the dominant type of rehabilitation and was counted only once. Thus, a paper (study) will appear in our database only once, but the factors monitored or area covered by the study may appear multiple times. Because a greater amount of biological effectiveness information was located for instream habitat improvement than for other categories, we discuss biological effectiveness in more detail for this rehabilitation category than for the other categories.

Results of Literature Review

We located 345 papers (published between 1937 and 2006) that reported results of scientific evaluations of the effectiveness of one or more habitat rehabilitation techniques (Table 2). Despite our global search, the vast majority of studies on both rehabilitation and effectiveness were from the United States, Canada, and Europe, whereas relatively few papers were from other countries (21 papers). Therefore, much of our review focuses on studies in North America and, to a lesser extent, Europe. Within the USA, the majority of the studies occurred in the western region (Figure 1) and most of these occurred after 1990. Since these are individual counts of papers, the number of projects implemented or evaluated is not necessarily reflected in the counts. For example, Hunt (1988) and Avery (2004) reported on a combined total of 103 trout stream rehabilitation projects in Wisconsin, but their papers only count as two studies. Most of the published literature on effectiveness focuses on instream rehabilitation (163 of 345 papers; Table 2). Biotic responses were measured more frequently than other parameters (217 studies for physical habitat, 33 for water quality, and 279 for biota). Fish were the most commonly monitored biota. Below, we provide summaries of our literature review for each category of techniques.

Road Improvements

A total of 26 papers from four countries reported the effects of road improvements on aquatic habitats. Of these studies, 25 were on forest roads. Only six studies examined biota, and only two of these examined fish (Scully et al. 1990; Glen 2002). Most of the other research we located on the effectiveness of road rehabilitation efforts focused on physical effects on the stream channel and occasionally on processes such as erosion rates and landslides in mountainous regions. Only a few studies reported water quality or biota (Table 2).

While many road rehabilitation techniques (e.g., removal, resurfacing, stabilization, removal of culverts, etc.) are widely utilized in mountainous areas to reduce fine-sediment delivery to streams and reduce hydrologic impacts of roads, few published evaluations of their effectiveness exist (Switalski et al. 2004). Evaluations of road surface erosion reduction tech-

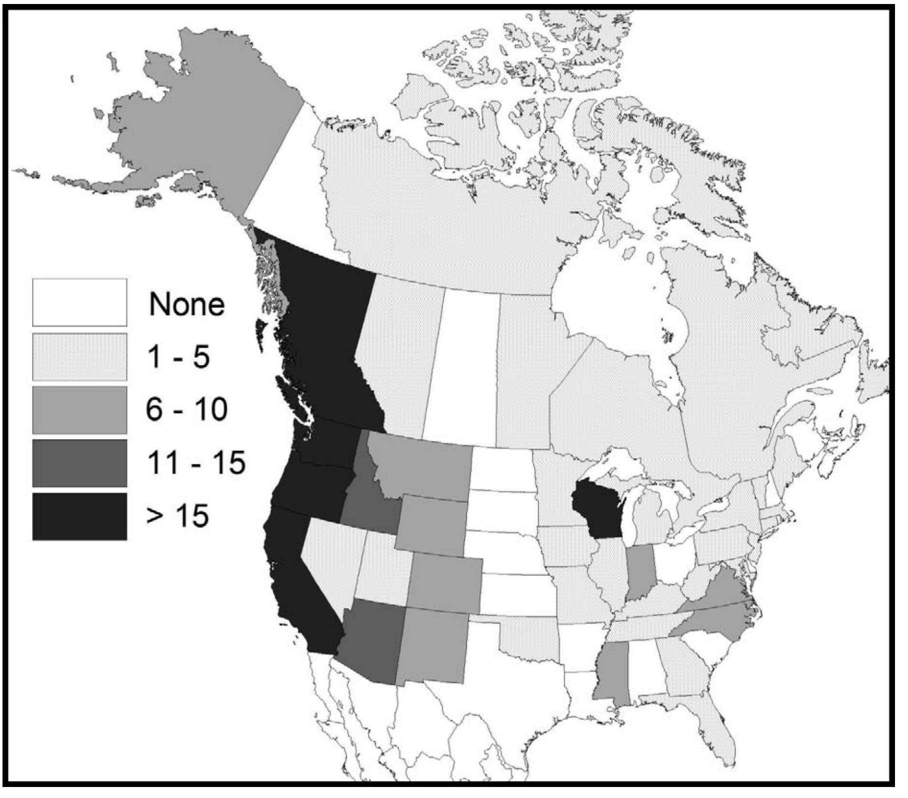

FIGURE 1.—Number of studies evaluating common stream habitat rehabilitation techniques used in each state or province in North America. Provinces or states with over 15 studies included British Columbia (22 studies), California (31), Oregon (44), Washington (27), and Wisconsin (16).

niques have generally been limited to comparisons of fine-sediment concentrations in road runoff at different traffic levels and with different surfacing materials. For example, a handful of studies have demonstrated that reducing truck tire pressure or traffic levels on unpaved forest roads can greatly reduce surface erosion (Reid and Dunne 1984; Bilby et al. 1989; Burroughs and King 1989; Foltz 1998; Foltz and Elliot 1998). Improving the road surface can greatly reduce erosion as well (Burroughs and King 1989). Increasing the thickness of road surfacing material (gravel) to 7.5–15.0 cm was reported to reduce surface erosion by more than 80% in some cases (Reid and Dunne 1984; Kochenderfer and Helvey 1987; Burroughs and King 1989). The road surface used can greatly reduce erosion as well (Burroughs and King 1989). These studies on both road surface material and tire pressure, while limited to the United States, suggest that when implemented properly, these methods can reduce surface erosion.

Road abandonment or complete removal has also been demonstrated to greatly reduce sediment delivery (Hickenbottom 2000; Madej 2001; Switalski et al. 2004). For example, Hickenbottom (2000) demonstrated that runoff and erosion approached those of natural slopes 12 months after road removal and recontouring in a Montana watershed. Madej (2001) reported reduced sediment delivery to streams after removal and treatment of 300 km of roads in Redwood National Park, California. Switalski et al. (2004) reviewed published evaluations of road removal and indicated that most studies had reported reductions in landslides and surface erosion but that little information was available on long-term hydrologic responses to road removal and no information was available on wildlife or fish responses. The type of treatment after road removal or closure (e.g., recontouring of slope, ripping of road surface, removal of stream crossing, placement of mulch, seeding, and planting) can influence the sediment production and infiltration capacity of the former road bed (Cotts et al. 1991; Maynard and Hill 1992; McNabb 1994; Luce 1997; Elseroad et al. 2003). In general, these studies have found that slope recontouring and site preparation (ripping and mulching of the former road bed) are most effective at inducing plant growth and reducing fine-sediment production, though the road's position on the slope and time since treatment also play a role in effectiveness of these methods.

Few evaluations of techniques for reducing road-related landslide hazards have been conducted. Harr and Nichols (1993) provided anecdotal evidence that road removal resulted in reduced landslide rates in mountainous areas. Cloyd and Musser (1997) examined a subset of over 1,200 km of Oregon forest roads that were stabilized, removed, or left untreated; they found a higher problem rating (erosion and mass failure severity) on untreated roads associated with stream crossings. Changes in turbidity associated with stream crossing and road rehabilitation have occasionally been examined; however, results generally show short-term, construction-related increases in turbidity (Brown 2002). Finally, it is important to note that geology plays an important role in the level of natural sediment delivery, the level of sediment delivery from roads, and the overall success of sediment reduction achieved by road resurfacing or complete road removal (Bloom 1998).

Removal or replacement of culverts and other road crossing structures is not only a common strategy for reducing landslide potential on steep slopes, reducing forest road erosion, and reducing runoff but is also a common technique for improving fish passage. Physical studies on channel response after culvert removal are rarely conducted or published. In a rare study on channel adjustment after culvert removal, Klein (1987) reported that postremoval channel adjustments in a California watershed were minimal when large woody debris or other channel roughness elements were present. The few published studies on culvert removal have, however, focused on biotic response or recolonization, which is usually the major objective of culvert replacement projects. Fish often colonize new habitats relatively quickly, and several studies have demonstrated the effectiveness of replacing stream culverts to restore fish access (Iversen et al. 1993; Bryant et al. 1999; Glen 2002; see also Floodplain Connectivity). However, if fish numbers are extremely low or if a culvert is only passable at some water levels or seasons, it may take several years for fish to colonize new habitats; therefore, long-term monitoring will be required to evaluate success. Studies comparing different types of habitat rehabilitation techniques for salmon have shown that removal of fish migration barriers leads to some of the largest increases in fish production. For example, Scully et al. (1990) indicated that 70% of the increases in fish production in rehabilitated Idaho streams were due to barrier removal versus instream and other rehabilitation techniques.

In addition to benefiting fishes, culvert replacement or other barrier removal projects may benefit invertebrates and wildlife (Yanes et al. 1995; Vaughan 2002). For example, Yanes et al. (1995) found that culverts both facilitated and inhibited migration of many mammals and reptiles, and Vaughan (2002) suggested that culverts inhibit upstream movement of many aquatic macroinvertebrates. Finally, the ability of various stream crossing types to allow for passage of fish and other aquatic organisms involves a complex relationship between the physical characteristics of the stream crossing (e.g., depth, velocity, and roughness) and the behavior and swimming performance of the fish or other biota (Clay 1995; Larinier 2002a, 2002b). Although the published literature is limited, it is clear that the replacement of culverts and other road crossing structures that prevent or inhibit fish migration can be a highly successful technique for increasing available fish habitat and production.

We located little information on effectiveness of methods for reducing urban or paved road impacts to stream channels. Much of the literature on urban stormwater management and hydrology has focused on modeling of potential changes (e.g., Johnson and Caldwell 1995; Sieker and Klein 1998) and examining wetland effects on processing stormwater runoff (Kohler et al. 2004). Booth et al. (2002) indicated that stormwater retention ponds have generally been inadequate for alleviating channel erosion or restoring the hydrologic regime in highly urbanized areas because of the small size of most ponds. Newer methods for stormwater reduction and for reducing hydrologic and water quality impacts via natural drainage systems (e.g., constructed swales, wetlands, and vegetated areas) have shown promise but are still in the early stages of development, and we located no published evaluations.

Riparian Rehabilitation

We located a total of 48 studies (from seven countries) that examined the effectiveness of various riparian rehabilitation methods on riparian conditions, aquatic habitat, and biota. Riparian rehabilitation techniques and studies of their effectiveness fall into two major categories: (1) fencing and grazing reduction and (2) silviculture treatments. We discuss the two separately, as their approaches to rehabilitation and the associated responses of riparian areas are different. Grazing management or reduction efforts typically are designed to remove or limit pressure on riparian areas (i.e., grazing) and allow vegetation to recover naturally (sometimes called passive restoration). Silviculture treatments restore riparian areas through replanting of trees and other vegetation, typically with protection from further harvest or vegetation removal.

Riparian silviculture.—The effectiveness of riparian silviculture techniques has been primarily evaluated through short-term examination (<10 years) of vegetation survival and growth (Jorgensen et al. 2000; Pollock et al. 2005). A number of factors affect the growth and survival of riparian plantings, including understory or overstory control and grazing by herbivores. Emmingham et al. (2000) examined over 30 riparian projects designed to convert deciduous riparian areas to coniferous riparian forests in coastal Oregon; those authors suggested that riparian silviculture treatments initially showed promise at establishing conifers in hardwood-dominated riparian zones. However, a lack of understory and overstory control and a lack of protection from browsing by deer *Odocoileus* spp., elk *Cervus elaphus*, American beavers, and mountain beavers *Aplodontia rufa* affected project success. Similarly, Sweeney et al. (2002) examined the success of different oaks *Quercus* spp. over 4 years under various riparian treatments and silviculture techniques. Protection from herbivores was the most important factor in determining oak seedling survivorship.

While riparian silviculture treatments are believed to improve fish habitat and increase fish production, no thorough research on fish response to riparian planting exists and only a few studies have examined other instream biota. Penczak (1995) found that fish diversity increased from 11 to 16 species in the Warta River, Poland, as riparian vegetation regenerated after removal. Parkyn et al. (2003) examined riparian fencing and replanting in New Zealand and demonstrated that replanted riparian buffers provided improvements in water quality and channel stability; however, nutrient and fecal contaminant responses were variable, and a shift towards less-tolerant, clean-water macroinvertebrate species was not observed. Parkyn et al. (2003) suggested that larger or longer buffers were needed to effect changes in water temperature and macroinvertebrate communities.

Techniques designed to restore floodplains (e.g., river widening, also termed levee setback) are also thought to benefit riparian forests. Rohde et al. (2005) reported that river widening projects in Switzerland led to enhanced establishment of riparian plants. However, the ability of a river widening project to promote colonization by typical native riparian plants and increase local plant diversity appeared to depend on the project's proximity to natural stream reaches. Dam removal and restoration of natural flood regimes can also improve riparian conditions; these techniques are discussed in the subsequent section on floodplain connectivity.

Evaluation of invasive species removal efforts typically focuses on the success of nonnative species eradication and native species recolonization (primarily native cottonwoods *Populus* spp. and willows *Salix* spp.). Taylor and McDaniel (1998), Roelle and Gladwin (1999), Sprenger et al. (2002), and other researchers have monitored and examined the success of various chemical, burning, mechanical, and hydrological treatments in removing tamarisks *Tamarix ramosissima* and the subsequent recolonization of native species. Application of a combination of these techniques, along with cottonwood and willow plantings and timed irrigations, has produced diverse riparian habitat (Taylor and McDaniel 1998). Roelle and Gladwin (1999) were able to prevent the establishment of tamarisk seedlings at a rehabilitation site by regular, controlled fall flooding.

Briggs (1996) indicated that passive riparian restoration (removal of the stressor) allows for natural recovery rates that are sometimes sufficient to preclude the need for hands-on rehabilitation. Natural recovery of forests is also a common practice for restoring seasonally inundated forests that provide critical fish spawning and rearing habitat. For example, in Cambodia, reforestation is used as an important fisheries rehabilitation technique to create fish spawning, rearing, and feeding areas in seasonally flooded forests adjacent to Tonle Sap (Great Lake) and the Mekong River (Thuok 1998). Natural recovery is thought to be an effective riparian restoration strategy under the right circumstances, but long-term monitoring is needed to validate this assumption.

Despite the dearth of studies examining biological effects of riparian restoration, many other studies have shown that protection of riparian areas reduces the sediment, nutrient, and pesticide concentrations delivered to streams (e.g., Osborne and Kovacic 1993; Barling and Moore 1994; Dosskey et al. 2005; Mayer et al. 2005; Puckett and Hughes 2005). A number of factors influence riparian buffer effectiveness, including flow path (surface or subsurface), buffer width, vegetation type, depth of rooted zone, and runoff. These studies fall in the gray area between rehabilitation and protection; we did not include them in our review, and they did not appear in our keyword search of library databases. There are also dozens of papers on this topic, and additional information can be found in the references cited above.

Fencing and grazing reduction.—Thirty-five studies of riparian grazing from seven countries were located; 25 of the studies focused on fencing and livestock exclusion, and 10 focused on rest–rotation grazing management (periodic removal of livestock). The various studies on the effectiveness of grazing reduction methods at restoring riparian areas have examined a broad array of different grazing systems, which hinders our ability to draw firm conclusions about the relative effectiveness of any grazing system other than grazing removal. Below, we summarize what is known about the effectiveness of grazing removal or reduction at improving riparian condition, physical habitat, and aquatic biota. This sequence also represents the chronological order in which systems recover after reduction in grazing.

Riparian conditions.—The relatively rapid improvement (5–10 years) in riparian vegetation and riparian functions, such as shade, sediment storage, and hydrologic effects (i.e., water storage and aquifer recharge), after livestock exclusion or dramatic reductions in grazing intensity have been documented in several studies (Elmore and Beschta 1987; Myers and Swanson 1995; Clary et al. 1996; Kauffman et al. 1997; Clary 1999; O'Grady et al. 2002). For example, in a comparison of currently grazed sites and sites with no grazing for 2–50 years prior, Robertson and Rowling (2000) found that understory vegetation was one order of magnitude higher and tree abundance was three orders of magnitude higher on ungrazed sites than on grazed sites. The percentage of bare soil was lower and the levels of fine and coarse particulate organic matter were higher on ungrazed sites than on grazed sites. Similarly, Platts (1991) reviewed grazing strategies in the USA, identified 17 riparian grazing systems, and indicated that light use and complete livestock exclusion provided adequate protection for riparian and fisheries resources. The success of rest–rotation grazing systems at allowing vegetation recovery is influenced by many factors, including number of days of grazing, season, seasonal livestock dispersal behavior, and level of compliance (Myers 1989). In a Montana study (Myers 1989), rest–rotation grazing systems that allowed for successful recovery of vegetation averaged 28 d in grazing duration, while unsuccessful systems averaged 59 d. Historically, grazing systems have not differentiated between riparian and upland range areas (Clary and Webster 1989). However, grazing systems that control the intensity and timing of riparian and upland usage are also thought to be beneficial (Elmore 1992). When coupled with intensive monitoring, rest–rotation and other seasonal grazing strategies have shown promise at protecting riparian and aquatic habitat (Myers and Swanson 1995), but these strategies require additional evaluation.

While grazing by native ungulates may have historically degraded some riparian and stream areas, there is evidence that ungulates can help maintain diversity of riparian vegetation (Medina et al. 2005). In a recent study in Scotland, Humphrey and Patterson (2000) found that reintroduction of cattle grazing increased plant community diversity. Conversely, the exclusion of excessive grazing by native herbivores can also assist in the recovery of riparian vegetation. For example, Opperman and Merenlender (2000) found significantly higher levels of woody plants (willows) along California stream reaches where fencing excluded Columbian black-tailed deer *Odocoileus hemionus columbianus*. Moreover, the exclusion of livestock may be followed by an increase in native ungulates, which can also negatively affect recovery efforts in riparian areas and the stream channel (Medina et al. 2005). These studies suggest that both native and domestic ungulates have similar positive or negative effects upon riparian conditions.

Physical habitat and channel conditions.—Instream habitat conditions recover more slowly than many riparian conditions (e.g., shade and plant growth); however, several studies in arid environments have reported positive effects of complete grazing removal or fencing on bank stability and channel features (Platts 1991; O'Grady et al. 2002; Medina et al. 2005). Myers and Swanson (1995) found that both complete livestock exclusion and rest–rotation grazing increased bank stability, tree cover, and pool habitat but that other management activities (e.g., road crossing and removal of coarse woody debris) negatively affected instream conditions. Clary et al. (1996) and Clary (1999) reported that width : depth ratios and substrate embeddedness improved after complete removal or reduction of grazing in two separate studies in Oregon and Idaho. Connin (1991) reviewed several riparian rehabilitation projects that involved bank protection and either fencing or grazing removal in the western United States; these projects generally produced increases in bank stability and riparian vegetation growth and improved channel conditions. In cases where livestock are excluded from only a portion of the riparian zone, the width of the exclusion or buffer zone is positively correlated with the level of fine-sediment reduction (Hook 2003). These studies demonstrate that grazing systems may also lead to recovery of streambanks, particularly if historic grazing was extremely heavy. Complete grazing removal appears to allow for better recovery of other in-channel factors, such as width : depth ratio, channel entrenchment, bank angle, and fine sediment. Recovery of these and other instream factors is often slower in deeply incised channels (Elmore and Beschta 1987; Myers and Swanson 1995).

Biotic responses.—We located 30 published studies examining the effects of grazing reduction on fishes or other aquatic biota. The current knowledge of the effects of grazing and grazing reduction on fish populations has been developed primarily by analyses of grazing effects on stream habitat characteristics (Platts 1991; Clary 1999). Much of the information is based on studies comparing sites with different levels of grazing, habitat quality, and fish numbers; these studies generally show higher stream temperatures and lower fish numbers in grazed sites or watersheds than in ungrazed sites (e.g., Myers and Swanson 1991; Platts 1991; Li et al. 1994; Wu et al. 2000). Platts (1991) and Rinne (1999) conducted thorough reviews on grazing in the western United States and indicated that although some studies demonstrated increases in fish numbers, fish and aquatic biota were rarely the focus of the studies. Rinne (1999) found that in most studies, the experimental design or duration was inadequate to effectively determine significant changes in fish numbers due to grazing removal or reduction. In a study of Oregon streams, Kauffman et al. (2002) reported that livestock exclusion yielded improvements in vegetation, stream morphology, and density of age-0 rainbow trout *Oncorhynchus mykiss* but not in density of adult or juvenile rainbow trout. Kauffman et al. (2002) suggested that the lack of juvenile or adult response was attributable to the short reaches sampled in their study. Medina et al. (2005) reported on three long-term case studies in the southwestern USA and found that in all three cases, results were inconclusive due to study design limitations, species interactions, upstream or watershed-scale effects, introduction of exotic species, and fisheries management (stocking and changes in fishing regulations).

Only a few published studies have examined the effects of grazing reduction on fishes or biota in other parts of the world. O'Grady et al. (2002), for example, reported an increase in numbers of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta*, and minnow *Phohincus phohincus* after bank stabilization with trees and fencing to exclude livestock in an Irish basin subjected to severe overgrazing. Parkyn et al. (2003) found that fencing and planting of riparian buffers produced rapid improvements in water quality and channel stability but had no detectable effect on macroinvertebrate fauna in New Zealand streams. Similar to North American studies, Parkyn et al. (2003) indicated that upstream, watershed-scale factors and short buffer reaches probably influenced results for biota. These limited studies emphasize the need for long-term, well-designed, watershed-scale monitoring of grazing reduction effects on aquatic biota.

Other factors.—Reduction in grazing can influence water quality, fish diet, and other biota. In a rare watershed-scale study, Meals and Hopkins (2002) reported that riparian fencing coupled with other bank protection actions reduced phosphorus levels by up to 20%. Similarly, Sovell et al. (2000) found lower fecal coliform and turbidity levels at continuously grazed sites than at rest–rotation grazed sites. Removal of grazing can lead to improvements in avifauna richness and abundance through changes in riparian community and associated changes in the water table (Diaz et al. 1996; Dobkin et al. 1998). Grazing can also affect fish growth and abundance by changing the plant community, thereby affecting fish prey and, in turn, fish diet, as was demonstrated by Laffaille et al. (2000) for European seabass *Dicentrarchus labrax* in a French marsh.

Floodplain Connectivity

A total of 90 studies from 16 countries examined connectivity and floodplain habitat rehabilitation techniques, including reconnection of existing floodplain habitat, remeandering, constructed habitats, dam removal, and restoration of natural flood regimes. The majority of these studies focused on creation or reconnection of floodplain habitats, and most examined physical and biological responses (Table 2). We discuss each of the previously mentioned floodplain techniques separately below.

Reconnection of existing floodplain habitats.—The benefits of reconnecting floodplain habitats are typically measured by quantifying the area or length of physical habitat that is reconnected. For example, in the Danube River, the reconnection of a former side channel and canal resulted in an additional 50 km of habitat. Reconnected floodplain ponds have proven to be effective at providing habitat for juvenile salmonids, such as coho salmon *O. kisutch* and Chinook salmon *O. tshawytscha* (Nickelson et al. 1992; Richards et al. 1992; Norman 1998; Roni et al. 2002, 2006a; Henning et al. 2006). They are also known to provide critical rearing habitat for a number of other fishes, including cyprinids, catostomids, and many other warmwater and coolwater fishes (Schmutz et al. 1994; Grift et al. 2001). Schmutz et al. (1994) reported the colonization of a reconnected section of the Danube River and found over 40 fish species after only 1 year. In the lower Rhine River, reconnection of floodplain lakes and channels led to an increase in abundance of rheophilic cyprinids. In Bangladesh and India, reconnection of secondary channels and floodplain lakes has been shown to be effective for increasing fish catch (Thompson and Hossain 1998; Rahman et al. 1999). For example, the reconnection of Singharagi Beel, Bangladesh, led to an increase in annual fisheries yield from 1,863 to 11,384 kg/ha (partly because of increased effort), and the percentage of catch composed of large migratory catfishes and carps increased from 2% to 24% (Payne and Cowan 1998). Similarly, Rahman et al. (1999) reported increased cyprinid harvest in Bangladesh after reconnection of floodplain channels and canals through dredging of silt (Rahman et al. 1999). Rapid colonization and use of reconnected habitats are not altogether surprising given that many freshwater fish species are entirely or partially dependent upon floodplain habitats for some or all of their life history stages (Welcomme 1985; Mann 1996; Cowx and Welcomme 1998; Buijse et al. 2002). The discharge and level of reconnection (complete or partial) affected the species composition (Schmutz et al. 1998; Grift et al. 2001; Simons et al. 2001).

Levee breaching.—Most of the information on project effectiveness for levee breaching and setbacks has focused on physical aspects and the lateral hydrologic connectivity of habitats. Levee removal and bank armoring allow the channel to migrate naturally and recover its former sinuosity and are becoming increasingly common. Changes in nutrient transport levels have been reported for levee removal projects that allow reconnection with wetlands (Childers et al. 1999a, 1999b). Florsheim and Mount (2002) demonstrated that levee breaching on the Cosumnes River, California, allowed for the successful restoration of floodplain features, such as sand splay complexes. Evidence from ongoing studies in Austria indicates that river channels begin to move laterally and recover some sinuosity and habitat complexity fairly quickly after levee removal (Jungwirth et al. 2002; Muhar et al. 2004). Levee setbacks and modifications on the Danube River have also been shown to benefit not only rheophilic fishes but also amphibians and dragonflies (Chovanec et al. 2002). Moreover, Hein et al. (1999) demonstrated that plankton biomass increased in reconnected habitats and that plankton production declined as habitat connectivity decreased. These and other European studies have demonstrated improvements in physical habitat and restoration of natural erosional and channel migration processes, as well as improvements in fish and riparian diversity and age structure (Jungwirth et al. 2002; Rohde et al. 2005).

Remeandering.—The effectiveness of remeandering can be measured in part by an increase in the total stream length after restoration of meanders. For example, in a review of Danish stream rehabilitation, Iversen et al. (1993) reported stream length increases ranging from 17% to more than 60% for five river meander reinstatement projects. Remeandering on the Brede, Cole, and Skerne rivers in Denmark and England is one of the more thorough ongoing evaluations of stream remeandering. Evaluation of these projects indicated an obvious improvement in habitat complexity and channel morphology, flood frequency, and amount of water passing onto the floodplain, as well as an increase in sediment deposition and sediment-associated phosphorus (Kronvang et al. 1998; Sear et al. 1998). Studies in the River Gelså and other remeandered Danish streams have demonstrated some small increases in macroinvertebrates, fish fauna, and aquatic vegetation (Iversen et al. 1993; Hansen 1996; Friberg et al. 1998). Improvements in both physical habitat and fish species diversity have also been reported from Austrian streams (Jungwirth et al. 1995). In contrast, Moerke and Lamberti (2003) reported little fish response to remeandering in two Indiana streams because upstream sediment input counteracted the benefits of habitat improvement. Similarly, Cowx and Van Zyll de Jong (2004) reported that persistent water quality problems and lack of riparian habitat prevented recovery of fish and habitat in a remeandered reach of the River Dearne, England. While most studies on remeandering have shown short-term success, long-term monitoring either has not been conducted or has not yet been reported. If not adequately addressed, water quality, sediment, and other watershed-scale problems can prevent recovery of biota even in the best-designed remeandering projects.

Constructed habitats.—Much of the literature on floodplain rehabilitation effectiveness in terms of fish response comes from studies on constructed ponds and channels. As with reconnected habitats, connectivity to the main river channel plays a large role in the physical and biological effectiveness of constructed habitats. Constructed floodplain habitats have been shown to be particularly effective at both providing habitat for and increasing survival of juvenile salmonids (Sheng et al. 1990; Raastad et al. 1993; Lister and Bengeyfield 1998; Solazzi et al. 2000; Giannico and Hinch 2003; Roni et al. 2006b). Excavation of groundwater channels is a particularly popular technique for creating spawning habitat for salmonid fishes (Bonnell 1991; Cowan 1991; Hall et al. 2000). Similar to surface-fed side channels, groundwater-fed channels also provide rearing habitat for juvenile fishes, particularly coho salmon (Bryant 1988; Bonnell 1991; Richards et al. 1992; Morley et al. 2005).

Constructed side channels and other off-channel ponds are effective for many other fish species, such as northern pike *Esox lucius* (Cott 2004), nase *Chondrostoma nasus*, other rheophilic fishes (Chovanec et al. 2002), and age-0 coarse fishes (Langler and Smith 2001). Habersack and Nachtnebel (1995) found that a constructed side channel of the River Drau, Austria, had a higher diversity of habitats, substrates, and macroinvertebrates and higher fish densities than main-stem river reaches. These studies demonstrate that properly constructed floodplain habitats can provide important spawning and rearing areas for a variety of fishes.

Dam removal.—Because dam removal is a relatively new technique, the published literature on its effectiveness is not extensive, though many of the benefits are inherently obvious (e.g., fish access and passage). We located a total of 14 studies from three different countries; nine of these studies examined effects on biota (primarily fish). Hart et al. (2002) summarized the results of several dam removal projects in the United States and reported more than 10 cases in which dam removal from both warmwater and coolwater rivers resulted in rapid colonization of former impoundment sites and upstream areas by migratory and resident fishes. For example, dam removal on the Clearwater River, Idaho, in 1963 reconnected the main stem, increasing both habitat quality and Chinook salmon runs (Shuman 1995). Similarly, removal of 150-year-old Edwards Dam on the Kennebec River, Maine, resulted in upstream movement by large numbers of American eels *Anguilla rostrata*, alewives *Alosa pseudoharengus*, Atlantic sturgeon *Acipenser oxyrinchus*, and shortnose sturgeon *Acipenser brevirostrum* within the first year and downstream migration of juveniles in subsequent years (Hart et al. 2002). Smith et al. (2000) reported improved fish passage after removal of a 3-m-high dam from an Oregon stream, but continued water withdrawal and other factors upstream of the former dam site prevented full recovery of physical and biological conditions. Kanehl et al. (1997) also examined the effects of a low-head dam removal in Wisconsin and found improvements in habitat quality, biotic integrity, and abundance and biomass of smallmouth bass *Micropterus dolomieu* at 5 years postremoval. The installation of bypass channels that facilitate fish access above diversion weirs has also proven to be a highly successful rehabilitation technique in European streams (Iversen et al. 1993; DVWK 2002). Clearly, dam removal has a number of benefits for migratory and lotic fishes.

Channel morphology and physical habitat downstream from a dam typically change after dam removal. Several studies have demonstrated increases in sediment transport and fine sediment, but changes in sediment depend upon the composition and levels of fine sediment trapped behind a dam prior to its removal. Downstream effects of dam removal on ecological attributes ultimately depend on how reservoir-derived deposits move into and through downstream reaches (Stanley and Doyle 2003). For example, Doyle et al. (2003) examined low-head dam (<3 m high) removal in two Wisconsin rivers and reported erosion of fine sediment that had been deposited in the former reservoir and increased deposition of fine sediment downstream. Hart et al. (2002) reviewed 20 dam removals in the USA, 14 of which documented increased sediment transport, but few of these studies were long enough to document changes in the channel downstream of the former dam sites. Chisholm (1999) reported anecdotal evidence on the positive effects of 25 dam removals in the United States. However, he also provided information on one dam removal (Fort Edward Dam on the Hudson River, New York) that is considered a failure because it resulted in the release of polychlorinated biphenyl-contaminated sediments into downstream reaches; these contaminants continue to have negative consequences for aquatic resources. Changes in downstream water temperature also typically occur after dam removal, as do shifts in the macroinvertebrate community, sediment supply, and turbidity (Hart et al. 2002). Increases in sediment supply after dam removal can negatively affect biota. For example, Sethi et al. (2004) reported that a postremoval increase in sediment supply was associated with a decline in unionid mussels.

Former impoundments are affected by dam removal because they are returned to river, riparian, and floodplain habitats as soon as the reservoir is drained (Hart and Poff 2002; Stanley and Doyle 2003). For example, fish and macroinvertebrates that were adapted to a high-sediment reservoir environment gave way to riverine fish and macroinvertebrates within 1 year of two separate dam removal projects in Wisconsin (Stanley et al. 2002; Stanley and Doyle 2003). In a related study on the Baraboo River, Wisconsin, Stanley et al. (2002) found that macroinvertebrate assemblages in formerly impounded (reservoir) stream reaches were similar to those in upstream and downstream reaches within 1 year of dam removal. Aquatic and riparian vegetation also change in former reservoir sites (Hart et al. 2002; Shafroth et al. 2002). These studies demonstrate the dramatic changes in physical habitat and riparian and aquatic flora and fauna that occur after dam removal. They also suggest that there are some negative consequences of dam removal, such as short-term channel instability and colonization of newly exposed riparian areas by invasive riparian species.

Restoration of natural hydrologic regimes.—In the absence of dam removal, restoration of the natural flood regime has been proposed as a method for restoring or improving a wide array of processes, such as connectivity of the floodplain, sediment transport, and regeneration of riparian vegetation. Because this technique is relatively new, information on its effectiveness is limited. The most notable test case involved attempts to restore the natural flood regime in the U.S. Grand Canyon (Stromberg 2001). Results of high-flow tests have shown some promise in this large river system that had a very dynamic flow regime prior to regulation. Recent restoration activities that simulate floods have resulted in (1) changes to riparian colonization, creating a closer approximation of natural colonization patterns, and (2) a reduction in nearshore woody vegetation that artificially established as a result of flood control (Mahoney and Rood 1990; Ellis et al. 2001; Stevens et al. 2001). Stevens et al. (2001) monitored the effects of flood simulations downstream of Glen Canyon Dam on the Colorado River and found that floods restored sandbar habitat and inundated patches of woody vegetation with as much as 1 m of sand. However, the woody vegetation was not eliminated, and backwater marshlands that had established after dam construction also remained. Similarly, Hill and Platts (1998) monitored the effect of altered flows in the form of flood simulations and increased base flows in the Owens River, California; they found that riparian vegetation rapidly recovered after the restoration of a more-natural flow regime and that instream habitat and fish abundance substantially improved concurrently with the changes in vegetation. Speierl et al. (2002) reported increases in species diversity and abundance after restoration of natural flow dynamics in the Main and Rodach rivers, Germany. Other studies have indicated that seedling survival and growth for some riparian plant species are higher under natural versus regulated flow conditions (Johansson and Nilsson 2002). Similarly, restoration of instream flows can lead to recovery of riparian forests, birds, and fish abundance and diversity (Rood et al. 2003). Studies on natural floods suggest the importance of these events for riverine ecosystems and support the use of flood restoration in regulated rivers (Galat et al. 1998; Modde et al. 2001). These studies on natural floods and the initial studies of natural flood regime restoration indicate primarily positive benefits for sediment transport, riparian vegetation, and aquatic biota.

In addition to high flows, adequate instream flows or base flows are needed to maintain aquatic and riparian biota and habitat (Petts and Maddock 1996; Stanford et al. 1996; Annear et al. 2002; Arthington and Pusey 2003). Methods for increasing instream flows on rivers with water diversions or for rewatering stream reaches are known to reduce water temperature, improve water quality, and generally benefit biota (Weisberg and Burton 1993; Petts and Maddock 1996). There is an extensive body of literature on instream flows, and it would be difficult to treat each study adequately in a review of physical habitat rehabilitation techniques. However, along with restoring floods, it is important that minimum instream flows are established and maintained to protect biota and ensure the success of other habitat rehabilitation actions.

Beaver reintroduction.—We located only five published studies examining reintroduction or removal of American beavers or European beavers *Castor fiber*. Beavers provide many important ecological functions and create floodplain and instream habitats used by fishes that depend upon slow-water habitats (Pollock et al. 2004). Beavers were also historically abundant throughout the northern hemisphere, although they have been eliminated from a large part of their ranges or are at lower-than-historic population levels (Pollock et al. 2003). Reintroduction of beavers has been proposed as a method of restoring the ecological functions described above and has been attempted on a limited basis in Europe, Russia, Mongolia, and North America. Studies conducted in the USA suggest that rapid recolonization, dam construction, and changes in physical habitat occur after American beaver reintroduction as long as the animals are not harvested or consumed by predators (Apple 1985; Albert and Trimble 2000; McKinstry et al. 2001; McKinstry and Anderson 2002). Merely reducing or banning commercial or recreational harvest (trapping) of American beavers has led to the slow recolonization of this species in many areas of the USA (Pollock et al. 2004). Studies in Poland have also shown that European beavers rapidly colonize habitats after reintroduction (Zurowski and Kasperczyk 1988). Despite the obvious benefits of beaver dams to some fishes, beaver dam removal is occasionally used as a fisheries enhancement tool for resident trout. Avery (2004) for example, reported that beaver dam removal was an effective strategy for increasing the number of brook trout *Salvelinus fontinalis* and brown trout available for angler harvest. Thus, beaver reintroduction will restore natural processes and can lead to improvements in some fish species but may not always meet management objectives for some resident sport fisheries.

Effectiveness of Instream Habitat Improvement

Instream habitat methods typically involve the placement of a variety of artificial (e.g., weirs, deflectors) and natural structures (e.g., logs, wood, boulders, and gravel) into the active stream channel to improve fish habitat (Table 2). Instream habitat improvement is popular and widespread and has a lengthy history; evaluations that were published as early as the 1930s can be found. Although we located 163 published evaluations from 16 countries, many individual techniques (e.g., gravel placement or placement of engineered log jams) have not been completely evaluated, and the placement of instream structures is still controversial in many areas. Other, more-common techniques, such as wood or boulder placement, have been evaluated in numerous studies in both North America and Europe. Because the literature on instream habitat enhancement is so extensive, we examine effectiveness separately in terms of durability, physical response, and biota. Within the biotic response, we discuss fish and macroinvertebrate responses separately.

Durability.—The majority of monitoring and evaluation efforts of instream habitat improvement projects have focused on determining effects on channel morphology and instream habitat (Hunt 1988; Reeves et al. 1991; Binns 1999; Roni et al. 2002). Early evaluations reported on the durability and longevity of instream structures and whether they created pools (Ehlers 1956; Gard 1972; Armantrout 1991; Frissell and Nawa 1992). Reported failure rates for various types of wood and boulder structures in North American streams are highly variable, ranging from 0% to 85% (Roni et al. 2002, 2005). The physical success of instream structures is influenced by many factors, including structure type, materials, and design; stream power; and the investigators' definition of failure or success. Failures reported in earlier studies often resulted from the use of inappropriate structures or a lack of understanding of larger watershed processes (e.g., Kondolf et al. 1996; Thompson 2002). More recently, highly artificial techniques (log and rock deflectors) are being replaced with techniques that mimic natural wood accumulations or habitat (e.g., single logs and log jams). These newer methods typically use logs that are large enough to stay within the channel; these logs function as natural wood accumulations and are often more durable and more effective at producing changes in habitat than traditional structures (Cederholm et al. 1997; Thom 1997; Roni and Quinn 2001a).

Physical habitat changes.—Despite highly variable results in durability, many studies in western North America have reported large (>50%), significant increases in pool frequency, pool depth, woody debris, habitat heterogeneity, complexity, spawning gravel, sediment retention, and organic matter retention after placement of instream structures (e.g., Crispin et al. 1993; Bates et al. 1997; Cederholm et al. 1997; Reeves et al. 1997; Binns 1999; Gerhard and Reich 2000; Roni and Quinn 2001a; Negishi and Richardson 2003; Brooks et al. 2004). Studies in low-gradient (<1.5%) midwestern streams have also demonstrated physical habitat changes, including increased depth and cover and narrower channels resulting from instream habitat improvement projects (Hunt 1988; Kern 1992; Avery 2004). Other projects designed to aggrade highly incised stream channels have produced increases in water depth, width, pool area, and bed elevation (reduced incision; Newbury and Gaboury 1988; Shields et al. 1993, 1995a). A few studies have reported increased bank erosion as a result of instream structures (Frissell and Nawa 1992; Thompson 2002, 2006), but the vast majority has reported significant improvements in fish habitat. Several European studies in low-gradient, channelized streams have demonstrated improvement in habitat complexity, depth, and organic matter retention (Näslund 1989; Jungwirth et al. 1995; Gerhard and Reich 2000; Laitung et al. 2002; Muotka and Laasonen 2002; Zika and Peter 2002). For example, Pretty et al. (2003) found increased depth and flow heterogeneity in rehabilitated stream reaches relative to control reaches in 13 English streams. Jungwirth et al. (1995) reported changes in physical habitat complexity (e.g., depth, velocity, and substrate) after placement of instream structures in Austrian streams. These studies indicate that while a variety of factors can affect the level of response, many instream structures lead to substantial improvements in physical habitat characteristics (e.g., complexity, depth, and channel morphology) as well as in organic matter retention.

Biological effectiveness.—Biological evaluations of different instream habitat improvement techniques have produced different results depending on the technique, region, species, and life stage examined and the duration of monitoring. The majority of these evaluations have focused on trout or juvenile anadromous salmonids, which historically were and continue to be the focus of most instream habitat improvement efforts in North America and Europe. In an effort to summarize the extensive biological evaluations, we discuss the responses of fishes, macroinvertebrates, and other biota in the subsections below.

Fish responses.—In a synthesis of the effectiveness of instream habitat improvement efforts for Pacific salmon, Roni et al. (2002, 2005) reviewed published evaluations of anadromous salmonid response to such structures in the U.S. Pacific Northwest. They found that while many studies reported positive responses by juvenile coho salmon, steelhead (anadromous rainbow trout), and cutthroat trout *O. clarkii* to instream habitat improvement, few responses were of sufficient duration to permit detection of statistically significant increases. The Roni et al. (2002, 2005) synthesis and previous reviews (Reeves et al. 1991; Beschta et al. 1994; Chapman 1996) emphasize the need for rigorous long-term evaluations of juvenile salmonid responses to instream habitat improvement. More-recent studies have emphasized the need to examine juvenile anadromous salmonid survival at a watershed scale

(Johnson et al. 2005; Paulsen and Fisher 2005). The results from these projects and those reviewed by Roni et al. (2002) are variable, but they do indicate that when implemented correctly, instream rehabilitation techniques benefit Pacific salmonid species and life stages that prefer pool habitats (e.g., juvenile coho salmon, Chinook salmon, and cutthroat trout).

Several studies have also demonstrated the positive effects of instream structure placement on juvenile Atlantic salmon (e.g., O'Grady 1995; Van Zyll de Jong et al. 1997; Kelly and Bracken 1998; Clarke and Scruton 2002). For example, Brittain et al. (1993) and Kelly and Bracken (1998) reported increased juvenile Atlantic salmon densities after placement of boulders, riprap, and deflectors in the Rye Water, Ireland, but no response was observed for brown trout. In a similar study in 13 Irish streams, "atlantic salmon and brown trout parr numbers" Gargan et al. (2002) found significantly higher parr numbers in stream reaches treated with rock weirs, revetments, and rubble mats (artificial riffles) but no difference in abundance of fry or older trout. These studies suggest that placement of instream structures generally benefits juvenile Atlantic salmon, a species with habitat preferences similar to those of steelhead.

Early work examining the effectiveness of instream structures for resident trout suggested that moderate increases in trout abundance, growth, condition, and survival were associated with placement of log weirs, dams, deflectors, and similar structures (e.g., Tarzwell 1938; Shetter et al. 1946; Gard 1961). Three compendiums on trout responses to instream habitat improvement in Wisconsin and Wyoming summarize much of the more recent work in these regions (Hunt 1988; Binns 1999; Avery 2004). In a review of 71 different instream habitat improvement projects installed in Wyoming between 1953 and 1998, Binns (1999) detected more than a twofold increase in wild trout abundance after treatment among the 46 projects for which fish data were available. Hunt (1988) and Avery (2004) synthesized evaluations of various types of projects in 103 Wisconsin streams and reported that streambank debrushing and installation of brush bundles produced disappointing results, whereas installation of deflector structures increased trout mean size and biomass and 75% of the examined projects yielded a 25% or greater increase in local trout abundance. While few of the 174 projects examined in these three studies were more than a few years in length, the large number of projects with positive results suggests that such projects are effective at increasing local abundance of many resident trout species. Other North American studies produced conflicting results (e.g., Broussu 1954; Saunders and Smith 1962; Hartzler 1983; Quinn and Kwak 2000). Thompson (2006) reanalyzed data from several studies conducted prior to 1980 and found that many were inconclusive because of limitations in study design. Despite some conflicting results, North American studies on instream habitat improvement demonstrate that these efforts generally increase local trout abundance and condition. However, multiple types of enhancement practices were implemented in many stream reaches, and few projects were monitored over the long term (>5 years); therefore, in most instances, it was not possible to determine which method led to the fish abundance increase.

Studies of rehabilitation of channelized European trout streams have produced more-consistent results than studies of American streams; several northern European studies have reported large increases in brown trout abundance after instream habitat rehabilitation (e.g., Näslund 1989; Hvidsten and Johnsen 1992; Linløkken 1997; Zika and Peter 2002). Näslund (1989) indicated that the most successful structures were boulder weirs (dams) and log deflectors, whereas boulder clusters and boulder deflectors appeared to be ineffective. O'Grady et al. (2002) and Gargan et al. (2002) examined the effects of a variety of boulder and wood structures on brown trout in treatment and control reaches of 20 Irish streams and found higher parr numbers in treated stream reaches. The relatively consistent results of the European studies can probably explained by (1) the more rigorous monitoring of these studies relative to many North American studies or (2) the high simplification of the European streams prior to enhancement, resulting in larger changes in habitat quality after the addition of instream structure (Roni and Quinn 2001a).

The evaluations of adult salmon or trout response to instream habitat structures or gravel placement have generally been limited to short-term studies demonstrating that adult salmonids spawn on accumulated gravel at weirs (Avery 1996; House 1996; Gortz 1998) or observations of spawning activity or redds near enhancement sites (Moreau 1984; Crispin et al. 1993; Iversen et al. 1993; House 1996; Table 3). Of the 14 papers we examined on enhancement of spawning areas, 13 reported some type of positive response in fry, adults, or spawning activity. Egg-to-fry survival after completion of these projects has varied by species and technique. Gortz (1998) found three times as many brown trout redds in restored reaches as in unrestored reaches of the River Esrom, Denmark, but found few brown trout fry, which indicated that the spawning was not successful. Merz et al. (2004) reported higher survival rates of salmon embryos at enhanced gravel sites in a California river. A lack of rigorous evaluation of adult salmon and trout responses to instream habitat

TABLE 3.—Summary of reviewed studies that examined responses of spawning salmonids to instream habitat improvement.

Study (location)	Techniques	Total years of monitoring (preproject years)	Observations
House 1984 (Oregon)	Gabions, rock weirs	5 (1)	Increased steelhead and coho salmon spawner abundance and percentage of entire spawner population using treated stream reaches
Moreau 1984 (California)	Boulder weirs, deflectors, clusters	2 (1)	Documented steelhead and Chinook salmon use of gravels trapped by placed structures
West 1984 (California)	Gravel cleaning, boulder placement	2 (1)	Chinook salmon spawner use increased up to threefold in some areas
House and Boehne 1985; House 1996 (Oregon)	Gabion weir placement	12 (1)	2.5-fold increase in coho salmon spawner abundance
Klassen and Northcote 1988 (British Columbia)	Gabion weirs	2 (1)	No difference in egg-to-fry survival of pink salmon *Oncorhynchus gorbuscha* between gabions and natural sites
Crispin et al. 1993 (Oregon)	Various wood and boulder weirs and structures throughout entire anadromous reach	2 (1)	Coho salmon spawner abundance and redds throughout stream increased fourfold after treatment relative to pretreatment numbers
Avery 1996 (Wisconsin)	Gravel riffles, sediment traps	8 (1)	No change in age-0 brook or brown trout abundance (sediment traps rapidly filled with sand)
Gortz 1998 (Denmark)	Gravel, boulders, stream deflectors	1 (0)	Five times more spawning trout in restored reaches than in control reaches
Yrjänä 1998 (Finland)	Gravel, boulder placement	1 (0)	Some evidence of brown trout spawning at sites, but this depended upon gravel retention and presence of boulders
Clarke and Scruton 2002 (Newfoundland)	Gravel addition	2 (0)	Initial results showed spawner use of gravels, but monitoring was discontinued before conclusive results were obtained
Merz and Setka 2004; Merz et al. 2004 (California)	Gravel addition	3 (1)	Adult Chinook salmon spawned on newly placed spawning gravel within 2 months of placement and consistently used site; salmon embryos artificially placed in enhanced spawning gravel had higher survival rates than those placed at unenhanced sites
Rubin et al. 2004 (Sweden)	Gravel addition, sediment trap	8 (0)	A higher percentage of eggs survived to the fry stage in rehabilitated spawning areas than in natural areas

improvement stems in part from the multiple generations and, thus, the long time frame (>5 years) required to detect an adult response to habitat alterations (Bisson et al. 1997; Korman and Higgins 1997). Nonetheless, evaluation of adult response is critical for projects focusing on enhancement of spawning habitat, and a review of the limited number of published studies suggests that adult use increases in treated areas (Table 3).

Most evaluations of instream habitat rehabilitation have examined responses of salmonid fishes; we did, however, locate 25 studies that examined responses of nonsalmonids (Table 4). Responses in these studies varied widely by species and region, and most studies were of limited scope or duration and focused on different fish species. Some studies reported on a handful of individual species (e.g., Lonzarich and Quinn 1995; Linløkken 1997; Roni and Quinn 2001a; Nicol et al. 2004). For example, Linløkken (1997) reported increased density of Eurasian minnow but decreased density of Siberian bullheads after placement of rock weirs. Other studies from areas with relatively high species diversity (>10 species) have reported increases in diversity or richness (e.g., Angermeier and Karr 1984; Shields et al. 1993, 1995b; Jungwirth et al. 1995). However, more than half the studies we examined either found no change or did not report findings on diversity or richness (Table 4). We draw three major conclusions from reviewing studies on nonsalmonid fishes. First, in very diverse fish communities, the increase in habitat complexity provided by instream habitat structures can lead to an increase in diversity. Second, projects designed for salmonids may have little effect on other species. Third, additional long-term monitoring and evaluations that consider all members of the fish community are needed.

Instream rehabilitation projects involve the use of a variety of techniques to improve habitat, making comparison of different techniques difficult; few studies have attempted to compare effectiveness among techniques. Binns (1999) reported larger increases in trout numbers in constructed plunge pools or log weirs (129% increase) than at log jams (69% increase) and rock weirs (66% gain) but cautioned that many techniques were employed at various sites. Avery (2004) attempted to compare effectiveness among structure types using several fish success metrics (total number of fish, number > 150 mm, and biomass) and suggested that cover, current deflectors, and beaver dam removal were the most successful for resident trout. Slaney et al. (1994) and Van Zyll de Jong et al. (1997) provided more-detailed comparisons of techniques within a given stream. For example, Van Zyll de Jong et al. (1997) examined the effects of three structure types in a stream in Newfoundland, Canada, and found increased numbers of Atlantic salmon (ages 0+, 1+, and 3+) at boulder cluster sites, increased density of both brook trout and juvenile Atlantic salmon with v-weir placement, and increased numbers of age-0+ Atlantic salmon at half-log (cover log) sites. However, these studies did not examine structure or habitat use at different flows. Work in an experimental channel by Mitchell et al. (1998) suggested that structure use varies by flow and location. Other studies have found a strong correlation between the number of structures placed or amount of physical habitat change and fish response (i.e., Kennedy and Johnston 1986; Roni and Quinn 2001a). This may also explain why projects in highly simplified streams seem to show the largest biological response.

Examination of changes in fish abundance at instream habitat improvement projects can be complicated by (1) immigration and emigration of fish from nearby habitats or watersheds and (2) the effects of instream structures on movements of fish that typically have seasonal habitat preferences (see Roni et al. [2005] for a detailed review). The question of whether instream habitat improvement increases fish production or simply shifts fish distribution should be an important component of project evaluation (Gowan et al. 1994; Frissell and Ralph 1998; Roni and Quinn 2001b). However, if increased reproduction and recruitment are not objectives of the restoration, then identifying the mechanism of local increases (i.e., from emigration or increased recruitment) might not be important.

Macroinvertebrate response.—Macroinvertebrates constitute an important food source for fish and are highly sensitive to habitat alteration, disturbance, and presumably, rehabilitation (Merritt and Cummins 1996; Karr and Chu 1999). We located 32 studies that examined macroinvertebrate response to placement of instream structures, and results of these studies were highly variable (Table 5). Tarzwell (1937, 1938), Gard (1961), Haapala et al. (2003), and others demonstrated an increase in macroinvertebrate abundance after instream habitat improvement. Other studies detected an increase in some functional feeding groups but not others (i.e., Wallace et al. 1995; Gortz 1998), or they detected an increase in macroinvertebrate diversity (Ebrahimnezhad and Harper 1997; Harper et al. 1998). Conversely, many other studies (e.g., Black and Crowl 1995; Hilderbrand et al. 1997; Laasonen et al. 1998; Larson et al. 2001; Brooks et al. 2002; Roni et al. 2006b) detected no difference in macroinvertebrate density or diversity in enhanced (by addition of various boulder and log structures) and untreated stream reaches. These studies suggest that macroinvertebrates were probably limited by primary productivity rather than by habitat complexity. The disparity in results among studies could be attributable to differences in scale of measurement, metrics examined, project objectives, and physical habitat change; alternatively, it may indicate that macroinvertebrates are neither sensitive to nor appropriate success indicators for fish habitat enhancement projects.

Effectiveness of Stream Nutrient Enrichment

We located a total of 18 studies (from three countries) that examined the effects of adding organic or inorganic nutrients to increase productivity in oligotrophic streams (Table 6). All studies on nutrient addition reported some positive response by fish or other biota (i.e., Johnston et al. 1990; Ward 1996; McCubbing and Ward 1997, 2000). Ward et al. (2003), in one of the largest and longest studies of inorganic nutrient addition to a stream, detected increases in periphyton, macroinvertebrate abundance, and juvenile coho salmon and steelhead growth and condition. Ashley and Slaney (1997) summarized the results of case studies of inorganic nutrient addition in five different British Columbia watersheds and found that periphyton, invertebrate biomass, and fish growth increased after nutrient addition. Studies of natural and artificial stream channels in southeast Alaska have reported increased fish condition, growth, and production after placement of salmon carcasses and carcass analogs (artificial carcasses made from fish tissue; Wipfli et al. 2003, 2004). After addition of inorganic phosphorus to an Arctic tundra river, Deegan and Peterson (1992) found an increase in growth of juvenile and adult Arctic grayling. Addition of organic nutrients in the form of fish carcasses has also been examined in anadromous fish streams in Alaska, British Columbia, Washington, and Minnesota (Table 6). These studies have reported increases in phosphorus, chlorophyll *a*, periphyton, macroinvertebrate growth, and fish growth (Schuldt and Hershey 1995; Wipfli et al. 1998, 1999; Chaloner and Wipfli 2002; Minakawa et al. 2002). Studies using stable isotope analysis have demonstrated the importance of salmon carcasses in aquatic food webs for primary productivity, macroinvertebrates, fishes, and even riparian vegetation and tree growth (Bilby et al. 1996; Helfield and Naiman 2001). Although additional study is needed, these studies

TABLE 4.—Reviewed studies that examined responses of nonsalmonids or the entire fish community to placement of instream structures. The exact number of species present or examined was not reported in every study (NA = not available).

Study (location)	Techniques examined	Number of years (preproject years)	Number of species	Species diversity or richness response
Shetter et al. 1946 (Michigan)	Log deflectors	8 (3)	8	Not reported
Hale 1969 (Minnesota)	Log weirs, deflectors, etc.	10 (3)	11	Not reported
Boreman 1974 (New York)	Log weirs, bank protection	1 (0)	5	Not reported
Angermeier and Karr 1984 (Illinois)	Placement of woody debris	4 (0)	12	No difference
Lyons and Courtney 1990 (reviewed 20 unpublished studies in the eastern USA)	Various boulder bank protection structures, channel meandering	Various case studies	33+ NA	Three studies reported increase in diversity
Shields et al. 1993 (Mississippi)	Boulder weir placement to aggrade incised channel	2 (1)	27	Doubled
Mueller and Liston 1994 (Arizona–California)	Artificial reefs in aqueduct	2 (NA)	NA	Increased
Jungwirth et al. 1995 (Austria)	Removal of bank protection, installation of groins and bedfalls	7 (4)	19	Increased diversity
Lonzarich and Quinn 1995 (Washington)	Cover placement in artificial channel	1 (0)	4	Higher in pools with structure
Shields et al. 1995a, 1995b (Mississippi)	Boulder weir placement to aggrade incised channel	3 (2)	19	Increased
Linløkken 1997 (Norway)	Rock weirs	9 (3)	3	No change
Shields et al. 1998 (Mississippi)	Stone structures, woody vegetation	5 (2)	48	Richness increased at one treatment site but remained the same at another
Shields et al. 2003 (Mississippi)	Woody debris, willow plantings	2 (0)	NA	No change
Pretty et al. 2003 (UK)	Deflectors, stone riffles	2 (0)	18	No difference between rehabilitated and control sites
Raborn and Schramm 2003 (Mississippi)	Boulder weirs to aggrade channel	2 (0)	85	Lower species richness in rehabilitated segments than in unaltered ones
Roni 2003 (Washington–Oregon)	Various wood placement techniques	3 (0)	7	No difference
Brooks et al. 2004 (Australia)	Engineered log jams	2 (1)	13	Increase in richness
Dauwalter et al. 2004 (Oklahoma)	Rock vanes, deflectors	3 (2)	>10 (NA)	Not reported
Nicol et al. 2004 (Australia)	Log placement	NA	1	Not reported
Knaepkens et al. 2004 (Belgium)	Placement of ceramic tiles for spawning habitat	NA	1	Not reported
Bond and Lake 2005 (Australia)	Log placement	2 (1)	3	Not reported
Lepori et al. 2005b (Sweden)	Boulder placement	1 (0)	6	Richness increased in treatment reaches
Price and Birge 2005 (Kentucky)	Boulder addition	1 (0)	16	No difference
Shields et al. 2006 (Mississippi)	Large wood addition	6 (2)	32	Richness increased

collectively suggest that the addition of inorganic nutrients or salmon carcasses or an increase in spawning fish can increase macroinvertebrate growth, fish growth, and salmonid survival in oligotrophic streams. Obviously, nutrient loading can be a serious water quality problem in many areas; thus, nutrient enrichment techniques apply only to oligotrophic streams in which production is limited by nitrogen or phosphorus. Kiffney et al. (2005) described approaches for assessing the nutrient status of a stream and whether nutrient addition is appropriate.

Discussion

Many historical and recent papers have emphasized the paucity of information on the success of stream and watershed rehabilitation projects and the need for monitoring and evaluation (e.g., Tarzwell 1937; Reeves et al. 1991; Roni et al. 2002; Bernhardt et al.

TABLE 4.—Extended.

Study (location)	Key findings
Shetter et al. 1946 (Michigan)	Small increase in abundance of slimy sculpin *Cottus cognatus* and minnows
Hale 1969 (Minnesota)	Abundance of mottled sculpin *Cottus bairdii* increased, while abundance of white suckers *Catostamus commersonii* and cyprinids decreased
Boreman 1974 (New York)	No difference in biomass or abundance of slimy sculpin, daces *Rhinichthys* spp., or creek chub *Semotilus atromaculatus*
Angermeier and Karr 1984 (Illinois)	Increased abundance and size
Lyons and Courtney 1990 (reviewed 20 unpublished studies in the eastern USA)	9 of 17 studies that examined fish response reported increase in abundance
Shields et al. 1993 (Mississippi)	Approximate 10-fold increase in fish biomass after treatment (27)
Mueller and Liston 1994 (Arizona–California)	Abundance was 20× greater in treatment areas than in control areas
Jungwirth et al. 1995 (Austria)	Increased abundance and biomass
Lonzarich and Quinn 1995 (Washington)	Higher survival of water column species in pools with cover, but no difference in growth among species
Shields et al. 1995a, 1995b (Mississippi)	Threefold increase in abundance; median fish size increased (NA)
Linløkken 1997 (Norway)	Percentage of Eurasian minnow *Phoxinus phoxinus* and brown trout increased; percentage of Siberian bullheads *Cottus poecilopus* decreased
Shields et al. 1998 (Mississippi)	Species composition shifted from small cyprinids and centrarchids to larger centrarchids, catostomids, and ictalurids
Shields et al. 2003 (Mississippi)	Small initial shift in species composition after treatment (NA)
Pretty et al. 2003 (UK)	No difference in total abundance, but European bullheads *Cottus gobio* and stone loaches *Barbatula barbatula* increased slightly
Raborn and Schramm 2003 (Mississippi)	Rehabilitation did not restore fish assemblage
Roni 2003 (Washington–Oregon)	Increase in abundance of juvenile Pacific lampreys *Lampetra tridentata* and *Lampetra* spp.; no response for sculpins *Cottus* spp. or giant salamanders *Dicamptodon* spp.
Brooks et al. 2004 (Australia)	Increase in abundance
Dauwalter et al. 2004 (Oklahoma)	No consistent differences for various species, including smallmouth bass, shadow bass *Ambloplites ariommus,* and several others
Nicol et al. 2004 (Australia)	No change in abundance of common carp *Cyprinus carpio* after placement of large woody debris
Knaepkens et al. 2004 (Belgium)	European bullheads used artificially placed substrates for spawning; this tile use was correlated with depth in meandering reaches but not canalized river reaches
Bond and Lake 2005 (Australia)	Short-term increases in abundance of the mountain galaxia *Galaxias olidus* after treatment
Lepori et al. 2005b (Sweden)	Increased total biomass and abundance but not when standardized by fish or biomass per area sampled
Price and Birge 2005 (Kentucky)	Index of biotic integrity was similar between restructured and control reaches
Shields et al. 2006 (Mississippi)	Increased fish size and biomass in treatment reach

2005). Although only a small fraction of the billions of dollars spent annually on stream and watershed rehabilitation is allocated to monitoring (Bernhardt et al. 2005), we located 345 papers that examined the effectiveness of various habitat rehabilitation techniques. Our review was global or international in extent, but the vast majority of the literature was from the USA, Canada, and western Europe; this emphasizes the need for evaluation of restoration actions in other parts of the world rather than relying on results from the developed world. In reviewing these studies, we found that most categories of techniques were in need of more-thorough evaluation, but some specific techniques (e.g., placement of boulders and wood in streams) had received considerable attention. Moreover, some techniques, such as placement of instream habitat improvement and reconnection of isolated habitats, have demonstrated benefits to fishes, whereas little or no information was available on the effects of road improvements and riparian rehabilitation tech-

TABLE 5.—Summary of reviewed studies that examined macroinvertebrate response to log placement, boulder placement, or some combination of these. All studies examined response at a reach or individual habitat unit scale. Study designs are posttreatment (PT; no preproject data); before–after (BA); and before–after, control–impact (BACI).

Study (location)	Enhancement type	Streams (*N*)	Design (years of monitoring)	Key findings
Tarzwell 1937 (Michigan)	Log deflectors, other structures	3	BA (2)	Increased abundance
Tarzwell 1938 (Arizona–New Mexico)	Log and rock cribs, deflectors, log weirs	2	PT (2)	Higher abundance in constructed pools than in natural pools
Shetter et al. 1946 (Michigan)	Log deflectors	1	BA (8)	Decreased abundance; however, some functional groups increased
Gard 1961 (California)	Log, rock, or stick dams	1	BA (3)	Increased biomass
Jester and McKirdy 1966 (New Mexico)	Log and boulder structures	9	PT (2)	Higher abundance in treatment reaches than in control reaches among 14 of 18 reach pairs
Black and Crowl 1995 (Colorado)	Log additions	1	BA (3)	No change in abundance
Laasonen et al. 1998; Muotka et al. 2002 (Finland)	Boulders (first study); boulders and gravel (second study)	22; 14	PT (2); PT(2)	Initially no difference in richness between rehabilitated and channelized sections; sampling 5 years later found an increase in richness within rehabilitated streams over time
Tikkanen et al. 1994 (Finland)	Boulders	1	BA (1)	Slight decrease in abundance immediately after rehabilitation; abundance recovered within 10
Wallace et al. 1995 (North Carolina)	Log additions	1	BA (4)	Increased abundance and biomass but not diversity
Ebrahimezhad and Harper 1997; Harper et al. 1998 (UK)	Constructed riffles (both studies)	1; 1	PT (2); PT (1)	Diversity higher in natural and shallow constructed riffles, lower in deeper constructed riffles
Hilderbrand et al. 1997 (West Virginia)	Log additions	2	BA (2)	No change in abundance, but some functional groups increased
Gortz 1998 (Denmark)	Gravel, boulders, constrictors	1	PT (2)	Increased abundance; no change in diversity
Mitchell et al. 1998 (Newfoundland)	Logs, boulders	1	PT (1)	No difference in drift or benthic density
Gerhard and Reich 2000 (Germany)	Log additions	2	PT (1)	No increase in species or diversity
Lemly and Hilderbrand 2000 (West Virginia)	Log additions	1	BA (2)	No difference in abundance; differences in communities in pools and riffles suggests that large increase in pool area may change reach abundance by functional group
Larson et al. 2001 (Washington)	Log additions	4	PT (2)	No change in benthic index of biotic integrity
Pretty and Dobson 2001 (UK)	Log additions	3	BA (2)	No change in abundance or diversity
Muotka and Laasonen 2002 (Finland)	Boulders	8	BA (2)	Increase in algae-feeding scrapers only
Purcell et al. 2002 (California)	Channel restructuring (opening up culverted stream)	1	PT	Index of biotic integrity and taxa richness improved in treated reach relative to control reach
Haapala et al. 2003 (Finland)	Boulders, boulder weirs	2	BA (2)	Higher abundance (densities)
Negishi and Richardson 2003 (British Columbia)	Boulder deflectors	1	BA	Increased abundance; little effect on taxa richness
Harrison et al. 2004 (UK)	Constructed riffles, flow deflectors	13	PT (1)	Little difference in macroinvertebrate diversity or richness between treatment and control reaches, but differences were found among macrophyte and benthic habitats
Korsu 2004 (Finland)	Boulders	1	BA (1)	Invertebrates recolonized reach to preproject levels within 2 weeks of disturbance
Lepori et al. 2005a, 2005b (Sweden)	Boulder, channel restructuring	7	PT (1)	No change in diversity
Merz and Chan 2005 (California)	Gravel addition	1	PT (1)	Within 4 weeks, abundance (densities) and biomass of macroinvertebrates on newly placed gravels was similar to or higher than that of natural gravel deposits

TABLE 5.—Continued.

Study (location)	Enhancement type	Streams (*N*)	Design (years of monitoring)	Key findings
Blakely et al. 2006 (New Zealand)	Boulder additions	1	BA (1)	No change in adult caddisfly diversity or caddisfly egg masses
Bond et al. 2006 (Australia)	Log additions	2	PT (1)	Within 4 weeks, rapid colonization of logs by algae and benthic macroinvertebrates, suggesting that log additions create hot spots of primary production
Spanhoff et al. 2006 (Germany)	Woody debris (branches)	1	PT (2)	Short-term differences in chironomid abundance (drift) between treated and untreated reaches (lower in reaches with placed wood); no difference in macroinvertebrate species diversity
Roni et al. 2006b; P. Roni, unpublished data (Oregon)	Boulder and log additions	23	PT (2)	No change in abundance or diversity

TABLE 6.—Summary of key findings of published studies that examined nutrient enrichment in streams.

References	Stream	Nutrient type added	Primary and secondary production	Fish
Johnston et al. 1990; Ward 1996; McCubbing and Ward 1997, 2000; Ward et al. 2003	Keogh River, British Columbia	Inorganic N and P	Increased periphyton standing crop	Increased juvenile salmonid density, growth, and survival
Deegan and Peterson 1992; Deegan et al. 1997	Kuparuk River, Alaska	P (phosphoric acid)	Chlorophyll increased (fivefold) caddisfly abundance was higher in treatment reaches; no differences for other families	Increased growth rates of adult and age-0 Arctic grayling *Thymallus arcticus*; increased neutral lipid storage
Schuldt and Hershey 1995	Stewart and French rivers, Minnesota	Salmon carcasses	Increased P, N, periphyton biomass	NA
Ashley and Slaney 1997	Salmon, Adam, Big Silver, and Mesilinka rivers, British Columbia	Inorganic nutrients	Increase in chlorophyll *a* and macroinvertebrate biomass	Increase in juvenile salmonid density and biomass
Bilby et al. 1998	Salmon, Big, A400, and Wasberg creeks, Washington	Salmon carcasses	NA	Increase in juvenile salmonid density; increase in marine-derived nutrients in fish tissue
Wipfli et al. 1998, 1999, 2003, 2004	Several artificial and natural stream channels in southeast Alaska	Addition of salmon carcasses and analogs (processed fish block)	No difference in artificial channels, but significantly higher in natural stream; increased macroinvertebrate abundance	Increased growth, condition factor, and production of salmonid fishes
Sterling et al. 2000	Artificial channels	Slow-release inorganic phosphate fertilizer	Increased periphyton and primary productivity	NA
Chaloner and Wipfli 2002	Fish Creek, Alaska	Salmon carcasses	Increased growth rate of macroinvertebrate collectors, but no consistent patterns for other groups	NA
Minakawa et al. 2002	Griffin Creek, Washington	Salmon carcasses	Increased macroinvertebrate growth (Trichoptera)	NA

niques on fishes. Below, we discuss the key findings for review of each rehabilitation technique category and give recommendations for prioritization and monitoring of projects. It is important to note that our recommendations are based on the review of published literature. We assume that the published literature is representative, but we recognize that there is probably a bias towards the publication of positive results.

Road Improvements

Despite the effects of roads on sediment delivery and hydrology and the large efforts underway to limit impacts of forest and urban roads on streams and their biota (Beechie et al. 2005), road improvements were the most poorly evaluated category of techniques. With the exception of studies on fish colonization after road crossing removal or upgrade, little biological monitoring was reported. However, techniques such as traffic reduction, road resurfacing, and road removal or abandonment appeared to be successful at reducing erosion and landslides and improving hydrology associated with roads in forested areas. The impacts of urban roads and the methods for minimizing those impacts have received considerable attention in the last decade (Booth and Jackson 1997; Booth et al. 2002). Many new techniques have been and are being developed for reducing impacts of urban stormwater, but their effectiveness is unclear, as we located only one small study during our search of the published literature. The one technique related to road improvement that has demonstrated a direct benefit to fisheries resources is the replacement of culverts or other stream crossings that prevent migration. The success of stream crossing removal or replacement in terms of physical and biological benefits appears to depend on the ability to transport sediment, restore other watershed processes, and provide year-round fish access.

Riparian Rehabilitation

Common techniques for restoring riparian areas and improving instream habitat (e.g, tree planting, installation of fencing, and removal of livestock) have demonstrated benefits for riparian vegetation. The level of information on riparian silviculture treatments, such as planting and thinning, is particularly scarce, and few studies have examined instream factors or biota after riparian treatment (Pollock et al. 2005; Roni et al. 2005). Passive restoration of riparian areas may be effective if the disturbance can be removed and if invasive species do not compete with native vegetation (Briggs 1996; Pollock et al. 2005). The most extensive published information on riparian rehabilitation effectiveness at improving streams focuses on the various fencing and grazing strategies. Similar to earlier literature reviews by Platts (1991) and Roni et al. (2002), we concluded that complete exclusion of livestock through removal or fencing has shown the most promising results in terms of vegetation, bank, and instream characteristics. Rest–rotation and other grazing systems have shown promise under proper management and under certain physical, morphological, and climatic conditions. Responses of the stream channel and biota to grazing and riparian silviculture treatments tend to lag behind vegetation recovery; thus, long-term, well-designed monitoring is required to detect any changes (Medina et al. 2005). The responses of instream conditions and biota to various riparian treatments were often influenced by upstream conditions, and it was often difficult to distinguish between failure of a particular technique and failure to consider broader processes during project implementation. Results were further confounded by a lack of consideration of geology, channel type, climate, exotic species, site preparation, native ungulates, effective control of grazing intensity and duration, size of the exclusion or buffer zone, and upstream processes or impacts. These are clearly important factors to consider when implementing a riparian rehabilitation project and associated monitoring program.

Floodplain Connectivity

This category of techniques is very diverse, and many of the techniques (e.g., levee setbacks and dam removal) have only recently been implemented on a broad scale (Roni et al. 2005). Floodplain rehabilitation is a relatively new science, and long-term studies documenting biological effectiveness are not currently available (Pess et al. 2005). In addition, the goals typically encompass broad ecological and cultural objectives. Thus, evaluation of a purely fisheries response to a project is difficult. It is clear that most techniques evaluated to date can lead to improvements in physical, hydrologic, and other natural processes; provide additional slow-water habitats; and provide additional habitat for fishes. However, adequate long-term studies documenting such improvements are rare or have not been published. Reconnection of isolated floodplain habitats is probably the most thoroughly evaluated floodplain technique, and several studies demonstrate its effectiveness at providing habitat for salmonid and nonsalmonid fishes (e.g., Grift et al. 2001; Giannico and Hinch 2003; Morley et al. 2005). Dam removal has also shown promise for improving habitat diversity, providing habitats for various fishes, and increasing species diversity. Levee removal, channel remeandering, and construction of floodplain habitats have produced positive results both physically and for biota, but long-term data on the success of these techniques are not yet available. Many factors influence the physical and biological effectiveness of projects, including habitat complexity, depth, wood volume, connectivity with the main channel, channel incision, flow volume, flow source, exotic species, project size, upstream flow regulation, and upstream water quality. Dam removal may produce some short-term negative impacts (e.g., increases in fine sediment or decreases in water quality) downstream or in former reservoir reaches, but such effects depend on the level and contents of sediments stored in the reservoir, whether attempts are made to remove or stabilize them, and the time period examined. In the absence of dam removal, restoration of natural flood regimes appears to improve restoration processes, reconnect habitats, and restore flood-dependent biota. Beaver reintroduction into their native habitat is another potentially important technique for restoring natural floodplain processes. As was the case for most techniques, long-term, broad-scale studies evaluating the success of various floodplain techniques were not located.

Instream Habitat Structures

The majority of published evaluations of rehabilitation were on instream habitat enhancement projects or instream structures. When implemented properly, these techniques can produce dramatic improvements in physical habitat and biota, particularly for salmonid fishes. However, given (1) the variability in results for various species and structure types, (2) the limited number of statistically rigorous studies, (3) the response differences among species or life stages, and (4) the cost of instream habitat improvement projects, it is apparent that such projects should be undertaken with careful consideration of scale, watershed conditions, and watershed processes and should be coupled with rigorous monitoring programs. Several books are dedicated to the appropriate application and design of instream habitat rehabilitation, and these books should be consulted (e.g., Slaney and Zoldakas 1997; Cowx and Welcomme 1998). The success of instream habitat enhancement projects is often tied to larger, watershed-scale issues, such as water quality, hydrology, sediment transport, stream gradient, riparian conditions, and upslope conditions. For many years, the need for a broader-scale perspective in implementing instream projects has been acknowledged (e.g., Aitken 1935; Beechie and Bolton 1999; Roni et al. 2002). The potential benefits of most instream structures will be short lived (<10 years) unless coupled with riparian planting or other process-based restoration activities that can lead to long-term recovery of deficient processes.

While placement of instream structures appears to be successful at increasing local fish abundance, particularly that of salmonids, results are highly variable among species, life stages, and structure types and little positive benefit has been documented for nonsalmonids. The most successful projects are those that create large changes in physical habitat and mimic natural processes (e.g., Roni and Quinn 2001a). Considerable information exists on fish response to instream rehabilitation (>140 studies), but most of these studies occurred on short stream reaches and documented only localized changes in abundance. Though most instream projects occur at a site or reach scale, these projects may produce or affect physical habitat and fish production responses in downstream reaches, in adjacent habitats, or throughout a watershed. Thus, changes in one stream reach may affect salmonid abundance in adjacent stream reaches (Gowan and Fausch 1996; Kahler et al. 2001; Roni and Quinn 2001b). Assessment of biotic and physical responses at a watershed scale is arguably more important (and more difficult) than examining reach-scale responses, such as changes in local fish abundance. Recent advances in tagging technology will provide tools for more accurately addressing questions about movement, survival, and changes in population size at the local, reach, and watershed scales.

Nutrient Addition

The addition of inorganic and organic nutrients to oligotrophic streams can lead to increases in growth and production of algae and zooplankton and, in some cases, fish growth. Obviously, this technique is not appropriate in many areas where nitrogen and phosphorus levels are either naturally high or elevated due to human activities (e.g., agriculture runoff and wastewater discharge). The drawback of nutrient addition is that continued application or an increase in natural nutrient delivery (recovery of depressed anadromous fish runs) is needed to maintain elevated production. However, little work has been done to quantify the duration for which benefits persist after nutrient addition ceases. Kiffney et al. (2005) outlined the many factors that must be evaluated prior to nutrient enrichment; these include baseline nutrient status (i.e., the nutrients that are limiting productivity) and the species composition of plankton, algae, macroinvertebrates, and fishes (top-down versus bottom-up control). The success of nutrient enrichment projects depends on an understanding of these factors and on the treatment of only those streams that are deficient in nutrients. Nutrient reduction is a common method in areas of high agricultural use or reaches below sewage treatment plants, but this technique is beyond the scope of our review.

Implications for Planning and Prioritization

Despite the broad range of rehabilitation techniques examined, several common factors appear to limit the success of projects (Table 1). Water quality, water quantity, erosion, and sedimentation prevent many projects from achieving full biological potential. These factors were particularly common among riparian (see Rinne 1999; Medina et al. 2005), floodplain connectivity (e.g., Moerke and Lamberti 2003; Cowx and Van Zyll de Jong 2004), and instream habitat projects (e.g., Avery 1996; Thompson 2006). Each factor limiting project success results from a lack of understanding of the physical and ecological context of the project, which clearly reinforces the point made by numerous authors that broader watershed processes must be considered when planning projects (e.g., Aitken 1935; Beechie and Bolton 1999; Roni et al. 2002; Wohl et al. 2005; Beechie et al. 2008, this volume). Unfortunately, many studies of restoration effectiveness also do not consider factors outside of their study area, making it difficult to improve project planning and design and thus to avoid future failures.

Avoidance of the common causes of project failure requires a clear process for using watershed assessments to identify and prioritize projects (addressed by Beechie et al. 2008, this volume). However, many restoration groups do not yet have comprehensive watershed assessments and instead select restoration projects opportunistically. In such cases, a sequence of habitat rehabilitation methods based on project effectiveness, watershed processes, and longevity of actions can be used to help maximize project success (Roni et al. 2002). Based on this global review of the literature on restoration effectiveness, we modify the Roni et al. (2002) approach and recommend a broadly applicable approach for sequencing stream and watershed restoration projects in the absence of watershed assessments (Figure 2). In this sequence, factors that most often limit the biological success of restoration projects are addressed first, and projects addressing other habitat factors are implemented later. Because poor water quality and low water quantity can prevent biological recovery in response to all other project types, major water quality and quantity issues should be addressed prior to considering other habitat rehabilitation actions. This should be followed by addressing key processes, such as sediment delivery and riparian conditions, which often limit success of instream rehabilitation efforts. After addressing these processes and overriding factors that potentially limit the effectiveness of structural habitat manipulations, one can consider issues of connectivity and habitat structure. If these issues are not addressed, either sequentially or simultaneously, then project failures similar to those reported in the existing literature are likely.

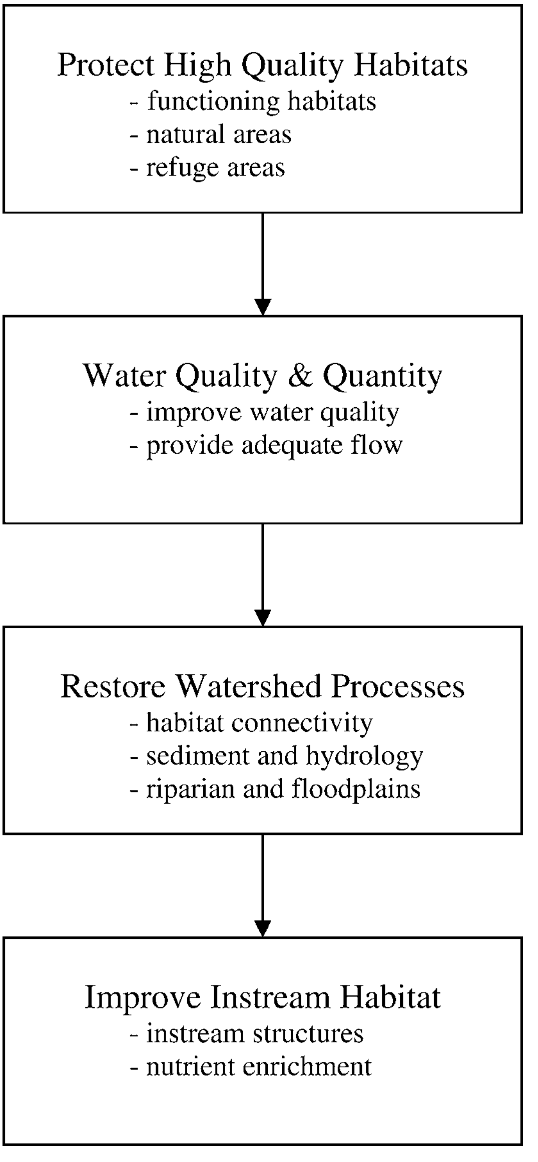

FIGURE 2.—Proposed interim strategy for sequencing stream rehabilitation techniques prior to considering other factors (e.g., project cost, species of interest, cost–benefit ratio, economic, social, and political).

Implications for Monitoring and Evaluation

Similar to considering watershed processes when implementing rehabilitation, the need for rigorous monitoring and evaluation has been noted for many decades (Tarzwell 1937; Reeves et al. 1991; Palmer et al. 2005; Roni 2005). Our extensive review of the literature on this topic demonstrates that despite the numerous published evaluations on effectiveness of habitat rehabilitation actions, there are three major needs related to monitoring and evaluation: (1) the need for long-term evaluation, (2) the need for watershed or broad-scale monitoring, and (3) the need for a consistent set of metrics for evaluation of project success. First, the monitoring duration or length in most of these studies was not more than a few years (average = 3.4 years; range = 1–24 years). There were, however, several retrospective posttreatment studies that collected only a few years of data but included projects that had been implemented more than 10 years before (i.e., Binns 1999; Roni and Quinn 2001a; Thompson 2006). Most of these evaluations were at a reach scale or even an individual habitat scale, and monitoring at the population, watershed, or basin scale is needed to understand the implications of a single project or a suite of projects (Roni 2005). Finally, it was difficult to compare effectiveness among projects within even a specific project type because of differences in metrics used. Compatible physical and biological metrics within and across projects are needed to allow comparison of success among techniques (Palmer et al. 2005). The immediate challenge for future monitoring and evaluation is to address these shortcomings of duration, scale, and metrics.

Summary and Conclusions

Our review of 345 papers on effectiveness of stream rehabilitation techniques indicates that some techniques, such as reconnection of isolated habitats, rehabilitation of floodplains, and placement of instream structures, have proven to be effective for improving habitat and increasing local fish abundance under many circumstances. Techniques for restoring the natural processes that create and maintain habitats, such as riparian rehabilitation, sediment reduction methods (road improvements), dam removal, and restoration of floods, have also produced encouraging results, but it may take years or decades before a change in fish or other biota is evident, and little or no long-term monitoring of these techniques has been conducted. Our review emphasizes the need for adequate assessment of watershed processes and factors limiting biotic production, consideration of upstream or watershed-scale factors that influence the outcome of reach-scale or localized rehabilitation projects, and monitoring and evaluation of adequate temporal and spatial scales.

Key research and monitoring priorities include examination of most techniques in areas other than the USA and Canada, where most research has occurred. Additional research on instream habitat enhancement structures is needed in other parts of the world, but such techniques have been extensively examined in the western and midwestern USA and in Canada. Examination of the effectiveness of riparian, road, and floodplain rehabilitation techniques in restoring watershed processes (i.e., delivery of wood, water, and sediment) and biota is needed in all geographic areas. Finally, few studies have conducted examinations at a sufficiently broad scale for determining effects of individual or multiple projects on an entire watershed or fish population. This is clearly one of the most pressing research needs and is probably attainable with recent technological advances in remote sensing and fish tagging.

Acknowledgments

We thank the NWFSC (NOAA Fisheries) and the Inland Water Resources and Aquaculture Service (FAO Fisheries Department) for financial support of this project. Devin Bartley of FAO deserves special recognition for helping make this entire project possible and coordinating our work at FAO in Rome, Italy. We thank the staffs of the NWFSC Library and FAO Fisheries Library for assistance in locating hard-to-find references, and we are grateful to Blake Fiest and Su Kim for assistance in creating maps. We also thank George Pess and three anonymous reviewers for helpful comments on earlier versions of this manuscript.

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