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Towards Greener Riprap: Environmental Considerations from Microscale to Macroscale

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ABSTRACT

Effects of riprap on riverine fish and macroinvertebrate habitats are strongly related to spatial scale. Three scales are recognized: areas approximately equivalent to the median stone diameter squared (microscale), areas on the order of the square of the channel width (mesoscale), and channel reaches at least ten or more channel widths long (macroscale). At the microscale, riprap typically supports dense, diverse populations of macroinvertebrates and compares favorably with natural bank sediments and woody debris as invertebrate substrate. Biological density and diversity appear to be positively correlated with the range and maximum of riprap stone size. Available evidence from rivers in the United States indicates that mesoscale habitats provided by intermittent structures such as spur dikes are superior to those provided by continuous revetments. Macroscale effects of comprehensive planform stabilization of large rivers on bed material size and cross-section shape (and thus frequency distributions of depth and velocity) have not been clearly established for all stabilized river systems, but drastic reductions in riverine wetlands and backwaters have been widely observed.

1 INTRODUCTION

Riprap is a fundamental tool of mankind for development and control of rivers, streams, and canals. This paper describes effects of riprap on habitats of macroinvertebrates and fishes in riverine ecosystems. The nature of these effects is strongly related to spatial scale. Three scales are recognized: areas approximately equivalent to the median stone diameter squared (microscale), areas on the order of the square of the channel width (mesoscale), and channel reaches at least ten or more channel widths long (macroscale). Small-scale effects reflect modifications to local hydraulic conditions; as scale increases, impacts on geomorphological processes become important. Below we relate the reported biological effects of riprap to physical phenomena, at least by hypothesis.

The effects of replacing natural vegetation and bank soils in riparian zones with riprap are important at all scales and are manifest in aquatic as well as terrestrial communities. However, we have limited

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the scope of our discussion primarily to aquatic habitats and species, and, therefore, little space is devoted to effects above the water's edge. Obviously, this is an artificial distinction. Natural bank and riprap structure habitats are compared herein; much of the value of natural banks is due to overhanging cover, root wads, woody debirs, and coarse particulate organic matter (leaves and twigs) provided by trees and shrubs.

2 MICROSCALE

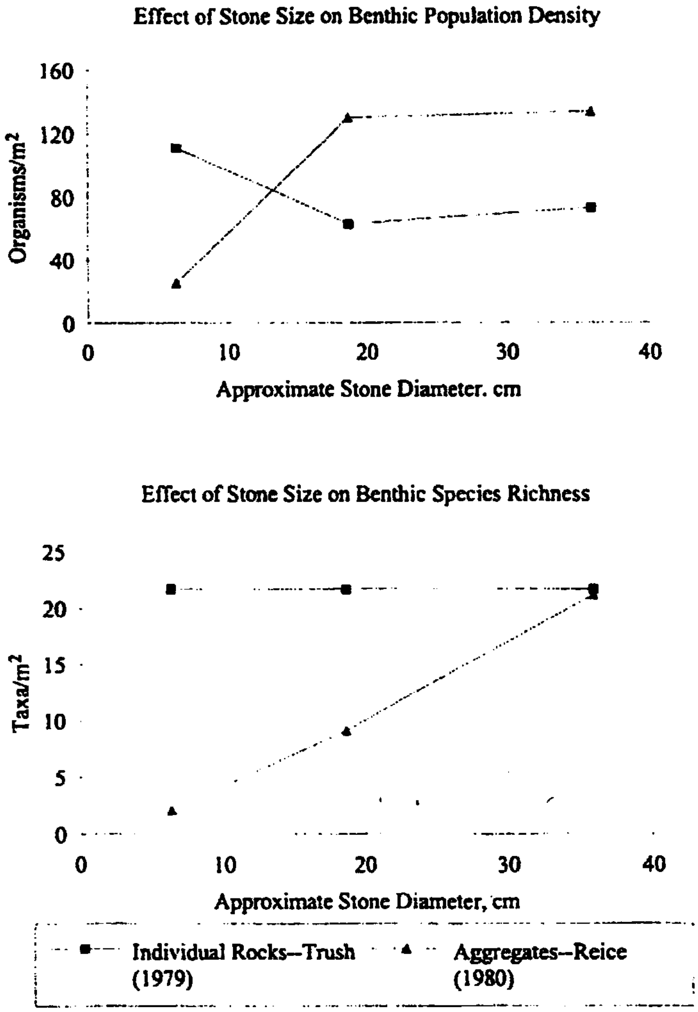
Flow forces are stressful for many aquatic organisms (Statzner et al., 1988) and, consequently, organisms that lack very streamlined body morphology seek out zones of reduced shear stress and turbulence in order to conserve energy. Sheltered microhabitats adjacent to flow fields that transport food and waste products to and from organisms are valuable habitats (e.g., a boundary layer adjacent to or within the surface layers of a riprap revetment). Visual observations indicate that flow adjacent to and within riprap structures in rivers is highly nonuniform. Nonuniformity is important because biological diversity is often associated with physical heterogeneity (e.g., Bournaud and Cogerino, 1986).

Quantification of physical heterogeneity adjacent to riprap is difficult. Data describing velocity fields at riprap blanket surfaces and within voids are scarce due to the difficulties of measurement (a review of techniques for such measurements in gravel stream beds is given by Williams and Hynes, 1974). Several investigators (e.g., Abt et al., 1991; Jain et al., 1988) report results of flume experiments where interstitial velocities for porous dikes or for rockfills placed on impervious embankments are measured using tracers or computed from head loss. Interstitial velocities are dependent upon hydraulic gradient and stone gradation; empirical relations have been derived from flume data. However, these relations are difficult to apply to bank protection because prediction or estimation of the local hydraulic gradient is problematic. Nevertheless, flow through rockfill voids is highly heterogeneous with laminar, turbulent, and transition regimes present (Jain et al., 1988); and void velocities are much lower than the channel velocities above and adjacent to the revetment. For example, Abt et al. (1991) measured interstitial velocities in flows just submerging riprap on slopes ranging from 1 to 20%. Median stone sizes ranged from 2.6 to 13.0 cm, and riprap layers were 7.6 to 30.5 cm thick. Mean interstitial velocities were 3 to 44 cm s^{-1}, which were two to three times lower than computed velocities for wide, open channel flows at similar depths and slopes with Manning's $n = 0.3$. Williams and Hynes (1974) measured current velocity in a stream of 36 cm s^{-1} but an interstitial velocity 10 cm below the bed surface of only 0.1 cm s^{-1}.

Benthic aquatic species include invertebrates that burrow into soft sediments (infauna) and those that attach themselves to rocky surfaces (epifauna). Some epifaunal species and smaller vertebrates (e.g., juvenile fishes), spend at least part of their life cycle in voids within matrices of noncohesive particles like a riprap structure (Williams, 1984; Hjort et al., 1984; Li et al., 1984). Some evidence suggests that macroinvertebrate populations within a riprap structure are more dense and diverse than those found on its outer surfaces (Mathis et al., 1982).

The number and type of epifaunal organisms on and in a natural sediment deposit in a stream reflects sediment particle size, size gradation, and particle stability (Minshall, 1984). If a riprap structure is stationary relative to natural movable beds, it follows that riprap gradation is the dominant microscale habitat factor for a given set of hydraulic conditions. Results of experiments using uniform artificial stones suggests that the population density and species richness of benthos respond to stone size in a complex fashion: both are higher for small rocks placed alone in the flow, but when aggregate deposits are considered, larger stones support higher densities (Figure 34.1). Minshall (1984) suggested that this phenomenon was due to the association of larger (and thus possibly more habitable) voids with larger particles. Others have pointed out that physical complexity generally increases with median particle size; physical heterogeneity implies more habitat niches are available, and thus a more diverse biological community may result.

Riprap revetments in sediment-laden streams often become locations for sediment deposition (Tockner, 1991; Fisher et al., 1991; Shields, 1991).


Effect of Stone Size on Benthic Population Density

Effect of Stone Size on Benthic Species Richness

Figure 34.1 Effect of stone size on benthic diversity and density. The effect is different for individual stones and aggregates, suggesting that voids within the aggregate matrix become more habitable as stone (and thus void) size increases. After Minshall (1984)

Thin layers (~1 mm) of fine sediments and algal growth on riprap surfaces provide "secondary substrate" that is utilize by benthic invertebrates. In addition, sediments deposited in riprap interstices can enhance habitat and benthic species diversity (Burress et al., 1982; Mathis et al., 1982), but sand deposits that cover riprap reduce habitat quality (Sanders et al., 1986). When placed is sand-bed systems with little naturally occurring sediment larger than sand, riprap provides an otherwise unavailable or very scarce stable substrate for invertebrate production (Witten and Bulkley, 1975).

Copious literature attests to the ecological value of microscale riprap habitats to invertebrates, and a sample of findings for large US rivers is provided in Table 34.1a. Riprap substrates compare favorably with natural banks as benthic habitat. The cited authors described the sampled "natural bank" habitats as steep, eroding banks that are typical of the types of habitats replaced by revetment; samples from stable banks and sandbars were not included. Generally, they reported that organisms inhabiting natural bank sediments were sampled by collecting sediment samples using various types of sampling dredges and returning the sediments to the laboratory for separation and processing of biota. Riprap was sampled using metal baskets filled with riprap and implanted on the riprap structures for a fixed period of time (Sanders et al., 1985), or by collecting all stones enclosed by an rectangular frame placed

Table 34.1 Mean benthic invertebrate species richness (and density in numbers per square meter in parentheses) for natural banks and riprap structures. Species richness and density values are means for a given location and a given time. Mean species richness values in different rows are not directly comparable because different sampling methods were used

(a) Natural banks and riprap revetments

River	Natural banks	Riprap revetments	Riprap/natural bank %	Source
Arkansas	22 (1737)	38 (853)	172 (49)	Sanders et al. (1985)
Willamette	33 (2043)	48 (19 619)	130 (476)	Hjort et al. (1984)
Upper Missouri	4[a] (68)	6[a] (1570)	150 (2300)	Burress et al. (1982)

(b) Natural banks and riprap spur dikes

River	Natural banks	Riprap spur dikes	Riprap/natural bank (%)	Source
Arkansas	22 (1737)	22 (900)	100 (193)	Sanders et al. (1985)
Upper Missouri	4[a] (68)	8[a] (3037)	200 (4467)	Burress et al. (1982)
Lower Mississippi	17 (4903)	not given (849–23 462)	(17–479)	Baker et al. (1988a and 1991

[a] Taxa enumerated by order only.

on the structure at random (Burress et al., 1982; Atchison et al., 1986; Hjort et al., 1984), although less quantitative methods (such as collecting all organisms from a fixed number of riprap stones) have also been used (Sanders et al., 1986; Baker et al., 1988b).

Woody debris is an important invertebrate habitat, particularly in sand-bed rivers. Benke et al. (1985) found that woody debris supported 60% of the total invertebrate biomass, although it accounted for only 4% of the habitat area in a low-gradient sand-bed river in Georgia. Baker et al. (1988a) found an average benthic macroinvertebrate density of 3121 m^{-2} representing an average of 21 taxa on large woody debris adjacent to natural banks on the lower Mississippi River. In the streams listed in Table 34.1, woody debris is usually more common along steep, eroding, natural banks than riprap revetments. Comparisons of habitat values of natural and revetted banks should allow for different woody debris densities. In channelized or unstable sand-bed rivers, riprap structures may partially serve the function (stable substrate for macroinvertebrates) that large woody debris does in relatively undisturbed rivers.

Microscale phenomena may also affect utility of riprap as fish habitat. Riprap size heterogeneity rather than mean size has been shown to be an important determinant of benthic fish habitat at artificial reefs in marine environments (Helvey and Smith, 1985). Farabee (1986) found that fish biomass catch per unit effort at a Mississippi River revetment constructed with 0.6 m diameter riprap was more than twice as great as for a similar revetment constructed with riprap fitting a 0.3–0.6 m gradation. Michny and Deibel (1986) and Schaffter et al. (1983) reported 30–90% fewer juvenile salmon were found at Sacramento River revetted banks than natural banks, and suggested that the rougher riprap surfaces prevented formation of low-turbulence zones preferred by the juvenile salmon for feeding. However, riprap locations showed higher numbers of fish species that preyed upon and competed with the juvenile salmon (Michny and Hampton, 1984). In another region, placement of riprap revetments created additional spawning sites for lake sturgeon (Folz and Meyers, 1985). Thus by altering near-bank flow fields, riprap revetments can induce shifts in fish species composition and relative abundance.

3 MESOSCALE

3.1 Revetments

At the channel-width scale, hydraulic conditions created by riprap structures can be beneficial or detrimental to habitat quality. Some investigators have suggested that riprap revetment placed on the outside of a bend induces formation of a narrower, deeper baseflow channel; conflicting data from the Sacramento River have been presented by Harvey and Watson (1988) and Buer et al. (1989). The overall biological impact of revetment depends upon the magnitude of channel alteration and the quality of the habit replaced by the revetment. Knudsen and Dilley (1987) compared summer and fall anadromous fish populations in five western Washington stream reaches before and after construction of riprap revetments. Fishes in smaller streams (mean discharge 0.4–2.4 $m^3 s^{-1}$) were adversely impacted—biomass (in grams m^{-2}) was reduced 26% in the revetted reaches, but increased 54% in unaltered control reaches. Effects were different for larger streams (mean discharge 4.9–11.6 $m^3 s^{-1}$): revetted reach biomass levels increased 227%, while control reach biomass increased only 30%. Since this study was limited to a short period of time (months), it may simply indicate that large and small stream communities respond over different times scales.

Local effects of revetment construction have also been studied. For example, Li et al. (1984) sampled adult fishes adjacent to natural banks, and continuous riprap revetments along the Willamette River, Oregon, and found 20 species near natural banks but only 10 adjacent to revetments, possibly due to more diverse physical conditions at natural banks. Additional studies that include comparison of fishes at natural and revetted banks are listed in Table 34.2.

3.2 Spur dikes and other intermittent structures

Studies comparing macroinvertebrate (Table 34.1b) and fish (Table 34.2) assemblages adjacent to continuous and intermittent bank protection structures have been performed in a wide variety of stream

Table 34.2 Mean fish species (mean numerical catch per unit effort) for natural banks (usually steep, eroding banks) and riprap revetments. Species richness values are means for a given location and a given time. Mean values in different rows are not directly comparable because different sampling methods were used. However, column-to-column comparisons in the same row are valid. Fishes were sampled by electrofishing unless otherwise noted.

River	Natural banks	Riprap spur dikes	Riprap revetments	Spur dike/ revetment (%)	Source
Willamette	13 (89)	not sampled	11 (281)	—	Hjort et al. (1984)
Willamette	20	9	10	90	Li et al. (1984)[a]
Sacramento	8 (21)	not sampled	10 (26)	—	Michny (1988)
Sacramento	10 (488)	not sampled	12 (330)	—	Schaffter et al. (1983)
Upper Missouri	8	14	10	140	Burress et al. (1982)[b]
Middle Missouri	not sampled	11 (26)	15 (66)	73 (39)	Atchison et al. (1986)[c]
Upper Mississippi	33 (41)	not sampled	33 (87)[d]	—	Farabee (1986)
Arkansas	10 (98)	13 (225)	13 (110)	100 (205)	Sanders et al. (1985)[e]
Batupan Bogue, Mississippi	25 (360)	25 (410)	18 (196)[f]	139 (209)	Knight and Cooper (1991)
Lower Mississippi	60	68	not sampled[g]	—	Baker et al. (1991)[h]

[a] Cumulative total number of species captured, not mean per site per sampling date.

[b] Electrofishing, hoop netting, seining, gill netting.

[c] Electrofishing. Hoop net results were similar.

[d] Two revetments were sampled. One was constructed with 30–60-cm diameter riprap, the other with riprap "that averaged" >60 cm diameter. The larger riprap site had mean numerical and biomass catches per unit of effort that were 130% and 250%, respectively, of the same values for the smaller stone revetment.

[e] Electrofishing. Use of additional sampling gears in areas around spur dikes yielded 16 additional species there.

[f] Structures sampled for this study were longitudinal toe dikes (windrows of stone placed parallel to flow along bank toes), and provided habitat similar to riprap blanket revetment placed on a graded bank.

[g] Lower Mississippi River revetments are articulated concrete mattresses (ACM) with riprap and asphalt on upper banks. Species richness for natural banks and those covered with ACM are similar (Pennington et al., 1983).

[h] Numbers shown are total numbers of species reported in literature. Fifty-five species have been reported for articulated concrete mattress revetments.

habitats. Readers unfamiliar with limitations of technology for sampling fish in rivers should be aware that data in Table 34.2 may reflect differential sampling efficiencies along different bank types, cyclical or climatic effects, etc. Also, species richness and catch per unit effort do not tell the whole story. For example, although investigators studying the Sacramento River found more species along revetments than natural banks, juvenile salmon preferred natural banks in significantly greater numbers Schaffter et al., 1983; Michny, 1988; US Fish and Wildlife Service, 1992). Nevertheless, the values in Table 34.2 are all means of data generated by repetitive sampling in time and space and represent the best information available.

Results presented in Tables 34.1b and 34.2 indicate that intermittent structures like spur dikes or groins usually provide aquatic habitats superior to continuous revetment and sometimes surpassing natural banks. The superior performance of spur-type structures as fish habitat is related to creation of stable pools (scour holes) at riverward tips (Witten and Bulkley, 1975; Knight and Cooper, 1991; Shields et al., 1993), creation of lentic (still water) habitat connected with the main stream (Backiel and Penczak, 1989), provision of a complex of depth-velocity-bed type combinations not found adjacent to continuous riprap blanket (Li et al., 1984; Beckett et al., 1983; Baker et al., 1988b), and preservation of portions of the natural bankline and associated riparian vegetation and woody debris (Li et al., 1984). Woody debris is an important determinant of mesoscale habitat quality. Higher levels of physical heterogeneity are associated with higher woody debris densities (Shields and Smith, 1992), and fish populations respond negatively to debris removal or absence (Angermeier and Karr, 1984; Hortle and Lake, 1983).

Li et al. (1984) examined the use of natural banks, continuous riprap revetments, and spur dikes in the Willamette River, Oregon, by larval fishes. Continuous revetments were poor habitat for larval fishes relative to natural banks, while spur dikes were of intermediate quality due to the physical heterogeneity generated by the typically complex flow patterns around the spurs. Shallow zones above the gradually sloping bars adjacent to the spur dikes were particularly good habitat. Similar findings were reported by Schiemer and Spindler (1989) for the Danube in Austria. Geometrically complex banklines along the Danube River that included gravel banks and littoral bays supported higher densities and diversities of juvenile fish than adjacent riprap revetments. Twelve species were captured from gradually sloping gravel banks and twelve species were also found in small bays in the inshore zone, but riprapped banks produced only three species.

3.3 Restoration and innovation

Because of the mesoscale effects described above, riprap structures have been widely used to rehabilitate aquatic habitats in streams damaged by channelization and erosion (Swales, 1989; Wesche, 1985). For example, Shields et al. (in Press) described habitat restoration for an incised channel in northwest Mississippi. Previous channel stabilization work (construction of a grade control structure downstream and placement of about 40 riprap groins) had been ineffective in restoring habitat quality. By adding low extensions to every other groin and placing a riprap toe along the opposite bank, scour hole volumes and depths were increased dramatically (Figure 34.2). For the same water surface elevation, mean maximum depth of scour holes at all 40 groins increased from 40 to 70 cm after restoration, and mean depth increased from 24 to 40 cm. After restoration the mean length of fish, number of fish species, and biomass catch per unit effort of electrofishing increased 81, 60, and 1142%, respectively (Shields et al., 1993). Favorable results for habitat restoration projects in channelized streams that featured riprap spurs and weirs have also been reported by Swales (1982), Edwards et al. (1984), and Carline and Klosiewski (1985). Design criteria are provided by Wesche (1985).

Innovative concepts for riprap structures—both intermittent and continuous—have been proposed to address economic, environmental, and engineering weaknesses of more orthodox approaches (Table 34.3). In general, these concepts produce mesoscale habitats superior to those found at more orthodox structures. However, all of them should be

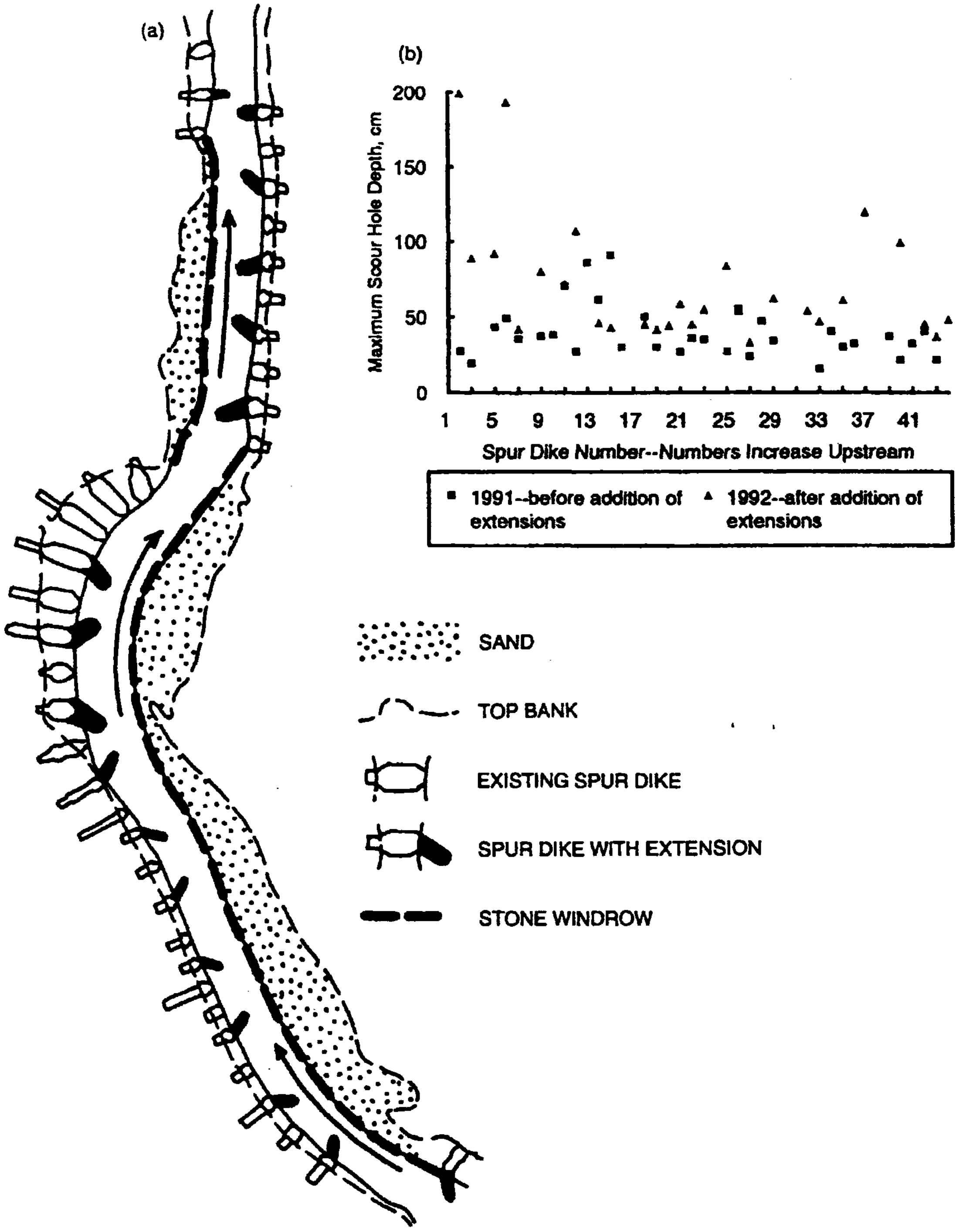


Figure 34.2 Modification of short riprap spur dikes at Hotophia Creek, Mississippi, to improve mesoscale habitats. (a) Stone added to modify habitat. Existing structures are unshaded, additions are shaded black. (b) Effect of spur dike extensions on availability of scour hole habitat. Maximum depth of scour holes at dike tips measured at nearly identical stages at midsummer before and after extension of every other dike

Table 34.3 Concepts for riprap structures with potential for providing mesoscale habitats superior to traditional designs

Concept[a]	Description	Objective	Benefits to habitat	Testing[b]	Remarks	Source
Bendway weirs	Submerged, level-crested spur dikes angled upstream	Develop and maintain navigation channel	Minimize disturbance of bank (shaping, clearing vegetation, etc.)	Model studies and prototype installation on middle Mississippi River, no biological studies	Developed expressly for a particular reach; applicability elsewhere may be questionable	Davinroy (1990)
Off bankline revetments	Windrows of riprap placed in shallow water a short distance from eroding with periodic gaps	Protect bank	Low-velocity habit created between structure and bank. Bank clearing eliminated. Gaps allow movement of organisms and recreational craft	Biological field studies on Middle Mississippi and Missouri Rivers	May be vulnerable to sedimentation. Stone requirements likely greater than for blank-type revetment	Niemi and Strauser (1991) Reynolds and Segelquist (undated) Kallemeyn and Novotny (1977)
Using larger stone gradation in traditional revetment	Upper end of gradation curve shifted to include a few large (−0.6 m) stones	Protect bank	Heterogeneity of voids increased. Large voids available for larger organisms.	Biological study at one field site	Potential adverse effects on revetment stability	Niemi and Strauser (1991) Farabee (1986) Kallemeyn and Novotny (1977)
Notched spur dikes	Gaps constructed or allowed to form in transverse training structures	Reduce sediment deposition in dike fields	Develop heterogeneous flow patterns and preserve low-velocity aquatic habitat contiguous with main channel	Several biological field studies that include limited physical data	Some locations are vulnerable to sedimentation or simply create additional high-velocity habitat	Shields (1984 and 1988)

Fish groins	Traditional riprap revetment with low ridges of riprap running from top bank to toe perpendicular to channel	Create eddies and zones of reduced velocity	Provide habitat for juvenile salmonids	Biological field study and physical modeling	When combined with plantings of woody vegetation, provides best replacement for natural bank as juvenlie salmon habitat	US Fish and Wildlife Service (1992)
Filling interstices with gravel	Traditional riprap revetment covered with a layer of gravel	Create near-bank hydraulic conditions similar to natural gravel banks	Provide habitat for juvenile salmonids	Biological field study		US Fish and Wildlife Serivce (1992)
Rearing bench	Gradually sloping (1V:5H) gravel bench parallel to channel placed at an elevation where it will be inundated at moderate flows	Create near-bank hydraulic conditions similar to natural gravel bar	Provide habitat for juvenile salmonids	Biological field study	Juvenile salmonid densities were higher than for riprap but lower than for natural banks	Michny and Deibel (1986)
Indented revetmnet	Traditional riprap revetment with periodic shelf-like indentations	Form shallow pools adjacent to the main channel	Provide low-velocity habitat	Physical model study and a biological field of similar concept	May be vulnerable to sedimentation. Quality of habitat provided unstable due to stage variation.	Schmit (1983) Zimpfer et al. (1988)

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[a] Terms used in this column are taken from literature listed in source column.
[b] Testing documented in sources.

viewed as experimental when applied to a setting for which test data are unavailable. Institutional and political factors arising from stabilization of the Sacramento River have led to development of a number of modified revetment designs intended to preserve riparian vegetation and anadromous fish habitat (Mifkovic and Petersen, 1975; US Fish and Wildlife Service, 1992). Most of these concepts are listed in Table 34.3. Despite development of these innovations they have not been extensively employed, and declines in riparian habitat and dependent species have been significant (Figure 34.3).

4 MACROSCALE

Riprap structures are major components of stream corridor management projects. In many cases,

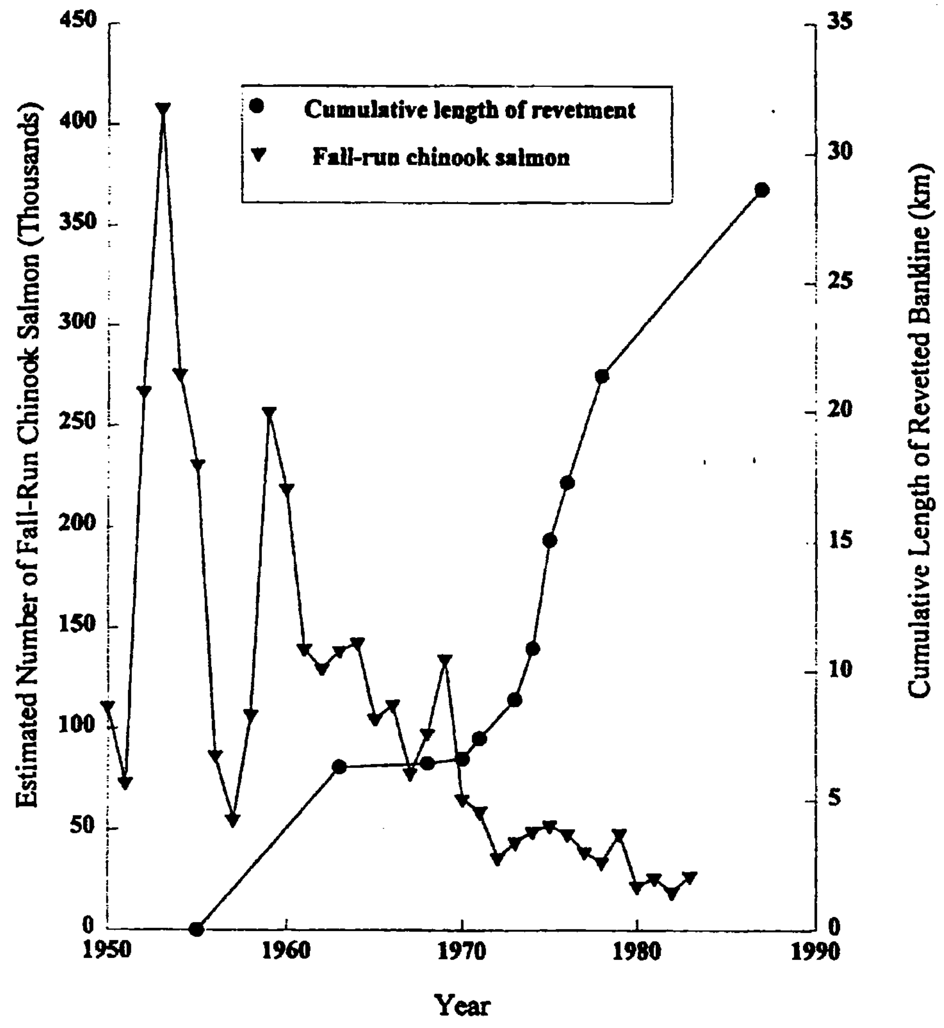

Figure 34.3 Cumulative length of riprap revetments constructed along the Sacramento River between river kilometer (RK) 311 and 391 versus decade average of estimated number of fall-run chinook spawners for the reach upstream of RK 391. The decline in fish numbers 1987–1992 was even more rapid, probably due to reduced streamflow. Revetment data are from Schaffter et al. (1983) and Michny and DeHaven (1987). Fish data are from Buer et al. (1984). This plot does not depict a simple cause-and-effect relationship. Decline in fish numbers reflects many influences in addition to river stabilization; however, the loss of juvenile rearing habitat immediately downstream of the spawning reaches is a likely factor

Table 34.4 Revetments and transformation of major rivers. Impacts on habitat and fishery reflect the influence of water quality degradation, impoundment of upstream and tributary reaches, levee construction, woody debris removal, channel straightening, and transverse training structures such as spur dikes

River	River kilometer (=0 at mouth)	Revetted bank (%)[a]	Impacts on habitat	Impacts on fishery	Sources
Mississippi	0–1570	45	River length shortened 229 km. flood-plain reduced 90% by levees	Unknown	Baker et al. (1988a), Fremling et al. (1989)
Missouri	0–1181	60[b]	River length shortened 64.4 km, water area reduced 34–66%, 2111 km² natural habitat lost from channel and meander belt	Commercial fish harvest reduced 80% in reach within state of Missouri	US Army Engineer District, Kansas City (1980), Nunnally and Beverly (1986), US Army Corps of Engineers (1990), Funk and Robinson (1974)
Sacramento	0–311	47	Freshwater wetland vegetation acreage in valley reduced 43% between 1939 and mid-1980s	Mean fall-run chinook salmon numbers upstream of RK 391 reduced 87% between 1950–59 and 1980–85	Keck (1990), Storfer (1992), Frayer et al. (1989), Buer et al. (1984)
Willamette	0–301	40	Four-fold decrease in surface water volume. Elimination of braided reaches, Removal of 550 snags km⁻¹	Unknown	Fletcher and Davidson (1988). Sedell and Froggatt (1984)
Rhine	0–1320	Unknown	Backwaters, braids and side channels greatly reduced. Bed degradation up to 7m. Area subjected to flooding reduced 85–94%.	"since 1915, a continuous and irreversible decline of catches has occurred."	Lelek (1989), Dister et al. (1990)
Vistula	0–640	"all stretches"	"...disappearance of islands and braided reaches, particularly in the lower course of the river." Channel width reduced by 50%, bed lowered 1.3 m (reach from Wloclawek dam to Swiecie)	Sharp decline in commercial fish harvest, especially of migratory species	Backiel and Penczak (1989), Babinski (1992)

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[a] Estimates generated by dividing total length of revetted bankline by twice the reach length.

[b] For RK 0-802 only.

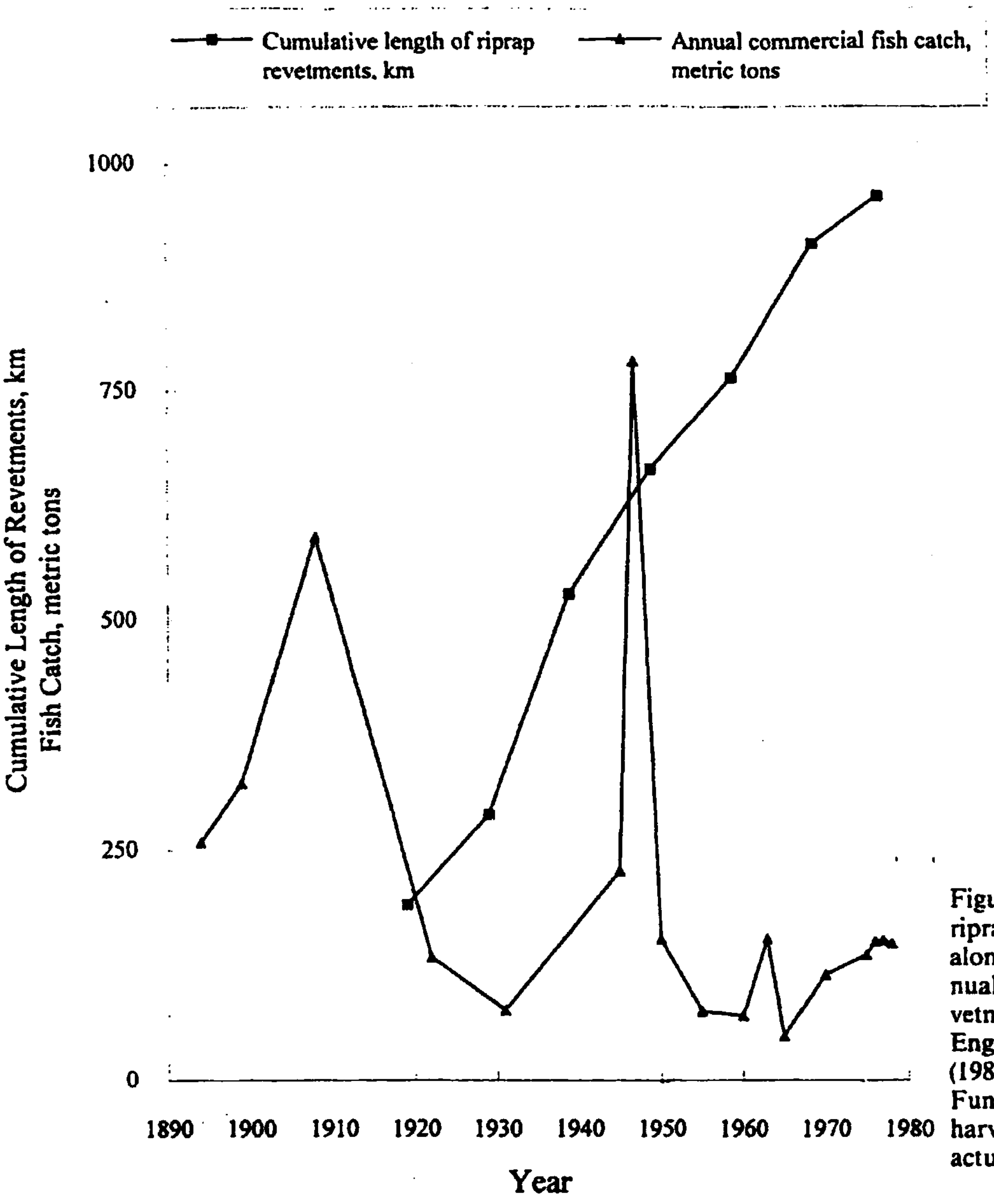

Figure 34.4 Cumulative length of riprap revetments constructed along the Missouri River and annual commercial fish harvest. Revetment data are from US Army Engineer District, Kansas City (1980). Fish catch figures are from Funk and Robinson (1974). Fish harvests are probably lower than actual for years prior to 1945 due to incomplete reporting

stream corridor development demands either preservation of a wide zone for channel migration or comprehensive stabilization of river planform using riprap training structures. The latter course of action has been chosen for many if not most of the major temperate zone rivers (Bayley, 1991). In many cases (e.g., Missouri, Willamette, Rhine, Vistuala) ecologically rich braided rivers have been confined to single channels with slight sinuosity, high velocities, and extremely low levels of habitat diversity. Channel bed degradation that follows channelization isolates the river and its tributaries from floodplain water bodies, often by draining abandoned channels and oxbows (Atchison et al., 1986; Lelek, 1989). Floodplain development requires flood control, and levees have often been constructed so close to river banks that the area of land subject to flooding is nearly eliminated (e.g., Dister et al., 1990). Bank stabilization, usually with riprap revetments, is usually required in order to protect levees.

Comprehensive stabilization of river planform has major, long-term implications for habitat quality and biodiversity because, as currently practiced, it leads to gradual but permanent elimination of lentic (backwater) habitats adjacent to the main channel (Table 34.4; Petts, 1989). Current thinking in stream ecology emphasizes the importance of periodic exchange of water and the sediments, nutrients, and organisms in it between the main channels of higher order rivers and lentic waters on their floodplains (Junk et al., 1989; Dister et al., 1990). Bayley (1991) suggested that river-floodplain systems with natural annual flood pulses have multispecies fish yields per unit area several times that of constant water level systems (impoundments or lakes). The area subjected to flood pulses is greatly reduced or even eliminated by orthodox river development projects. Floodplain development facilitated by flood control and channel stabilization projects often exacerbates the process of backwater elimination (Vanderford, 1980; Dister et al., 1990). Long-term effects on ecosystem components and their economic value are hard to estimate because of the paucity of preproject data, but available findings indicate these effects are significant. For example, the commercial fish harvest from the Missouri River in the state of Missouri declined at least 80% between 1947 and 1978 (Figure 34.4). The actual decline may have been greater than 80% because catch reporting has been more efficient in recent years.

Recorded backwater sedimentation rates for US rivers range from 1 to 18 cm vertical accretion per year (McHenry et al., 1980 and 1984; Shields and Gibson, 1989). The rate of formation of new backwaters is extremely low because channel migration rates have been greatly reduced by impoundment and channel stabilization, usually with riprap structures. For example along the lower Missouri River, construction of dikes and revetments coupled with closure of upstream reservoirs has resulted in conversion of almost half of the aquatic habitat to terrestrial habitat. Virutally all of the backwater habitat has been lost in some reaches, leaving only the less productive main channel (Sandheinrich and Atchison, 1986). Overall habitat diversity has declined greatly. Conversely, morphologic changes on the lower Mississippi River associated with channel stabilization and upstream flow regulation have been relatively mild (Nunnally and Beverly, 1986). This difference in channel response may be due to the lower historical sediment load and the lower elevation of the training works relative to mean and peak stages on the lower Mississippi relative to the Missouri. Bed degradation along the Missouri has also exacerbated reduction of backwater area.

Comprehensive bank stabilization projects along gravel-bed rivers reduce the movement of gravel from eroding banks into the channel. Although it has been suggested that extensive bank protection might reduce gravel supply enough to adversely impact gravel-spawning fishes, field studies on the Sacramento (Harvey and Watson, 1988) and Willamette (Klingeman, 1989) Rivers have been inconclusive. Even channels with virtually all of their banklines protected receive gravel from bed erosion and tributary reaches.

5 IMPLICATIONS

Designers of streambank erosion control and channel training structures who wish to address environmental concerns are faced with several gaps in the state of the art. Environmental approaches for these efforts typically involve use of intermittent structures, plant materials (alone and in combination with stone), and backwater sediment management (Henderson, 1986). Since experience with these approaches is not as well documented as for orthodox riprap revetment, there are higher levels of uncertainty regarding project performance. We suggest that reward and risk are proportional, and note that at least some orthodox views of environmental measures (i.e., vegetation on revetments) are unrealistically conservative (Shields, 1991).

Use of plant materials alone or in conjunction with riprap is extremely attractive from an environmental (i.e., aesthetic and habitat conservation) standpoint. The state of the art in this area is rapidly expanding, and design textbooks have recently been produced (Schiechtl, 1980; Gray and Leiser, 1982; Coppin and Richards, 1990). The emphasis on biotechnical alternatives to riprap in this volume is interesting and commendable.

Although some biotechnical approaches to bank protection are somewhat elaborate and require specialized expertise to design and implement, others are as simple as planting dormant willow posts (e.g., Shields et al., 1993). However, institutional, political, and psychological barriers to widespread adoption of biotechnical approaches by the civil engineering community are deep-seated. Those who believe that riprap specialists will abandon the skills they have spent a lifetime developing to embrace others for the sake of environmental quality have a decidedly more sanguine view of human nature than we do.

Habitat conversion due to backwater sedimentation is one of the most major environmental issues associated with large river channel stabilization. Methods for restoring river corridor habitats degraded by sedimentation are diverse (Schnick et al., 1982; US Army Corps of Engineers, 1990; Patin and Hempfling, 1991) and range from planting aquatic macrophytes and reflooding leveed floodplans (Sparks, 1990), to excavating notches in existing spur dikes (Shields, 1984). Combinations of dredging and placement of dredged materials to build islands or levees are common (Patin and Hempfling, 1991; Shields, 1987). However, many of these techniques are inordinately costly, marginally effective, and take a piecemeal approach to ecosystem restoration (e.g., Niemi and Strauser, 1991; Shields, 1988). In contrast, Bayley (1991) proposed restoration of natural flooding over a large, contiguous river-floodplain area by purchasing land, removing levees and modifying reservoir operations for a river reach between two navigation dams as an interim first step in "restoring the watershed". Although the ecological benefits of such a project are apparent, the economic and political obstacles appear intractable to us.

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