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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).

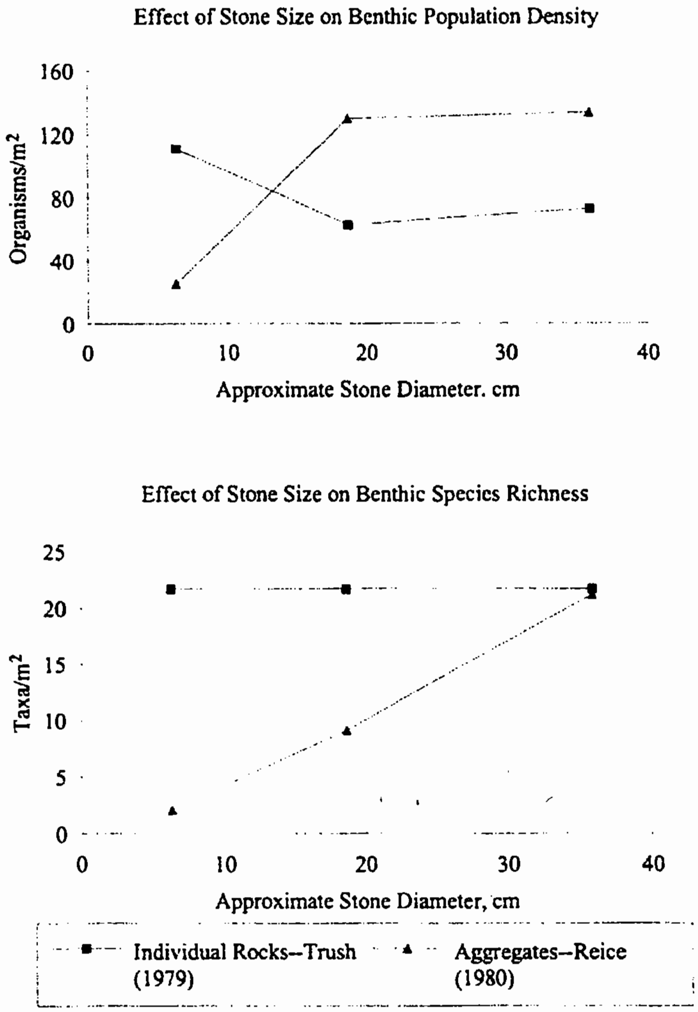

Figure 34.1 Effect of stone size on benthic diversity and density. The effect is different for individual stones and aggregates, suggesting that voids within the aggregate matrix become more habitable as stone (and thus void) size increases. After Minshall (1984)

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

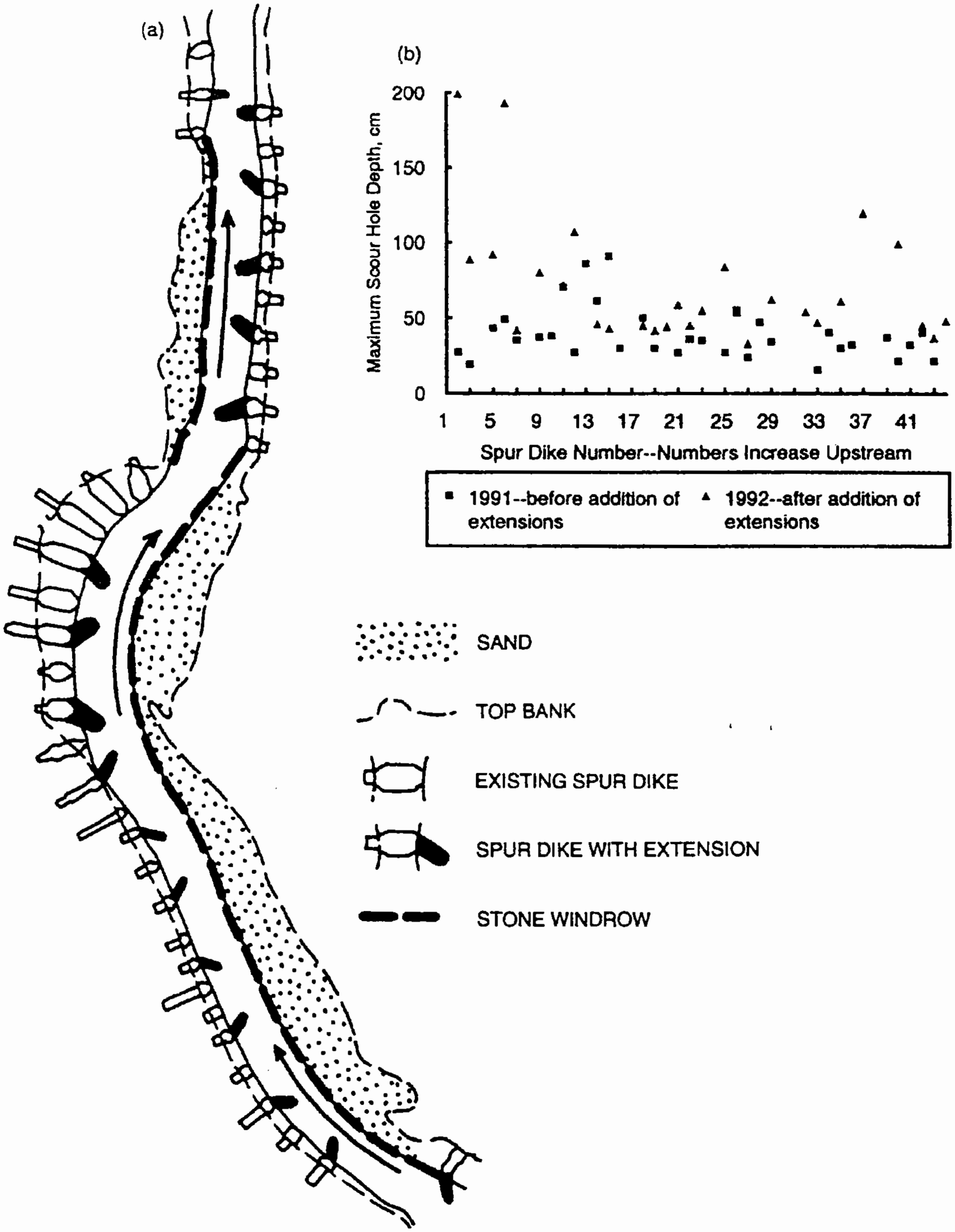

Figure 34.2 Modification of short riprap spur dikes at Hotophia Creek, Mississippi, to improve mesoscale habitats. (a) Stone added to modify habitat. Existing structures are unshaded, additions are shaded black. (b) Effect of spur dike extensions on availability of scour hole habitat. Maximum depth of 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,

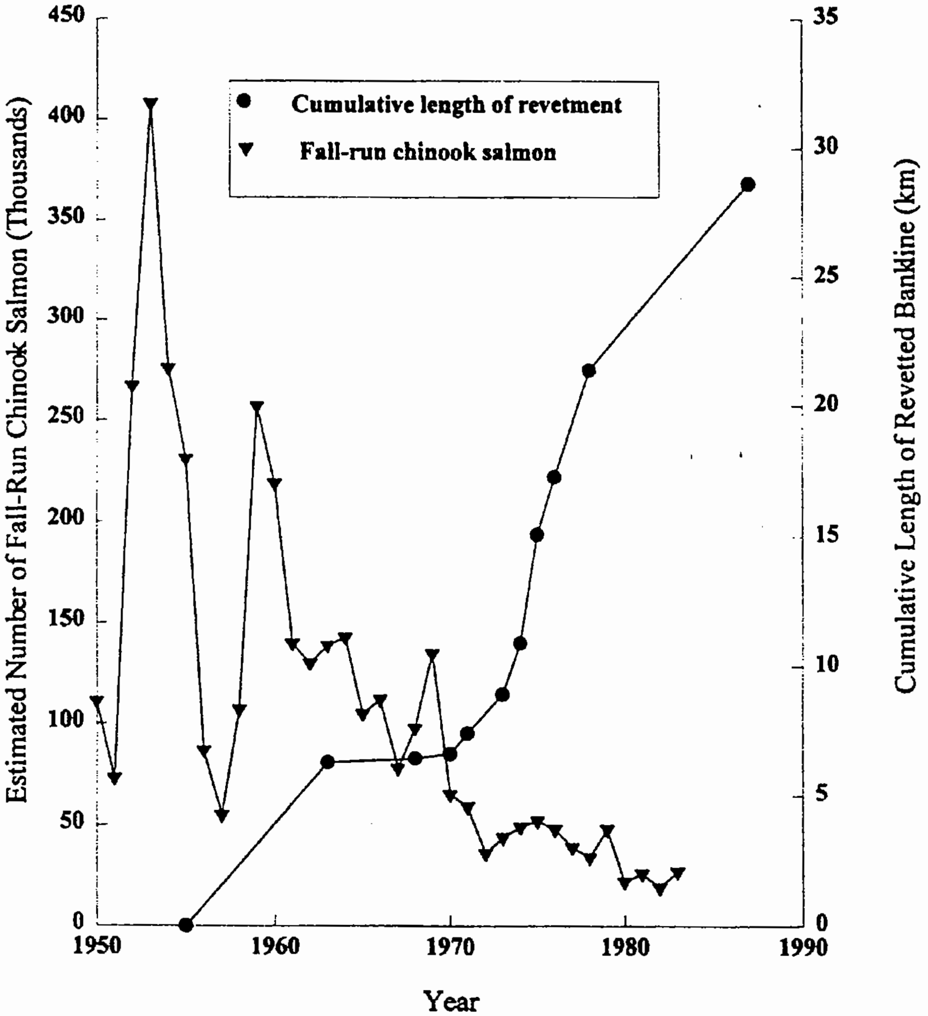

Figure 34.3 Cumulative length of riprap revetments constructed along the Sacramento River between river kilometer (RK) 311 and 391 versus decade average of estimated number of fall-run chinook spawners for the reach upstream of RK 391. The decline in fish numbers 1987–1992 was even more rapid, probably 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 km^2 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 7 m. 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.

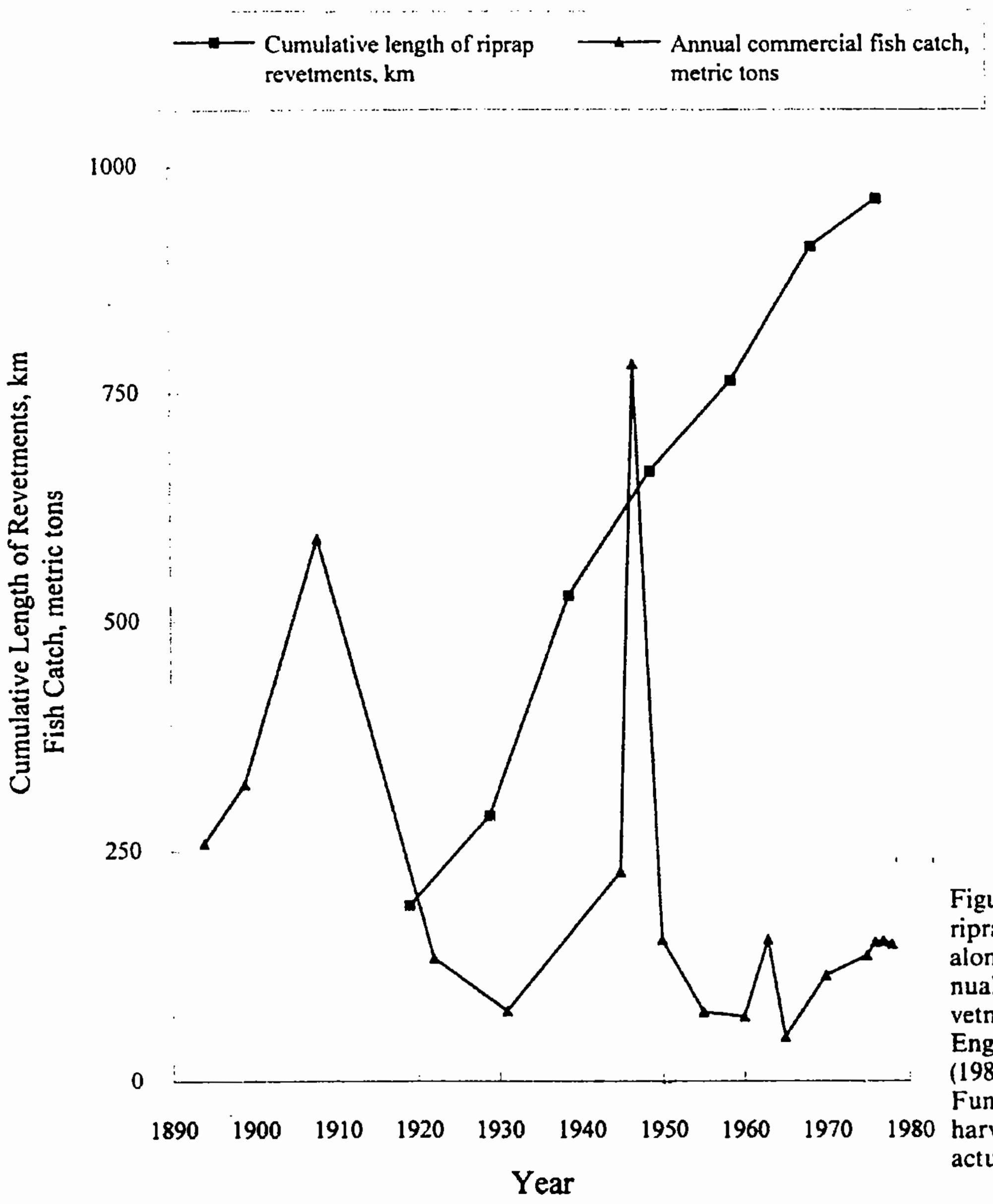

Figure 34.4 Cumulative length of riprap revetments constructed along the Missouri River and annual commercial fish harvest. Revetment data are from US Army Engineer District, Kansas City (1980). Fish catch figures are from Funk and Robinson (1974). Fish harvests are probably lower than actual for years 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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Fate of Lower Mississippi River habitats associated with river training dikes

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ABSTRACT

1. Regions of reduced velocity adjacent to spur dikes along the Lower Mississippi River are valuable aquatic habitats. Similar zones along other large rivers have been converted to terrestrial habitats by sediment deposition.

2. Repetitive hydrographic surveys of 26 representative groups of dikes are examined to determine the direction and rates of change.

3. Since the dikes were constructed, the aquatic volume and area of associated low-velocity habitats have been reduced by 38% and 17%, respectively. Examination of time series shows that most changes occur shortly after construction, and after initial adjustment, habitat area and volume fluctuate about a condition of dynamic equilibrium.

4. Sedimentation rates were most rapid for dike fields constructed on the inside of bends to prevent chute development. Dike fields built to force or maintain thalweg crossings exhibited erosion rather than deposition.

INTRODUCTION

Human impact on large river morphology has followed a remarkably similar pattern worldwide (Welcomme, 1989). Generally speaking, development of major rivers has tended to decrease spatial and temporal heterogeneity of aquatic habitats by eliminating multiple channels and backwater habitats (Brookes, 1988; Lelek, 1989; Dister *et al.*, 1990). For example, during the past 100 years the lower Missouri river has been converted from a braided channel to a low-sinuosity meandering channel, and water surface has been reduced by 50–70% (Morris *et al.*, 1968; Hallberg *et al.*, 1979). Similar changes have been reported for the Vistula (Babinski, 1992).

Spur dikes, groynes, and similar structures are frequently key components of large river development projects (Derrick *et al.*, 1989). Formerly, river engineers tried to design dike fields so that the low velocity zones around them would rapidly fill with sediments (Anding *et al.*, 1968), potentially enhancing their effect of diverting flow into the navigation channel. More frequently, designers ignored effects of dikes on aquatic areas immediately adjacent to the structures, and most early research on dike performance focused on main channel phenomena. However, low-velocity zones and scour holes adjacent to and between dikes have been shown to provide extremely valuable habitats in large rivers (Pennington and Shields, 1993) and small streams (Bulkley *et al.*, 1976; Knight and Cooper, 1991). A number of techniques for enhancing spur dike habitats have been proposed and tested, although on a limited scale at present (Shields, 1984, 1988; Shields *et al.*, in press). Concern exists over the long-term sustainability of high-quality habitats associated with dike fields. When aquatic areas within dike fields are converted to terrestrial habitat by sedimentation, low-velocity habitats become increasingly scarcer along the river corridor. Lateral migration, and the

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concomitant creation of new backwaters and other low-velocity areas, is virtually eliminated by extensive river training (Shields and Milhous, 1992; Shields *et al.*, in press). Thus, the nature and magnitude of sedimentation between and adjacent to spur dikes hold important ecological implications for rivers. Nunnally and Beverly (1986) attempted to quantify the magnitude of sedimentation associated with Lower Mississippi River (LMR) dikes by comparing low-water aerial photographs taken in 1962 and 1976. They reported that total water area changed little between the two dates. However, secondary channel area decreased, and off-channel areas (e.g. sloughs) increased, reflecting the river training strategy of closing the upstream entrances to secondary channels. This paper aims to describe the temporal dynamics of sedimentation in aquatic areas adjacent to LMR dikes. Additionally, sedimentation is related to local channel morphology and dike field location.

STUDY SITE

The LMR is the reach of the Mississippi River from its mouth to the Ohio River confluence. This reach is free of impoundments and has been developed for navigation and flood control using upstream and tributary reservoirs, levees, bend cut-offs, floodways, dredging, and river training structures. During the period of data collection for this study (1958–1987), the channel was free of large-scale instability. Major avulsions and bend migrations were prevented by river training structures and control structures regulating flow into the Atchafalaya distributary. However, many forces were at work on the physical system, including closure of upstream reservoirs, a series of 16 man-made meander cut-offs constructed between 1929 and 1942, and continual dredging to maintain navigation depths at thalweg crossings. Observed responses to these forces include a 48% reduction in annual suspended sediment yield (Keown *et al.*, 1986), slight fining of bed sediments (Queen *et al.*, 1991), and generally wider, shallower flow with more middle bars (Winkley, 1977). Water surface elevations at low flow indicate that the bed has degraded by as much as 3.3 m near the upper end of the reach containing cut-offs and dikes and aggraded up to 1 m near the lower end during the period 1962 to 1988 (Elliot *et al.*, 1991). Fremling *et al.* (1989) and Baker *et al.* (1991) provide detailed descriptions of the LMR, its biota, and their habitats.

River training structures found in the LMR include revetments made of articulated concrete mattresses, which generally occur on concave banks, and about 440 stone dikes located between RK 531 and RK 1527 (Derrick *et al.*, 1989). The total length of dike structures constructed since the early 1960s in the LMR was 330 km (up to 1985) and 475 km have been authorized (Baker *et al.*, 1991); additional dikes are constructed each year. Dikes have been designed and constructed in about 125 groups (dike fields) of 2–12 structures per group to achieve reach-specific objectives (Baker *et al.*, 1991). Dike frequency per unit length of river is inversely related to sinuosity (Winkley, 1982).

DIKE FIELD HABITATS

Regions of reduced velocity between and adjacent to dike fields (hereafter referred to as 'dike field pools' or simply 'pools') are important LMR habitats (Figure 1). Water quality and biotic communities of dike pools resemble main channel communities during high flows, when physical conditions typical to main channel occur, and lentic habitats during lower stages (Beckett and Pennington, 1986). At low to moderate flow, these pools are characterized by relatively great depths (up to several metres), and slow ($< 1\ \mathrm{m\,s^{-1}}$) or no current. Because pools are warmer and less turbid than flowing water habitats, primary productivity often reaches relatively high levels, particularly during late summer and autumn (Baker *et al.*, 1988). Secchi disk depths in the river main channel are normally < 30 cm, but are about twice as great in lentic dike pools (Beckett and Pennington, 1986; Baker *et al.*, 1988). Algal blooms and thermal stratification occur in lentic dike pools during warmer months with attendant changes in water quality: oxygen supersaturation occurs in surface waters with anoxia in deeper regions (Beckett and Pennington, 1986; Baker *et al.*, 1991).

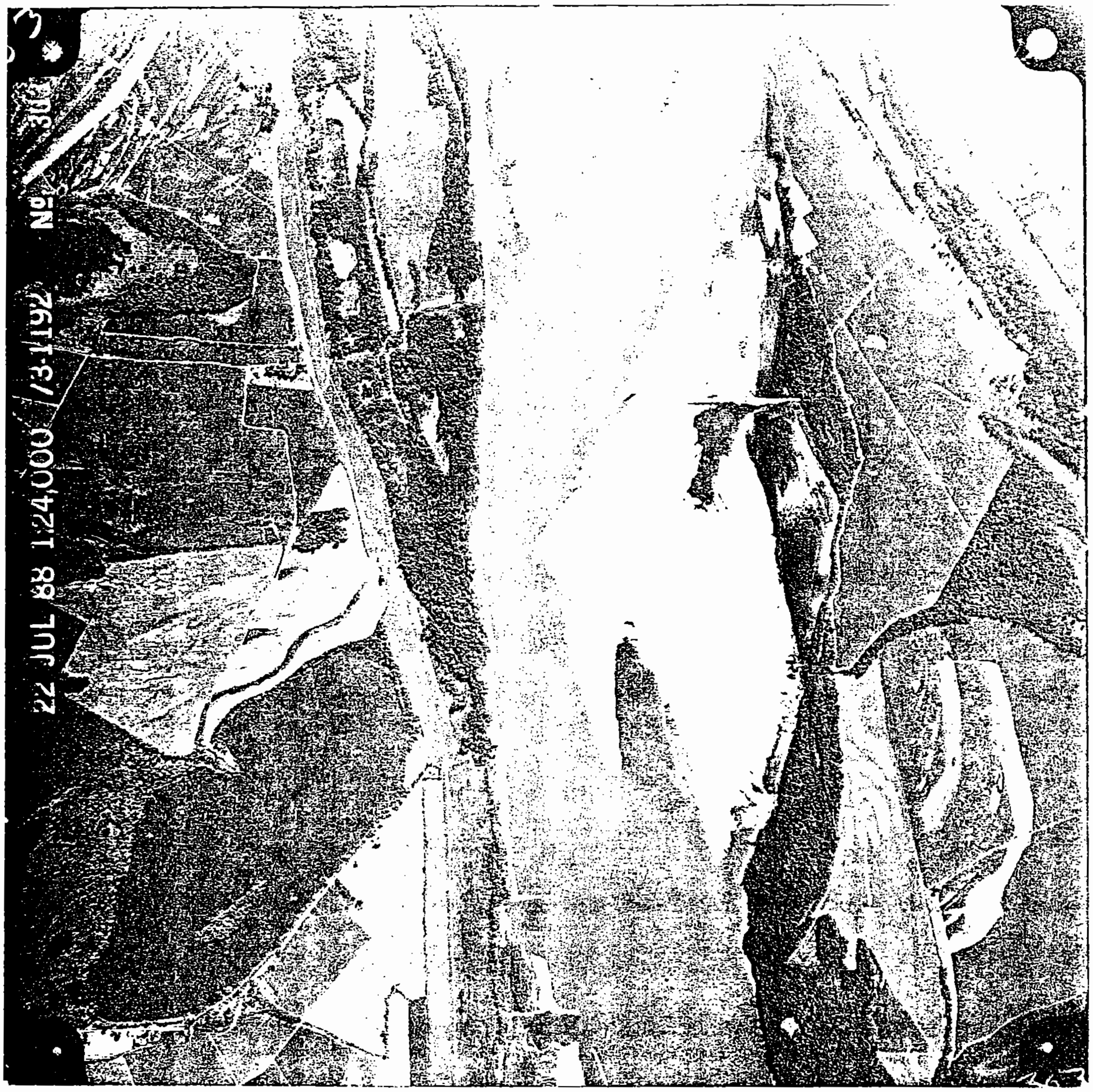

Figure 1. LMR dike fields at low flow, about RK 1133. Flow is from top to bottom of photograph. Note dike field pools at upper right centre and lower left centre. Photo courtesy of US Army Corps of Engineers.

Recent developments in large river ecology have focused attention on the importance of interactions between rivers and floodplains (Junk *et al.*, 1989). Floodplain aquatic habitats along large rivers generally exhibit high primary productivity, while main channels generally exhibit low primary productivity. Production of floodplain habitats is periodically made available to fish living in the river during higher flows (Modde and Schmulbach, 1973; Eckblad *et al.*, 1984; Beckett and Pennington, 1986). Dike field pools may function similarly to floodplain habitats in that they exhibit relatively high primary productivity compared with other mainstream habitats (Baker *et al.*, 1988). This production may be particularly important when levee placement or habitat conversion has reduced seasonally flooded area confluent to the river.

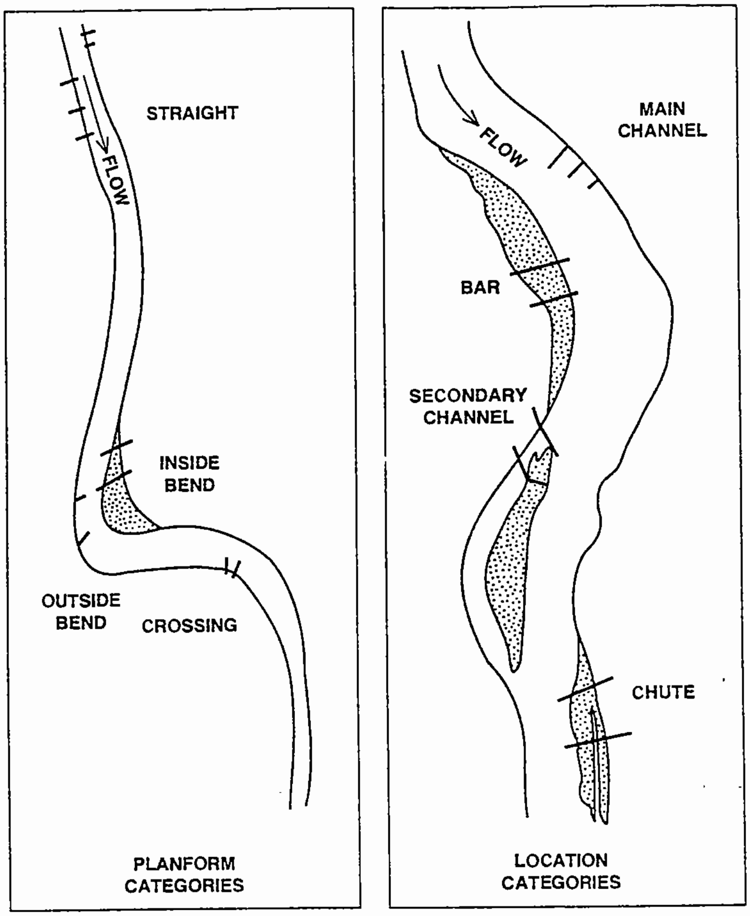

Figure 2. Two-part classification scheme for LMR dike field settings. Each dike field was classified based on the type of reach where it was located, and on the geomorphological feature within the reach upon which the dikes were placed.

Beds of pools are typically covered by fine sediments, although large regions of sand and gravel are found in pools during and immediately after high flows, suggesting seasonal fluctuation (Baker *et al.*, 1988). The spatial and temporal variations in currents within dike pools generate complex mosaics of bed types (Beckett *et al.*, 1983; Baker *et al.*, 1988). These mosaics support diverse invertebrate assemblages (Beckett *et al.*, 1983) that include species typical of both higher-energy habitats (e.g. lotic sandbars) and lower-energy habitats (e.g. sloughs). For example, Beckett and Pennington (1986) reported that *Hexagenia* spp., a large, trophically important organism, was found only in silt substrates in dike pools. Observed *Hexagenia* population densities (50–160 organisms m^{-2}) compared favourably with reported densities for lentic habitats.

The stones comprising the dike structures are inhabited also by large numbers of caddis flies, chironomids, and other epibenthic invertebrates (Beckett and Pennington, 1986; Baker *et al.*, 1988). Some workers have suggested that populations of hydropsychid caddis flies are limited in many large rivers by the availability of suitable substrate (Fremling, 1960; Benke and Wallace, 1980). Because the stone surfaces furnish stable, rocky substrate that is in short supply in the LMR ecosystem, and because the dike

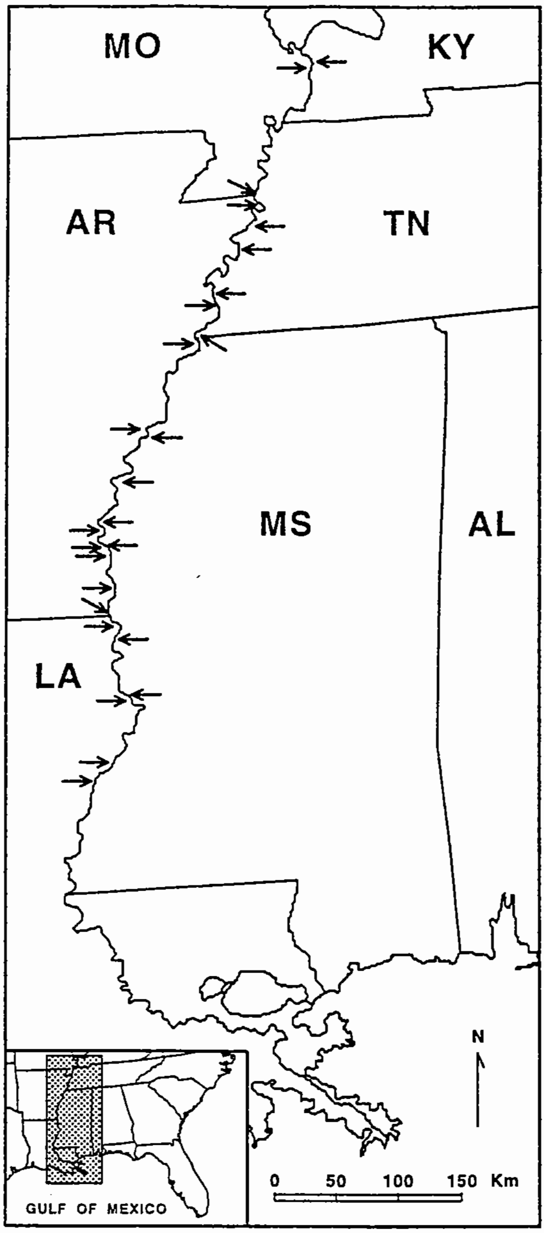

Figure 3. Location of 26 LMR dike fields selected for study.

structures are pervious enough to allow colonization deep below their surfaces, reported macroinvertebrate densities per unit area for the dikes are an order of magnitude greater than for mud substrates in nearby slackwater habitats (Beckett and Pennington, 1986).

A series of studies of LMR ichthyoplankton summarized by Beckett and Pennington (1986) highlight the importance of dike pools to riverine fishes. Species composition of larval fish samples from moving water habitats such as the main channel or lotic side channels was dominated by shad (*Doromosa* spp.), freshwater drum (*Aplodinotus grunniens*), and river carpsucker (*Carpiodes carpio*). Lentic pools within dike

Table 1. Distribution of all LMR dike fields and dike fields selected for study among location categories, %. Study dike fields in parentheses. Row and column sums are not equal to totals due to rounding.

Reach planform	Dike field location				Totals
	Bar	Chute	Main channel	Secondary channel	
Inside bend	7 (4)	12 (8)	1 (0)	16 (24)	35 (35)
Outside bend	0 (0)	0 (0)	2 (0)	4 (4)	6 (4)
Straight	3 (4)	10 (8)	12 (15)	22 (24)	47 (50)
Crossing	0 (0)	1 (0)	7 (4)	5 (7)	12 (12)
Totals	9 (8)	23 (15)	22 (19)	46 (59)	100 (100)

fields had distinctive larval fish assemblages very similar to sloughs and other types of riverine backwaters, supporting high densities of centrarchids and atherinids. Therefore the dike pools serve to replace natural backwater habitats that are slowly being converted to terrestrial habitats by sedimentation. Mouths of flooded tributaries, which serve as alternative nursery habitats in other large rivers like the Ohio, are unavailable along much of the LMR, since confluences are uncommon (Beckett and Pennington, 1986).

Dike pools are also important habitats for adult fish. Studies of LMR dike pools have detected up to 68 species with biomass densities as high as 2000–4000 $\mathrm{kg\,ha^{-1}}$ (Baker *et al.*, 1991). A wide range of fish sizes has been taken from these areas (Baker *et al.*, 1988). These fishery characteristics probably reflect the temporal and spatial heterogeneity of dike pool habitats—a mix containing woody debris, dike structures, lotic and lentic sandbars, eddies, plunge pools, scour holes, etc. (Beckett and Pennington, 1986). Dike pool fish assemblages may be divided into two groups. The first group is composed of species ubiquitous in all LMR habitats, while the composition of the second group varies with river stage from a lotic assemblage at high water to one typical of backwaters at low water (Nailon and Pennington, 1984; Beckett and Pennington, 1986).

Islands and bars within dike fields furnish habitat for birds. Sigrest and Cobb (1987) surveyed 10 dike fields and reported 92 bird species. Migrant swallow and blackbird species comprised 90% of the observed individuals.

In terms of habitat quantity, dike field pools are also significant along the LMR. Baker *et al.* (1991) estimated that pools occupied 8.5% of total LMR aquatic habitat at low river stage, but their definition of pools included low velocity areas downstream of islands and bars as well as regions within dike fields. However, they noted that most of the pool habitat is associated with dike fields. Nunnally and Beverly computed an area for pools and sloughs in diked reaches equivalent to 4.3% of total aquatic habitat at low stage in the reach between RK 515 and RK 1535, while Cobb and Clark (1981) estimated that dike pools comprised 3% of the low-stage aquatic habitat in the reach between RK 772 and RK 853. Since all lentic habitats comprise only about 30% of the total aquatic habitat at low stage (Baker *et al.*, 1991), dike field pools are significant features.

METHODS

A two-part classification system based on reach planform and dike field location was used to classify each of 107 LMR dike fields (Figure 2). The classification system included four reach types and four location types for a total of 16 possible categories. Reach types were straight, inside bend, outside bend, and crossing while locations included bars, secondary channels, main channel, and chutes. Location classification depended on the relationship of the dike field site to river stage: secondary channels carried flow at all stages, chutes carried flow only at higher stages, and bars were entirely terrestrial at low stage. Since river

Table 2. Statistical summary of results, pool area and volume for 26 LMR dike field pools.

Dike field pool variable	Minimum	Maximum	Mean	Standard deviation	Sum
Period of record, yr	4	26	18	6	–
Initial area, ha	54	1299	377	297	9815
Most recent measured area, ha	52	928	313	223	8125
Equilibrium area from regression, ha	52	870	343	227	8930
Initial volume, km^3	1.2	89	18	18	464
Most recent measured volume, km^3	0.25	46	11	10	287
Equilibrium volume from regression[a], km^3	0.00	44	11	10	283

[a] Statistics computed using results of regression except for three time series which were fitted by eye rather than regression. See text for details.

reaches containing dikes often undergo morphological changes following dike and revetment construction, dike fields were classified based on conditions at the time of construction or shortly thereafter.

Twenty-six LMR dike fields were selected for study (Figure 3) which were representative of all LMR dike fields. The distribution of study sites among the location categories was similar to the distribution of the 107 classified dike fields (Table 1). For example, 46% of the 107 existing fields were located in geomorphological settings classified as secondary channels, and 58% of the 26 study sites were in secondary channels. Similarly, 47% of the existing dike fields were in straight reaches, and 50% of the surveyed subset were in straight reaches. The importance of secondary channels is underscored by their area: dike fields classified as secondary channels comprise 40% of the area occupied by existing and proposed dike systems. The study sites also comprised a large fraction of the total LMR dike field habitat. The total pool area and volume (more recent measurements) of the study sites was comparable to that computed by Cobb and Magoun (1985) for all of the dike fields in the LMR reach between RK 515 and RK 982, which is about half of the LMR reach containing dikes.

Dikes in the selected fields were built between 1957 and 1983; 23 of the 26 fields were completed prior to 1975. Sequential hydrographic surveys of each study field were obtained by the US Army Corps of Engineers using standard techniques. These data were used to compute a time series of dike field pool water areas and volumes for each site. Between 5 and 11 surveys (mean = 7) were available for each field, and the mean time between surveys was 3 years.

Dike field pools were delineated on surveys according to criteria specified by Cobb and Magoun (1985). Pool areas were measured in a plane 3 m higher than the river stage historically equalled or exceeded 97% of the time; pool volumes were below this plane. Dike field pool area was the area circumscribed by the bank line, line segments connecting the channelward tips of the dikes, and line segments making a 45° angle from the tip of the first and last dikes in the field to the bank line. In cases where a sandbar extended downstream of the last dike, a chute channel was typically found downstream of the last dike between the middle bar and the bank line. In these cases, the pool boundary line was drawn from the channelward tip of the last dike to the bar to its downstream end; the line was then extended across the mouth of the chute. This approach for defining pool boundaries was intended to provide a standardized, objective way to analyse data that varied strongly in time and space. Based on visual inspection and aerial photographs of large numbers of dike fields, this approach effectively delineated low-velocity habitat in most cases.

Inspection of computed dike pool areas and volumes showed that the most rapid change occurred during the first five years following construction, after which a condition of dynamic equilibrium existed. Since the time series for the 26 sites were of various lengths, regression analyses were used to generate an equilibrium area for each dike field pool. Regression functions of the form:

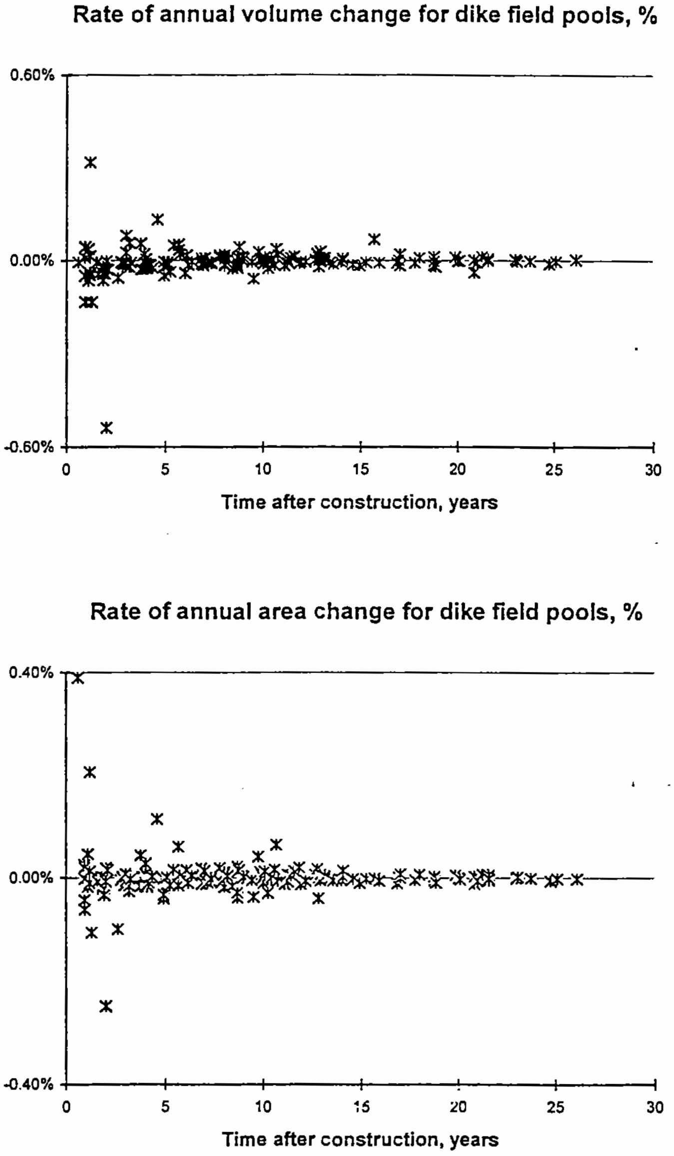

Figure 4. Annual rate of change (%) of dike pool volume and area versus time since dike construction in years.

$$A_t/A_i = A_e/A_i + [1 - A_e/A_i]e^{-Kt} \qquad (1)$$

were fit to each time series, where: A_t is the dike field pool water surface area at time t, A_i the initial dike field pool water surface area (immediately after construction), A_e/A_i the dimensionless equilibrium pool area, K the regression coefficient, and t the time elapsed after construction of the first completed dike in a field in years. Similar regression functions were fitted to the time series of pool volumes.

Although pool sedimentation is driven by stream flow and sediment discharge, elapsed time was used as the independent variable in the regressions for purposes of simplicity. This had minimal impact on the

Table 3. Distribution of initial dike pool volume in km^3 (area in ha) by setting.

	Dike field location				
Reach planform	Bar	Chute	Main channel	Secondary channel	Totals
Inside bend	1 (54)	30 (872)	0 (0)	153 (3419)	185 (4345)
Outside bend	0 (0)	0 (0)	0 (0)	16 (417)	16 (417)
Straight	4 (97)	17 (365)	39 (946)	180 (3036)	239 (4956)
Crossing	0 (0)	0 (0)	2 (64)	22 (545)	23 (609)
Totals	5 (152)	47 (1236)	41 (1010)	371 (7417)	464 (9815)

resultant equilibrium areas because cumulative discharge and elapsed time were highly correlated. Year-to-year variation in cumulative LMR discharge is relatively small—the coefficient of variation of annual discharge was only 23% for the period 1960–1986.

RESULTS

Changes observed in the 26 dike fields are summarized in Table 2. Twenty-one and 12 of the 26 fields declined in volume and surface area, respectively. One field increased in volume (+142%) yet decreased in area (−22%) over the period of record, but eight dike fields showed net increases in pool area while volume decreased. Total net deposition in the 26 dike fields (177 km^3) was equivalent to about 38% of their initial volume. The mean annual rate of volume change was −2.0%. Total surface area of the 26 fields decreased by about 17%, or 1690 ha. The mean annual rate of area change was −1.3%. Most changes in volume and area occurred during the first five years after construction. Annual percentage rates of change are plotted against time after construction in Figure 4. Evidently LMR dike fields undergo an initial period of rapid adjustment, but asymptotically approach a condition of dynamic equilibrium.

The function selected for regression of the pool area time series fitted the observed data well, and the mean standard deviation of residuals for the 26 regressions was only 0.11. Dimensionless equilibrium areas (equilibrium area divided by initial area) averaged 1.02, and 13 were greater than or equal to 1.0. Only one was less than 0.57. Equilibrium areas based on regression were close to the most recently observed measured areas (Table 2).

Regression of volume time series was less successful because pool volumes for three of the 26 sites fluctuated erratically. Regression of these three time series resulted in unrealistic values for dimensionless equilibrium volume (36.92, −1.44 and −1.89). If these values are replaced by more reasonable values based on fitting curves to time series by eye, summary statistics for equilibrium volumes are very close to those for the most recently measured volumes (Table 2).

The distribution of initial pool volume and area among the 16 classifications is shown in Table 3. About 90% of initial pool volume and 87% of initial pool area were located in divided flow reaches ('secondary channel' category) in dike fields that were placed on straight or convex banks. Effects of dike field location on pool sedimentation rates are depicted in Figure 5. Sedimentation rates were most rapid for dike fields constructed on the inside of bends to prevent chute development. These areas have lost about 444 of 872 ha. Dike fields built to force or maintain thalweg crossings exhibited erosion rather than deposition, with total area increasing from 609 ha to 868 ha.

DISCUSSION

These findings confirm hypotheses put forward by Nunnally and Beverly (1986) and the US Army Engineer District, Vicksburg (1976) that most LMR dike fields experience rapid sedimentation during the first few

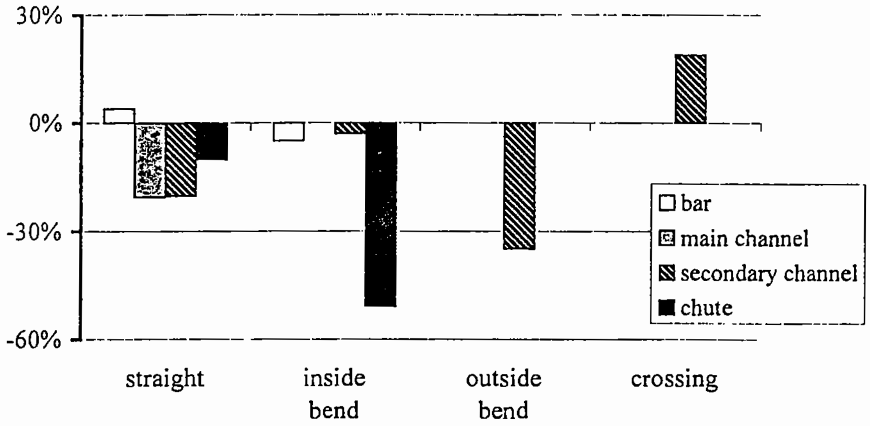

Figure 5. Percentage change in dike pool area for 26 LMR dike fields by dike field classification (Figure 2). An increase in pool area for the only main channel crossing dike field from 64 to 219 ha produced a figure of 243% for that category. This value is not shown on the graph.

years after construction and then fluctuate about a condition of dynamic equilibrium. Similar behaviour has been noted in Middle Mississippi River dike fields (Smith, 1986) and for other types of riverine backwaters adjacent to the main channel (Shields and Abt, 1989). Sediment deposition in LMR dike fields has been less dramatic than for the Missouri River, and this is possibly related to the wide range of river stages (up to 14 m annually) and the relatively low crest elevations of LMR dikes: crests are generally submerged half of the time. Physical model studies summarized by Franco (1967) showed that dike field sedimentation is inversely proportional to dike elevation. Additional factors include the lower historical sediment load in the Mississippi, and bed degradation along the Missouri, which has exacerbated reduction of backwater area.

The ecological value of LMR dike field pools has been documented (Beckett *et al.*, 1983; Conner *et al.*, 1983; Baker *et al.*, 1991), and the importance and value of aquatic habitats associated with stone spur dikes has been established for the Arkansas (Sanders *et al.*, 1985), the Willamette (Li *et al.*, 1984), the Middle Missouri (Atchison *et al.*, 1986), and the Vistula (Backiel and Penczak, 1989) Rivers. Dike pools converted to terrestrial habitats by sedimentation are unlikely to be restored. When dike pools are filled with sediments, riverine habitat quality also declines because highly diverse partially lentic habitat is lost, leaving a more uniform mix of lotic habitat types. Consequently, an overall loss of 17% of initial surface area and 38% of the initial volume of dike pools is of considerable concern. Information presented here could be used to assess and perhaps manage impacts of future dike field construction activities on aquatic habitats.

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ABSTRACT

The papers in this book were presented at the National Conference on Hydraulic Engineering, August, 1988, Colorado Springs, Colorado. The objective of this conference was to provide a forum for discussion and exchange of information on issues related to hydraulic engineering. Discussion areas included sediment transport, open channel and stable channel design, alluvial fan hazards, overland flow and watershed modeling, scour and erosion, hydraulic structures, computational hydraulics, river mechanics, bays and estuaries, and numerical modeling. Papers were also presented that focused on the 50th Anniversary of the Hydraulics Division, ASCE. Papers from a special session on the changing role of the Bureau of Reclamation are also included.

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Effectiveness of Spur Dike Notching

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Introduction

During the last century, river-training structures--dikes and revetments--have been used to stabilize over 3,500 miles (5,600 km) of major waterways in the United States. Dikes are typically placed at an angle to the channel and force the flow toward an opposite bank protected with revetment that roughly parallels the channel. Dikes have been constructed of stone, timber pilings, and metal jacks; revetments have been made of wood mattresses, timber pilings, stone riprap, and articulated concrete. Quarry-run stone is presently the most common material for both dikes and revetments.

Comprehensive channel-training projects have been associated with morphologic changes along the Missouri and Mississippi Rivers. For example, the water surface area of the Iowa portion of the lower Missouri River decreased 34 percent between 1947 and 1976. Changes in lower Mississippi River low-stage water surface area between miles 320.0 and 929.0 during the period of dike and revetment construction (1964-76) were minor. However, the area of bars and islands decreased by 36 percent while the area of isolated dike-field pools increased from 0.21 to 5.37 square miles (54 to 1,390 ha) (Nunnally and Beverly 1986). These changes represent losses in the quantity and diversity of aquatic habitat. However, the dike and revetment structures themselves, and the relatively shallow areas of lowered velocity immediately adjacent to dikes, provide very valuable habitat to the riverine ecosystem (Sandheinrich and Atchison 1986). For example, velocities in the main channel of the study reach of the Missouri River tend to be higher than that preferred by most species of sport fish. However, velocities in the dike fields are only 25 to 35 percent as great (Pennington et al. 1988, Atchison et al. 1986).

In designing and maintaining river-training works, engineers can ameliorate environmental effects using several different techniques (Shields 1984). The most widely employed technique has been to construct notches in spur dikes (or to allow notches to remain in damaged dikes) to prevent sediment accretion below the dike and to develop diverse depth, velocity, and bed material within the dike field conducive to a diverse aquatic community. Despite the fact that over 1,500 notches have been constructed along the Missouri River and several dozen along the Mississippi River, the physical and biological effects are not well documented (Burch et al. 1984). The purpose of this paper is to describe the physical effects of notching several spur dikes along the middle Missouri River.

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Study Area

The dikes studied are in a reach of the Missouri River centered near Omaha, NE, between river miles 517 and 677.5. Flow is controlled by six main stem dams located upstream of the study reach. The channel throughout the study reach is flanked by stone dikes and revetments. Most spur dikes extend less than 100 ft (30 m) into the channel from the present bank line. The hydrology of the river in this reach and the operation of the associated projects are described by Slizeski, Andersen, and Dorough (1982).

The active portion of the channel is very uniform relative to unstabilized rivers, with a near-constant width of 650 ft (200 m) and sinuosity of about 1.2 above Omaha and 1.4 below. Discharges generally range between 25,000 and 35,000 cfs (700 to 990 cu m/sec) during the April through November navigation season, and are held between 6,000 and 20,000 cfs (170 to 570 cu m/sec) during the period December through March. Velocities in the main channel are rather high, ranging from 5 to 7 fps (1.5 to 2.1 m/sec) during navigation-season discharges. Velocities between spur dikes are lower, and small bars of fine-grained sediments sometimes develop there.

Notches were constructed in 20 spur dikes in the study reach during 1982 and 1983. All notches were about 20 ft (6 m) wide at the construction reference plane (CRP) elevation and had invert elevations of about 5 ft (2 m) below the CRP. The CRP is a sloping plane corresponding to water surface elevations for discharge that is equaled or exceeded 75 percent of the time during the navigation season. Stone excavated from each notch was piled approximately 50 ft (15 m) downstream to create a low reef, as shown in Figure 1. Results presented below are from 12 of the 20 dikes: five located below the Platte River confluence (the downstream reach) and seven located upstream of Omaha (the upstream reach).

Data Reduction and Analysis

Detailed, sequential hydrographic surveys were made of areas immediately adjacent to the notched dikes at roughly semiannual intervals beginning just before construction and continuing for 2 to 3 years. The areas surveyed extended from at least 100 ft (30 m) upstream of each dike to 200 ft (60 m) downstream of each dike, and 300 ft (90 m) channelward from the intersection of the dike and the bank line (Figure 2). A boat-mounted Raytheon fathometer was used to sound depths along closely spaced ranges. Data from 12 of the dikes were found to be of sufficient quality for further analysis after initial reduction and screening (Pennington et al. 1988).

Survey data were used as input to a kriging computer routine that interpolated elevations at each node of a grid for each survey. Whenever there were too few points for accurate interpolation, the program generated missing value codes. Surveys with insufficient spatial coverage were removed from the data base. Gridded data were used to create two- and three-dimensional contour plots and to compute the mean and standard deviation of the bed elevation referenced to the CRP.

Figure 1. Aerial View of Notched Dike at Extreme Low Stage Showing Reef just Downstream of Notch. Reef is Normally Submerged. (Photo Courtesy of K. A. Myers, US Army Engineer District, Omaha)

Mean depth and standard deviation of depth were computed for three equal subareas as shown in Figure 2. Areas enclosed by contours at elevations equal to 0, -2, and -4 ft (0, -0.6, -1.2 m) below CRP were measured from the two-dimensional contour plots using a digitizer. Additional details regarding data reduction and analysis are given by Pennington et al. (1988) and Myers (1986).

Results

Riverbed topography near the dikes responded to notching, especially in the downstream reach. The area of dike-field aquatic habitat increased after notching at most of the study dikes. Effects on area at the CRP elevation were minimal, but area enclosed by the -4 ft (-1.2 m) CRP contour substantially increased. Notching changed habitat area little in the upstream reach, but much more in the downstream reach (Table 1).

Depths adjacent to dikes also responded favorably to notching. Mean bed elevations adjacent to the 12 dikes decreased an average of 2.0 ft (0.61 m) after notching (Table 2). Greatest changes in mean bed elevation occurred immediately downstream of notches (subareas B) and in the downstream reach. Bed elevation change in the two subareas downstream of the notch (B and C) was nearly four times greater in the downstream reach than in the upstream reach. Comparison of contour

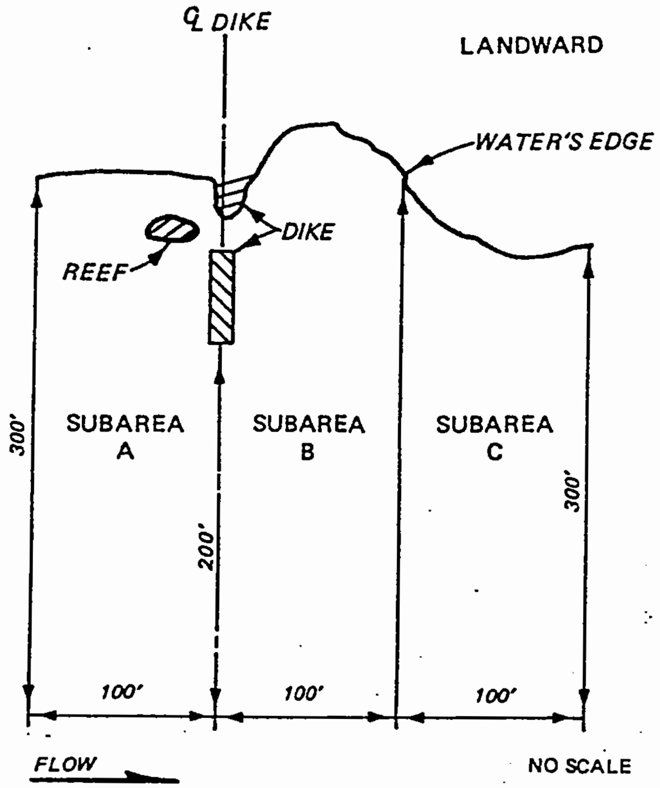

Figure 2. Sketch of Survey Area and Subareas

TABLE 1.--Change in Bed Area Below Indicated Elevation After Notching, in Percent (Acres*)

Location (No. of Dikes)	-4 CRP	-2 CRP	0 CRP
Both reaches (12)	11.2 (1.4)	7.0 (1.0)	3.5 (0.6)
Upstream reach (7)	1.2 (0.1)	-0.7 (-0.1)	-1.3 (-0.1)
Downstream reach (5)	32.1 (1.3)	21.4 (1.1)	12.0 (0.7)

*1 acre = 0.4047 ha.

TABLE 2.--Mean Bed Elevation Change After Notching in Feet (Meters)

Location (No. of Dikes)	Entire Area	Subareas A	B	C
Both reaches (12)	2.0 (0.6)	1.2 (0.3)	3.1 (1.0)	1.7 (0.5)
Upstream reach (7)	1.1 (0.3)	1.1 (0.3)	1.9 (0.6)	0.3 (0.1)
Downstream reach (5)	3.2 (1.0)	1.5 (0.5)	4.7 (1.4)	3.5 (1.1)

plots and standard deviations of depth revealed that bed topography near the dikes became more diverse after notching. The changes described above are based on the difference between the prenotching survey and the most recent survey. Surveys from the intervening period showed some variation, as shown in Figure 3.

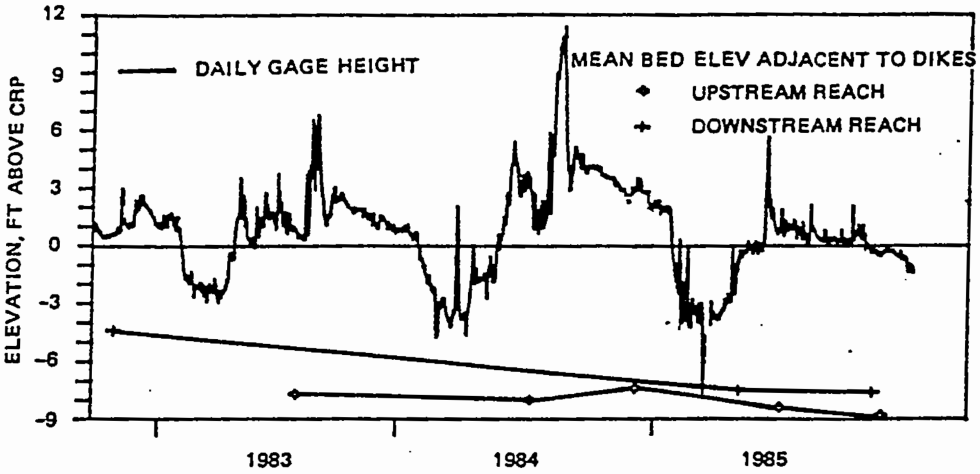

Figure 3. Stage Hydrograph for Missouri River at Blair, NE, and Mean Bed Elevations Adjacent to Notched Dikes. The Fall 1982 Elevation for the Downstream Reach and the Spring 1983 Elevation for the Upstream Reach Represent Prenotching Conditions

Correlation analysis was used to detect association between response variables (changes in area and elevation) and independent geometric variables such as bend radius and channel width. Dimensionless ratios of the variables were used in the analysis. Results were largely inconclusive. The only evident factor governing differential response to notching was the difference in stage hydrographs that was experienced in the upstream and downstream reaches. The downstream reach is influenced by uncontrolled flow from the Platte River and experiences stages that are generally higher relative to CRP and more variable than the upstream reach. Greater depths of flow through the notches would tend to cause more scouring.

Conclusions

Small but important increases in low-velocity channel border habitat can be achieved by an aggressive program of spur dike notching. Habitat response to a specific notch is difficult to predict but is related to the depth of flow through the notch.

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ENVIRONMENTAL GUIDELINES FOR DIKE FIELDS

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ABSTRACT

Dikes have been used to stabilize and train long sections of the Missouri, Mississippi, and other major meandering rivers. Design criteria for dike fields have usually been limited to flood control and navigation objectives. However, recently completed biological field studies have made possible formulation of general dike design criteria based on ecological considerations. As long as dike fields remain aquatic they provide extremely valuable habitat for fish and macroinvertebrates. The crux of the environmental design problem, therefore, is to design dike fields which do not fill with sediment yet still meet river training objectives.

Methods for controlling dike field sediment accretion include varying basic design parameters such as dike length and crest elevation, constructing gaps or notches in dikes, and using dikes which are not attached to the bank. Additional techniques which may be employed to manage existing dike fields include selective repair of failures, dredging deposited sediments, using dredged material to modify habitat, and placing additional rock or other structures underwater to develop aquatic habitat.

Dike notching is presently the most widely employed environmental feature. Although there is some controversy regarding notch effectiveness, the preponderance of presently available biological data favors notching. Most existing notches have been designed based on intuition, but a compilation of experience allows formulation of a more rational approach. A standard notch design should not be used; instead, a range of notch sizes and configurations should be constructed to provide spatial and temporal habitat diversity. Primary design parameters for notches include location (both within a dike field and along the crest of a given dike), shape, width, and depth.

Introduction

Dikes are longitudinal structures placed in waterways to develop and stabilize channels in desirable alignments. Series of dikes are often used to constrict low flows, thus scouring deeper channels and reducing dredging requirements. Dikes have been used widely on major alluvial rivers throughout the United States. Early training works were mainly single or multiple rows of piling clusters connected by stringers, but almost all structures built in the last 20-30 years have

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been continuous embankments,of stone. Training works on most U.S. rivers are nearly complete, and most ongoing work is limited to maintenance and relatively minor additional construction. Dike designs are described by several writers (3, 14, 11). This paper synthesizes available information regarding environmental aspects of dike design. A more extensive treatment is presented by Burch et al. (3).

Hydraulic Effects

Effects of dike field construction on river morphology and hydraulics vary greatly from location to location. For example, the combined effects of reservoirs and training works have converted the lower Missouri river from an extremely dynamic, braided stream with many islands to a single channel with gently sinuous, almost uniform bends. Water surface area has been reduced by 50-70 percent (12, 20). Most of this reduction has been in ecologically valuable backwater and off-channel areas. On the other hand, dikes have caused much smaller change in water surface area along the lower Mississippi (21). The effects of dikes on middle Mississippi River widths and stages have been the topic of lively debate (30 with discussions). Bearing in mind, then, that the nature and magnitude of dike field effects vary from river to river, the following is a cumulative list of effects: bed degradation, increased thalweg depths (32), decreased widths and water surface area at normal and low stages (12, 20, 21, 28), lower stages for low flows, and higher stages for high flows. These effects may be offsetting -- for example, reduction in channel width reduces flow conveyance, but the resultant scour increases conveyance.

On a more local scale, dike fields produce complex patterns of flow and sediment transport. Greatest turbulence occurs in the vicinity of the riverward tips of spur dikes, and teardrop-shaped scour holes develop. When flows just overtop dikes, deep scour also occurs along the downstream faces. Velocities just downstream of dikes are reduced during normal to low flows, allowing finer sediments to be deposited. Bars often form between dikes. When river stage falls below the dike crest elevation, quiescent and near-quiescent conditions develop within and nearby dike fields.

Biological Effects

Dike fields - as long as they remain aquatic - provide habitat in short supply in the "economy" of the riverine ecosystem. Dike structures provide stable, stony, substrate which is rare in most large alluvial rivers, and the resulting density and diversity of benthic macroinvertebrates (fish food organisms) is indeed impressive, especially relative to the adjacent sediments. One lower Mississippi River dike was found to support 2 to 10 times as many taxa of macroinvertebrates with a density of 3 to 4 orders of magnitude greater than adjacent sediments or nearby channel areas (2, 19). Similar findings have been reported for the Missouri and upper Mississippi Rivers (16, 15).

In addition to providing productive substrate, at normal and low stages dikes create areas of low velocity which are valuable habitat for fish, macroinvertebrates, and some wildlife species. Naturally occurring low-velocity habitats such as chutes, sloughs, floodplain lakes, and abandoned channels are extremely diverse and productive, but are often eliminated as rivers are leveed and channelized. Beckett (1) noted the similarity of macroinvertebrate communities found in lower Mississippi River dike fields at low flow (quiescent conditions) to those found in backwaters. Several Missouri River investigators have noted the ecological importance of quiescent waters associated with training structures (25, 31). Studies of several habitat types found along the Missouri and Mississippi Rivers have shown more adult and larval fish species inhabitat dike fields than any other habitat type (5, 7, 22, 33). Dike fields may thus, in a sense, replace the natural backwaters lost due to channelization.

As noted above, long-term effects of river training on riverine hydraulics and morphology in some cases include reductions in total water surface area and backwater area due to stabilization of the channel and sediment accretion around the dikes. Declines in game fishery, commercial fish harvest, fish diversity, and wildlife populations along the Missouri River have been attributed to the construction of training works (12, 13, 18, 20, 26). The effects of dike construction on ecology of other major rivers have not been thoroughly investigated. Investigation is hampered by the lack of pre-dike data and unaltered reaches for comparison and to provide a control.

Environmental Features

Despite the difficulty of quantifying benefits of dike field environmental features, incorporation of environmental considerations into river engineering projects and testing of environmental features is a worthwhile endeavor. Recent findings concerning river ecology, biological responses to environmental features, and the habitat requirements of various fish and wildlife species make possible a more rational, less intuitive approach to environmental feature design. In addition, the advanced stage of most river training projects means that opportunities for modification of river training practices are rapidly diminishing.

Variation of Design Parameters

Dike designers normally must select dike field location, dike plan, crest elevation, crest profile, dike length, the angle of dike with the channel and the sequence of construction for a given reach. Of these parameters, dike field location is probably the greatest determinant of the rate and extent of sediment accretion within the dike field (and thus its lifetime as aquatic habitat), but is less easily manipulated than the other parameters because of constraints imposed by engineering objectives. There is little information presently available regarding the effects of dike design parameters on scour and deposition within the dike field relative to the amount of information available regarding main channel processes.

Franco (1967) reported results of a series of physical model tests of dike design parameter variations. The physical model was a sand-bed model similar to a reach of the lower Mississippi River. Dike fields tested each had three dikes. Although the purpose of the study was to evaluate the ability of various dike designs to develop the navigation channel, it was reported that dike fields with crests sloping riverward and fields with crest elevations stepped up at each successive dike downstream experienced lower within-field deposition than level crested or stepped-down fields.

Franco's work was preliminary and he cautioned against indiscriminate application of his findings to river training design. His results do indicate potential for achieving environmental objectives by varying basic design parameters. In addition to the results noted above, Franco also mentioned the effects of crest elevation and L-heads on within-dike field deposition.

Low Elevation Dikes

Franco observed that the area covered by deposition downstream of the model dikes generally increased with a decrease in length-weighted average dike elevation. Effects of a wide range of crest elevation on the elevation of dike field sediment deposits were not reported. Considerable prototype experience with low elevation dikes is available because of the wide variation in crest elevations employed. Dikes on the upper Mississippi are almost all continuously submerged (impoundments were constructed after the dikes), while some of the dikes on the Missouri River are lower than normal due to degradation or design. In general, lower Mississippi River dikes are overtopped more than middle Mississippi or Missouri River dikes. In some cases, low elevation dikes are built and then raised in subsequent years if necessary to meet river training objectives. Most of the continuously submerged dikes along the upper Mississippi have not filled with sediment, and several investigators have noted their habitat value to fish (10, 23).

L-heads

Franco also tested L-head dikes. The L-heads restricted sediment-carrying bottom currents from moving into the area between the dikes. Flow over the L-head produced scour along the landward face of the trail portion of the dike. The L-head dikes reduced maximum scour at the ends of the dikes and the elevation of deposition between the dikes, compared to the other dike systems modeled. Biological studies along the Missouri River have revealed that small backwaters behind L-head dikes support dense and diverse aquatic communities (5, 27).

Notches

Notches are gaps or indentations in the crests of dikes. Notches may be constructed in new dikes, excavated in existing dikes, or allowed to remain after failure of a portion of a dike. The purposes of designed notches is to allow water to flow through the dike field at intermediate stages to develop or maintain side channels and chutes and prevent additional sediment accretion. Over 1600 dike notches have been constructed along the Missouri River and about 64 have been built in middle Mississippi River dikes. A few notches have been built in upper Mississippi River dikes (some to allow passage of recreational boats), while notches on the lower Mississippi are limited to unrepaired failure notches (3).

Typically, flow through a notch causes a scour hole to develop immediately downstream, and a small bar may form below the scour hole. Missouri River notches have been generally effective in halting or slowing sediment accretion in dike fields. Morphology of the area behind a notched dike is highly variable with time, and thus long periods of observation are required to properly evaluate notch effects. Scour and deposition occur erratically through time depending on hydrographic variations (31). Where notches cause significant increases in dike field current velocities, substrates tend to be coarser and less stable above and below the notch (1, 8, 29).

Most investigators have concluded that dike notches have had beneficial effects on aquatic habitat, either by creating small chutes, submerged bars, and additional aquatic edge or by halting or reducing sediment deposition. However, notch effects are subject to great spatial and temporal variations. Hydrographic variations, dike field design, dike design, and notch design affect performance of notches. Table 2 summarizes biological studies of habitats adjacent to notched dikes.

Notched L-heads

Some of the references in Table 2 report conflicting results of notching L-head dikes. The four notched L-heads in the Missouri River miles 160-179 study area provided more aquatic habitat than similar, unnotched structures but the quality of the habitat was marginal. Habitat diversity was poor and species richness and catch rates were low. Conversely, notched L-heads and revetments in the Missouri River mile 530-565 area provided better habitat than notched spur dikes. Jennings (17) reported the Missouri River notched L-head dikes he studied provided marginal habitat for zooplankton, benthos and fish that was inferior to areas adjacent to notched spur dikes but superior to main channel border. Smith et al. (29) noted that bed samples taken downstream of notched dikes contained more sand than unnotched dikes, but samples taken downstream of notched L-heads contained less sand than those from notched spur dikes. Beckett et al. (1) reported a deep failure notch in a lower Mississippi River L-head dike created undesirable high velocity conditions within the dike field. A shallower notch might have provided more desirable results.

Rootless and Vane Dikes

A few low-elevation rootless dikes have been built between existing dikes in Missouri River dike fields, and there are a few rootless structures along other rivers because of flank failures or increased water levels due to impoundment. Vane dikes are found in some reaches of the Missouri and lower Mississippi. No quantitative information is available regarding effects on habitat. Burke and Robinson (4) reported that inspections and hydrographic surveys around Missouri River rootless dikes indicated the structures have been effective in developing habitat diversity and preventing sediment accretion.

TABLE 2. Results of Biological Studies of Notched Dikes

Survey Area	Effect of Notches[1]	Major Findings and Conclusions	Reference
Missouri River. Channelized and unchannelized reaches in South Dakota, Nebraska, and Iowa. Notched and unnotched dikes.	+	Largest fish catches in the channelized reach came from habitats created at these structures and were similar to catches from backwater and chutes in the unchannelized reach.	18
Missouri River, Missouri. Spur dikes, L-heads, parallel revetments. (All notched.)	+	Chutes below the spur dikes provided better habitat than L-heads. Enclosed pools behind revetments provided valuable habitat.	17
Missouri River miles 168-186. Notched, rootless, or low elevation dikes and high unnotched dike.	0	Most species and number and weight of fish collected at high unnotched dike in slack water. Habitat favorable for fish at all dikes.	25
Missouri River miles 160-179. Notched spur dikes, notched L-heads, notched revetments.	+	Notches maintained and enhanced chute habitats downstream of spur dikes and enclosed pools behind revetments.	24
Missouri River miles 462-476. Notched L-heads and notched revetments.	+	Structures provided habitat for adult fish and nursery areas for young fish. Preservation of low velocity habitat important.	24
Missouri River miles 530-565. Notched spur dikes, notched L-heads, notched revetments.	+	Best habitat in dike fields with diverse depths and velocities, large areas of still water. Notched spur dikes less valuable than other notched structures.	24

(Continued)

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[1] + = Beneficial, 0 = No Effect, - = Detrimental

TABLE 2 (Concluded)

Survey Area	Effect of Notches[1/]	Major Findings and Conclusions	Reference
Missouri River miles 712-704. Notched spur dikes, notched L-heads, notched revetments.	-	Spur dike notches created only high velocity habitat. Revetment notches beneficial by connecting pools behind revetments to the river, allowing fish to enter, spawn, and leave before winter. However, they may increase the rate of sediment deposition.	24
Upper Mississippi River Pool 13. Notched and unnotched spur dikes (submerged). Data before and after notch construction.	-	Benthic macroinvertebrates increased in main-channel border area after notching. No change in side channel benthos or fish. Negative effects (increase in deposition and removal of rock substrate) outweighed positive.	8
Middle Mississippi River miles 95-115. Spur dikes and L-heads (notched and unnotched).	+	Benthic macroinvertebrate diversity higher at notched dikes. No significant difference in fish diversity. Smaller fish at notched dikes. Notches provided habitat diversity.	29
Lower Mississippi River miles 506-566. Unnotched spur dikes and a notched L-head.	-, +	High velocities and sandy, unstable substrate in vicinity of notch. Less benthic macroinvertebrates in vicinity of notch than in other dike fields. Fish diversity slightly greater in dike field with notch.	1, 22

A chute usually develops between a rootless dike and the bank and a low sand bar develops downstream. In some cases rootless dikes have resulted in erosion of the adjacent bankline.

Minimum Maintenance

Flood flows sometimes result in minor damage to dikes such as crest degradation, unraveling channel ends, breaching, or flanking. The lowered and/or irregular crest profiles which result may cause complex flow patterns within the dike fields and improve habitat. If damaged structures remain functionally adequate, it may be advantageous to postpone all or part of the repairs, thus saving money and improving habitat. Some structures (such as old pile dikes) have been routinely allowed to deteriorate and several biological investigators report they are valuable as cover for fish.

Design of Environmental Features

A comprehensive approach to riverine habitat management is recommended over intensive concentration at isolated locations, except when prototype testing is conducted. A comprehensive program should be initiated by conducting a habitat mapping study (6). Goals may then be set for the temporal and spatial distribution and composition of habitat. Composition refers to the breakdown of total acreage among various habitat types (dike field, main channel, natural bank, slough, etc.).

If the results of mapping and goal setting indicate dike field aquatic habitat should be enhanced and/or preserved, the following steps may be followed when designing dike fields:

(1) Evaluate the long-term potential of the dike field as aquatic habitat. The location of dike structures with respect to the thalweg influences the size gradation of sediment deposits and the sediment accretion rate and pattern more than the type or location of notches or other types of structural modification. Location has been observed to be even more important than basic design parameters. Dike fields located in natural depositional zones such as convex bank point bars tend to fill rapidly, while dike fields subject to direct current attack tend to remain open.

(2) Based on the above evaluation, determine if design modifications or environmental features are in order. Dike fields prone to fill rapidly are probably poor candidates for environmental work. However, the preference of many important species for still or slowly-moving water indicates that "depositional" dike fields may provide valuable habitat prior to filling. An ecologically "ideal" dike field would provide still or slowly moving water connected with the main channel at low and intermediate stages, but would scour at high stages.

(3) Consider manipulation of the basic dike design parameters to control the elevation and areal extent of sediment deposition within the dike field. At some sites, longer, lower dikes, L-heads, or vane

dikes might achieve river training goals but produce lower sediment deposits.

(4) Qualitatively project the depths, velocities, and resulting habitat conditions likely to occur in the dike field. Examination of conditions at existing dike fields in similar locations may be helpful.

(5) Consider structural modifications such as notches or rootless dikes.

(6) Consider management techniques such as dredging accumulated sediments, placing dredged material to change flow patterns or form islands, relocation of notches, placing additional stone, constructing reefs and fish attractors, and minimum maintenance.

Notch Design

Although most existing notches were designed based on intuition and professional judgement, a compilation of experience indicates a more rational approach is now possible. A notch designer should first study the design and performance of notches in locations similar to the site in question. If no notches have been constructed in similar situations, perhaps there are a few failure notches. Next, he must determine which dikes to notch. Assuming that dike fields or river reaches that should contain notched structures have been identified during habitat mapping and goal setting, the following criteria should govern selection of specific structures (31):

(1) Notches should not be placed near structures where small amounts of bankline erosion or bed scour might cause problems.

(2) Notches in spur dikes are generally more effective in developing open water than notches in longitudinal dikes.

(3) Notching two adjacent dikes is frequently effective, with the upstream notch and backwater serving as a settling basin for downstream areas.

(4) L-head dikes constructed just upstream from tributary inflows may be notched to prevent sediment buildup at the tributary mouth.

(5) Both notched and unnotched structures provide habitat for distinct assemblages of fish. Therefore, not every dike should be notched.

(6) Experience on the Missouri River indicates selected dikes should be accessible by floating plant and free of sediment deposits, or with only recently accreted sediment deposits free of established vegetation.

(7) If a large number of notches are to be constructed, locations notched first should be those which tend to produce the best habitat. Along the Missouri River, greatest success has been experienced with notches in L-heads or crossing control dikes. Notches in these

locations tend to preserve or develop chutes and enclosed pools. Notches in spur dikes have demonstrated the next highest rate of effectiveness, with longitudinal dikes in the middle of bends third.

After the structures to be notched are identified, the notch should be located on the dike plan and notch dimensions determined. Notches should be far enough from the bankline to prevent flanking problems. The distance from the notch to the riverward tip should be varied from dike to dike to produce diversity. A variety of notch widths, shapes, and depths should be used throughout a reach to provide spatial and temporal habitat diversity. Notches may be either trapezoidal, triangular, or irregular stair-step or saw tooth shapes may be used to develop local habitat diversity. Flow through a triangular notch increases more rapidly with increasing depth than for a trapezoidal notch.

Notches must be wide enough to develop desirable habitat, yet not wide enough to induce damaging erosion, structural failure, or undesirable effects on the navigation channel. Wide notches are less susceptible to debris blockage. For a given notch depth and location, increased width tends to reduce scour downstream of the notch. In general, notch width should be 10-25 percent of the riverward length of the structure, and should increase with dike angle.

Two basic approaches should be used for selecting notch depth: choose a depth that will allow flow almost all the time, or choose a depth that will allow flow only at moderate and high stages, thus providing slack water at low stages. Notch depth should increase with the range of stage fluctuations. Extremely deep notches are effective at developing high velocities and a resultant downstream scour hole. However, once the scour hole is formed, lower velocities and resultant finer-grained substrate are more desirable from a habitat standpoint. In some cases, therefore, it may be advantageous to construct deep, wide notches at first and partially close them after some initial development.

Monitoring

Since there are so many unknowns associated with dike field environmental features and dike design in general, monitoring efforts associated with river stabilization programs should be extended to within dike field phenomena, particularly dike fields with environmental features. Such monitoring will allow estimation of maintenance costs and refinement of design criteria for environmental features. The response of dike field habitat to features such as notches are a function of the subsequent hydrologic record. Therefore, long periods of time (10-20 years) may be required to thoroughly evaluate effects of environmental features.

Conclusions

Dikes and dike fields provide important aquatic habitats along major alluvial rivers developed for navigation. There are several methods for managing, preserving, and enhancing these habitats as dikes are constructed and maintained. Application of recent research findings allows somewhat rational design of dike field environmental features; however, the primitive state of the art and magnitude of potential benefits warrant further investigation.

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