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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

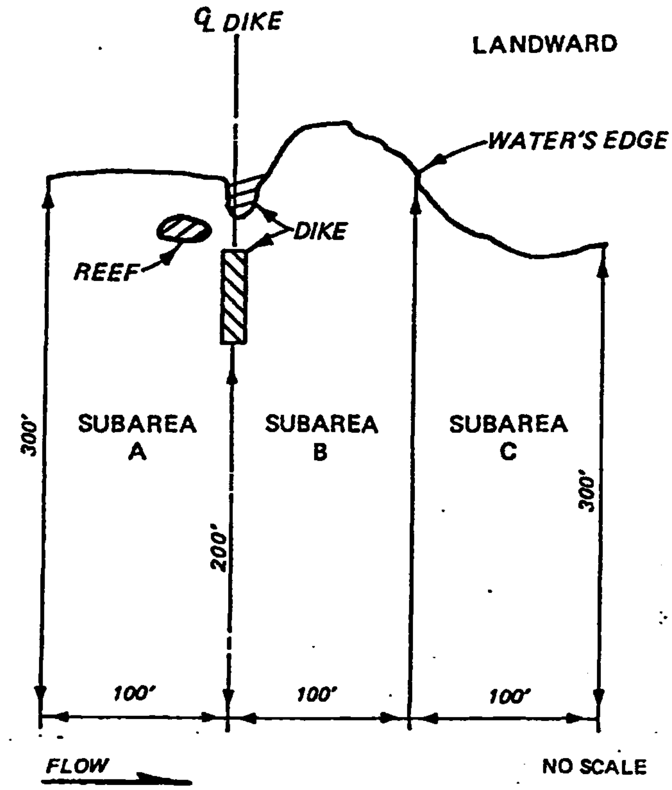

Figure 2. Sketch of Survey Area and Subareas

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	Subareas B	Subareas 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.

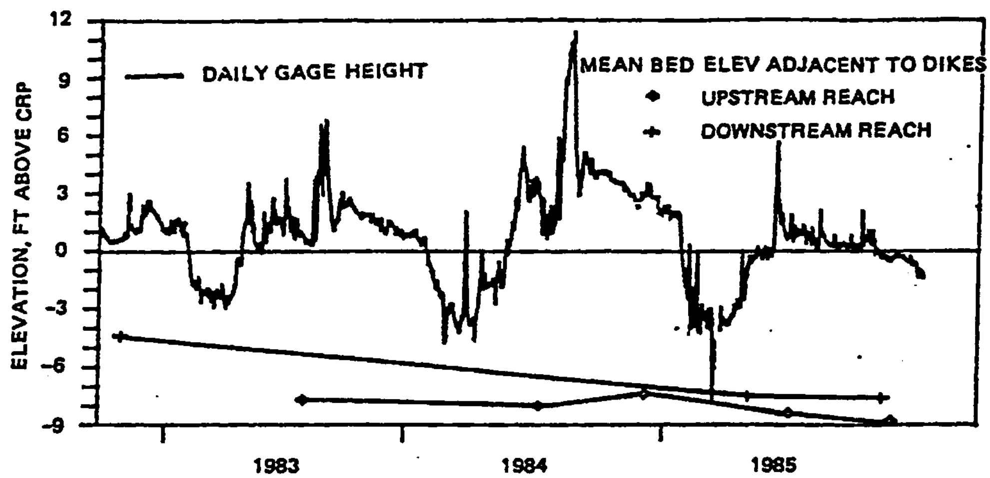

Figure 3. Stage Hydrograph for Missouri River at Blair, NE, and Mean Bed Elevations Adjacent to Notched Dikes. The Fall 1982 Elevation for the Downstream Reach and the Spring 1983 Elevation for the Upstream Reach Represent Prenotching Conditions

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)

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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