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F. D. Shields, Jr.
ARS, USDA
National Sedimentation Lab
P.O. Box 1157
Oxford, MS 38655

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Fate of Lower Mississippi River habitats associated with river training dikes

F. DOUGLAS SHIELDS, JR.
USDA-ARS National Sedimentation Laboratory, PO Box 1157, Oxford, MS 38655-1157, USA

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.

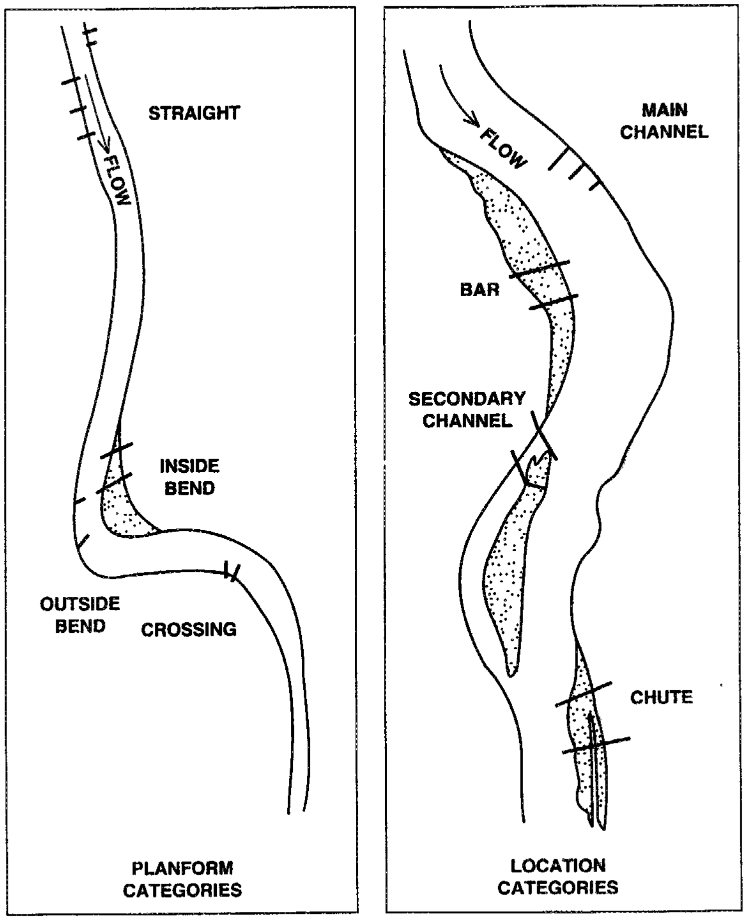


Figure 2. Two-part classification scheme for LMR dike field settings. Each dike field was classified based on the type of reach where it was located, and on the geomorphological feature within the reach upon which the dikes were placed.

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

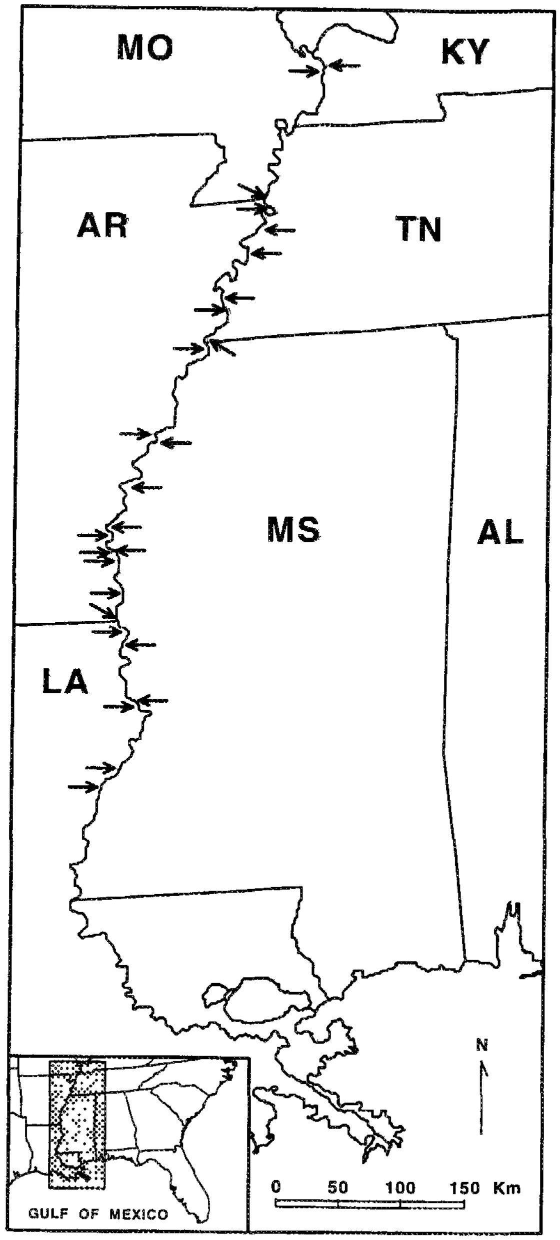


Figure 3 Location of 26 LMR dike fields selected for study.

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 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

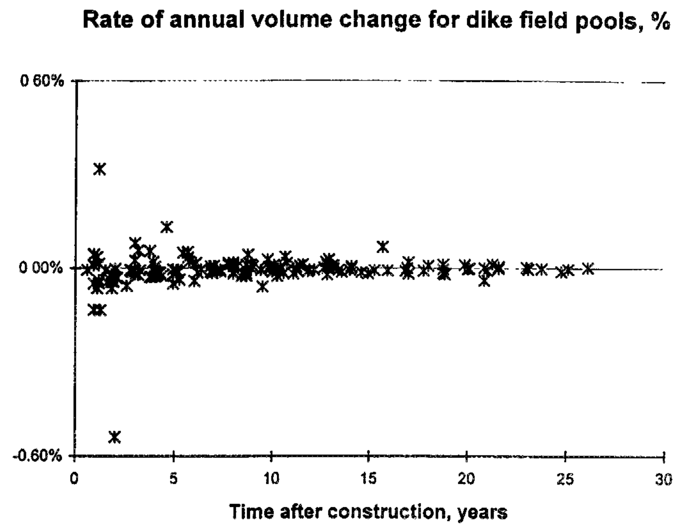
reaches containing dikes often undergo morphological changes following dike and revetment construction, dike fields were classified based on conditions at the time of construction or shortly thereafter.

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:



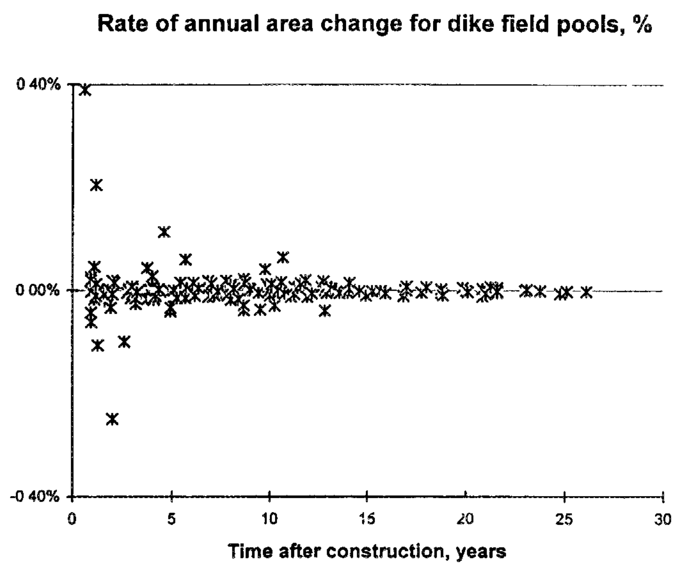


Figure 4. Annual rate of change (%) of dike pool volume and area versus time since dike construction in years.

$$A_t/A_1 = A_e/A_1 + [1 - A_e/A_1]e^{-Kt} \tag{1}$$

were fit to each time series, where: A_t is the dike field pool water surface area at time t, A_1 the initial dike field pool water surface area (immediately after construction), A_e/A_1 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

Reach planform	Dike field location				
	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

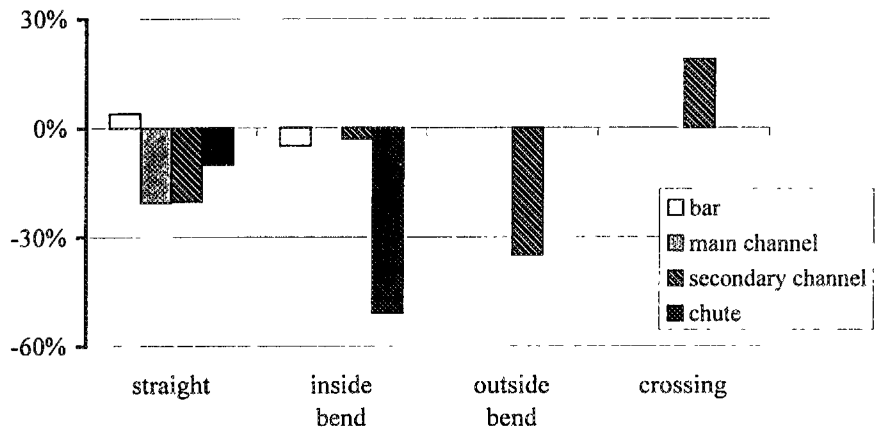


Figure 5. Percentage change in dike pool area for 26 LMR dike fields by dike field classification (Figure 2) An increase in pool area for the only main channel crossing dike field from 64 to 219 ha produced a figure of 243% for that category This value is not shown on the graph.

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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