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AQUATIC HABITAT CHANGE IN THE ARKANSAS RIVER AFTER THE DEVELOPMENT OF A LOCK-AND-DAM COMMERCIAL NAVIGATION SYSTEM

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ABSTRACT

The McClellan–Kerr Arkansas River Navigation System (MKARNS), completed in 1971, required the construction of 17 locks and dams and associated navigation works to make the Arkansas and Verdigris Rivers navigable for barge traffic from the Mississippi River to Catoosa, Oklahoma. We used a Geographic Information System to assess habitat changes in the 477-km portion of this system within Arkansas from 1973 to 1999. Total aquatic area declined by 9% from 42 404 to 38 655 ha. Aquatic habitat losses were 1–17% among pools. Greatest habitat losses occurred in diked secondary channels (former secondary channels with flow reduced by rock dikes) and backwaters adjacent to the main channel. Most of the area of dike pools (aquatic habitat downstream of rock dikes), diked secondary channels and adjacent backwaters were <0.9 m deep. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: aquatic habitat; backwaters; impoundment; navigation; sedimentation; warmwater rivers

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INTRODUCTION

Inland waterways suitable for navigation traversed approximately 40 000 km of lentic and lotic systems in the United States prior to 1976 (Harper, 1978), and recently constructed systems have increased that distance. Throughout most of this distance, sufficient water depth for commercial river traffic is maintained by dams, thereby converting rivers into strings of impoundments (Nielsen *et al.*, 1986). These impoundments greatly expand the river surface area and alter the diversity of aquatic habitats (Tyser *et al.*, 2001). Although initially creating a greater area of aquatic habitat, impoundment contributes to habitat loss due to sedimentation (Nielsen *et al.*, 1986; Sheehan and Rasmussen, 1999).

Sedimentation is a significant threat to off-channel habitats in impounded river systems (Breitenbach and Peterson, 1980; Nielsen *et al.*, 1986). In all rivers, altered and unaltered, sediment-laden flows spread into off-channel areas such as backwaters and floodplain lakes during elevated discharge events. When the current subsides, the sediments settle out. In rivers with unaltered hydrographs the natural cycle of drying of the off-channel areas consolidates and stabilizes the accumulated sediments and promotes vegetation growth in these areas. Sedimentation in off-channel areas often is accelerated in regulated rivers, including rivers altered by navigation impoundments, because normal flows are confined to the navigation channel in an effort to use the hydraulic energy to dredge the channel. Further, the stable water levels necessary to maintain sufficient depth for navigation preclude the drying and subsequent stabilization of the sediments in off-channel areas and further exacerbate the effects of sedimentation (Moyer *et al.*, 1995; Theiling, 1995; Sheehan and Rasmussen, 1999; Schramm, 2004).

Although amounts and rates vary depending on watershed characteristics, geomorphology and hydrology, sedimentation is a natural occurrence in all rivers and fills in the abandoned channels. Unregulated rivers are spatially dynamic; the flows are continuously creating new channels and abandoning old ones and diverse habitat

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persists over time. In many rivers modified for navigation, including the Arkansas River, the channel is 'locked' in its course by engineering structures (*viz.*, dikes and revetments) to control flow patterns. Because no new habitat is created post-impoundment, sedimentation of off-channel habitats in these rivers results, over time, in a loss of aquatic habitat diversity and area. For example substantial losses off-channel habitat area resulting from sedimentation were predicted for the serially impounded upper Mississippi River (Breitenbach and Peterson, 1980; UMRBC, 1982; Gent *et al.*, 1995). More recent studies (WEST Consultants, 2000; Rogala *et al.*, 2003; Theis and Knox, 2003) indicate earlier predictions of sedimentation were exaggerated; nevertheless, sedimentation continues. The consequence of the net loss of off-channel habitat is reduced abundance, or even the loss, of fishes dependent on the off-channel habitat (Bertrand, 1997; Gutreuter, 1997; Schramm, 2004), loss of fishing habitat and reduction in recreational fishing effort. It is important to recognize that not only the area but also the quality of off-channel habitat is important (e.g. Wiener *et al.*, 1998; Winemiller *et al.*, 2000; Schramm, 2004).

The McClellan–Kerr Arkansas River Navigation System (MKARNS), completed in 1971, required the construction of 17 locks and dams and associated navigation works to make the Arkansas and Verdigris Rivers navigable for barge traffic from the Mississippi River to Catoosa, Oklahoma. An additional lock-and-dam was constructed where the MKARNS connects to the Mississippi River in 2004. Within the 477 km Arkansas reach (i.e. Pools 2–13, the portion of the Arkansas River within the state of Arkansas), the associated navigation works included channel alteration to facilitate navigation by commercial shipping and shorten the navigation distance, installation of 1177 rock dikes to direct flows to the navigation channel and reduce flows through secondary channels and bank stabilization with 410 km of rock rip-rap revetment.

The MKARNS converted the entire Arkansas portion of the Arkansas River into a series of impoundments, and substantial recreational fisheries developed in the expansive, lentic aquatic habitat. A 1987 study conservatively estimated 840 000 angler trips and direct expenditures of $1.62 million per year for fishing on the Arkansas River (Limbird, 1993). In 1992, fishing usage was almost 4 million angler days (USACE, 1992). A current estimate of annual economic value, based on statewide estimates and proportion of anglers that primarily fish the Arkansas River, is at least $20 million (Quinn JW, Arkansas Game and Fish Commission, personal communication).

Given the importance of off-channel habitat to many sport fishes (e.g. Schramm and Lewis, 1974; Koel, 2004; Schramm, 2004) and to fishing opportunities and the high likelihood of sedimentation of off-channel habitats, Arkansas Game and Fish Commission fishery managers requested an assessment of changes in aquatic habitat over the approximately 30-year history of the MKARNS. Thus, the first objective of this project was measurement of changes in aquatic habitat areas in the 11 navigation pools of the MKARNS in Arkansas. Habitat quality is also essential to sustain fisheries. Although many factors affect habitat quality, large amounts of excessively shallow water can adversely affect fish populations and angler access and are indicative of sedimentation. Therefore, a second objective was to quantify the areal extent of shallow water in selected habitats.

METHODS

Satellite imagery was selected to estimate aquatic habitat areas because it was readily available for more frequent time intervals and it was less expensive to acquire and use than aerial photography. In planning this assessment, the lower resolution of satellite imagery than aerial photography was considered less important because aquatic habitat area assessments were conducted at spatial scales of entire navigation pools and the entire Arkansas reach of the MKARNS. Satellite imageries for time periods shortly after project completion and recent time periods, rectified to digital ortho quarter quads (DOQQs), were used to construct mosaics of the Arkansas River from Pool 2 to the Arkansas–Oklahoma state line midway in Pool 13. Minimal cloud cover is essential to delineate habitats and, particularly for the purpose of this project, to separate land from water. Within our time frame of concern (1971–2004), 1973 multi-spectral scanner satellite imagery was the earliest and 1999 thematic mapper satellite imagery was the latest that had less than 10% cloud cover, and the 2000–2002 DOQQs were the most recent rectified imagery that met the 90% cloud-free criterion. Satellite imagery from 1973 was obtained from the U.S. Geological Survey EROS Data Center and represented the time period shortly after impoundment. Satellite imagery for 1999 was obtained from the Arkansas Geostor data warehouse (Center for Advanced Spatial Technologies, University of Arkansas, http://www.cast.uark.edu/cast/geostor). The MKARNS was built for navigation and pool levels are maintained relatively stable to provide sufficient depth for navigation. Nevertheless,

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the MKARNS is a river and subject to relatively sudden water-level fluctuations. The pool elevations on the dates of satellite imagery differed by a maximum of 0.31 m between 1973 and 1999. For purposes of our analyses, these pool-level differences were considered to have minimal effects on aquatic habitat areal estimates.

Habitat classification

The mosaics were subjected to unsupervised classification procedures in ERDAS Imagine (Leica Geosystems Geospatial Imaging, LLC, Norcross, Georgia, U.S.). Initially we categorized pixels into 25 spectral classes. Visual comparison of the 25-spectral class imagery with DOQQs indicated that 10 spectral classes were optimal to accurately delineate aquatic and terrestrial habitats.

The classified images were imported into ArcGIS (Environmental Systems Research, Inc., Redlands, California, U.S.; version 9.1) and converted to a polygon data layer. All aquatic habitat polygons were combined into a single polygon. With the aid of river navigation charts (USACE, 2003), this polygon was fractionated into seven confluent aquatic habitat types: main channel, dike pool, open secondary channel, diked secondary channel, slough, adjacent backwater and remote backwater (Table I). The habitat delineation and terminology was based on classifications used by Rasmussen (1979), Baker *et al.* (1991) and Armantrout (1998) with modifications made to best describe the habitats on the Arkansas River. Area of each habitat type in each pool was calculated based on attribute table information accessed through ArcMAP.

Accuracy assessment

Estimating the area of aquatic habitats from satellite imagery depends on assigning a correct habitat type to pixels. Conventional habitat designation accuracy assessment (Lillesand *et al.*, 2004) evaluates the classification accuracy of randomly generated points within each designated habitat type by comparison with the known habitat type; in our case, this meant comparing the habitat designation from unsupervised classification of satellite imagery with aerial photographs. Because our purpose was estimation of aquatic habitat areas, we were particularly concerned about the correct habitat classification of pixels that formed the habitat boundary, especially the aquatic–terrestrial boundary that defined most of the boundaries of the different aquatic habitats. To better assess the accuracy of the habitat boundaries, we assessed the habitat designation accuracy of pixels from the satellite

Table I. Definitions of habitat types used in this report

Habitat type	Definition
Main channel	The present navigation channel where commercial traffic may occur. The main channel extends laterally to the river bank, to an island or to the boundary of a confluent habitat
Open secondary channel	A former river channel lateral to the main channel and separated from it by an island at normal waterway stages
Diked secondary channel	A former river channel lateral to the main channel and separated from it by an island at normal waterway stages. Diked secondary channel, in contrast to open secondary channel, has rock dikes at the upstream end to block or reduce water flow through the secondary channel
Slough	A former river channel lateral to the main channel and separated from it by land at normal waterway stages. Sloughs are not separated from the main channel by dikes, but they are connected to the main channel at only the downstream end. Sloughs have a length at least two times the width
Dike pool	Area downstream of transverse dikes or landward of dikes parallel to the main channel. Dike pools are confluent with the main channel during normal waterway stages
Adjacent backwater	Aquatic areas lateral to the main channel and partially separated from the main channel by land during normal waterway stages. Adjacent backwater habitats are confluent with the main channel at normal river stages
Remote backwater	Backwater areas $\leq$6.0 miles from the channel border and connected to the main channel by a tributary or channel

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imagery in the habitat transition zones (i.e. between land and water or between two different aquatic habitats). Transition zones (termed 'buffer' in ArcMap 9.1) were created that represented a zone with a width 1.5 times the pixel size of the satellite imagery on each side of habitat boundaries on the polygon data layer. This approach concentrated the points for habitat designation accuracy in the portions of the polygon data layer where habitat designation errors that would influence aquatic habitat area were most likely to occur. The modified habitat designation accuracy assessment was conducted separately for each year for a subsample of the pools selected for relatively high habitat diversity. In each pool, 360 points were randomly distributed in the transition zones of prevalent habitat types. We then evaluated the habitat designation accuracy of the randomly generated points in each habitat type by comparison with the 1-m resolution DOQQs to determine omission and commission errors. Omission errors cause an underestimation of habitat area on the satellite imagery maps (e.g. an adjacent backwater habitat point on the aerial photograph is classified as a different habitat on the satellite imagery), whereas commission errors cause an overestimation of habitat area on the satellite imagery maps (e.g. a point in a different habitat in the aerial photograph is classified as an adjacent backwater habitat on the satellite imagery). Omission and commission error rates were multiplied by the transition-zone area for each habitat type to develop upper and lower accuracy intervals for habitat area estimates. These accuracy intervals were interpreted as changes in aquatic habitat area that cannot be attributed to measurement accuracy, such that a change in habitat area with no overlap in accuracy bounds can be expected to be the result of actual change in habitat area and not an artifact of measurement precision, in this case pixel size on the satellite imagery.

Specifically for our analysis, the pixel size was 60-m square in the 1973 satellite imagery and 30-m square in the 1999 satellite imagery; hence, the transition zone of each habitat was 180-m wide on the 1973 polygon data layer and 90-m wide on the 1999 polygon data layer. This analysis was conducted for three of the 11 pools (Pools 2, 6 and 12) of the MKARNS in Arkansas. In each pool, transition zones were established for five prevalent habitat types: main channel, dike pool, open secondary channel, diked secondary channel and adjacent backwater habitats. The transitions zones for the 1973 polygon data layer were compared to DOQQs developed from 1972 aerial photography obtained from the U.S. Army Corps of Engineers and rectified using the 2000–2002 DOQQs. The transition zones for the 1999 polygon data layer were compared to 2000–2002 DOQQs obtained from the Arkansas Geostor. Pool elevations differed by less than 0.21 m between satellite and aerial imagery for the three pools evaluated on both years of comparison, and changes in habitat boundaries associated with differences in pool elevations were considered minor.

The accuracy intervals calculated for the five habitats in the three pools were then used to calculate accuracy intervals for these habitat types in the other eight pools and for the entire Arkansas reach of the MKARNS. For a given habitat type, the upper and lower accuracy intervals were standardized to the area of transition zone for that habitat in that pool to provide upper and lower error rates. The mean of these rates was then used to develop upper and lower accuracy intervals for the remaining eight pools and the entire Arkansas reach of the MKARNS. These mean error rates are actually mean omission and commission error rates weighted for the transition-zone area for each habitat type.

Shallow-water assessment

Fisheries are affected by both aquatic habitat area and quality. The fishery quality of habitats is influenced by numerous variables, but depth is one that is indicative of sedimentation, affects habitat suitability for fish and anglers and is amenable to spatial analysis. Areas of shallow ($\leq$0.9 m) and deep ($>$0.9 m) water in dike pool and off-channel habitats were calculated for Pools 2–12. The choice of 0.9 m to separate shallow and deep habitats was arbitrary but based on the assumption that 0.9 m is a depth that allows boat access and that many anglers consider sufficient for fishing. Using a boat-mounted depth recorder with GPS mapping capabilities (Lowrance X-15; Lowrance, Tulsa, Oklahoma, U.S.) the 0.9-m depth contour in each site classified as dike pool, open secondary channel, diked secondary channel or adjacent backwater habitat was navigated and recorded during the summer and autumn, 2005. For each site, the 0.9-m depth contour was transferred to the rectified 1999 Arkansas River mosaic, area of deep water was calculated by ArcMAP and that area was subtracted from the site area on the 1999 Arkansas River mosaic to determine percentage of shallow-water area for each habitat type.

Table II. Habitat designation accuracy assessment of 1973 satellite imagery

Satellite imagery habitat designation	Aerial photography habitat designation						Commission error (%)
	Main channel	Dike pool	Diked secondary channel	Adjacent backwater	Dry land	Total points	
			Pool 2				
Main channel	74	0	0	0	11	85	12.9
Dike pool	0	17	0	0	8	25	32.0
Diked secondary channel	0	0	26	0	3	29	10.3
Adjacent backwater	0	0	0	40	11	51	21.6
Dry land	17	1	5	7	140	170	17.6
Total points	91	18	31	47	173	360	
Omission error (%)	18.7	5.6	16.1	14.9	21.6		
Overall accuracy							82.5
K-hat							0.74
			Pool 6				
Main channel	86	0	0	0	8	94	8.5
Dike pool	0	19	0	0	3	22	13.6
Diked secondary channel	0	0	34	0	4	38	10.5
Adjacent backwater	0	0	0	15	3	18	16.7
Dry land	4	2	6	11	165	188	12.2
Total points	90	21	40	26	183	360	
Omission error (%)	4.4	9.5	17.6	42.3	9.8		
Overall accuracy							88.6
K-hat							0.82
			Pool 12				
Main channel	89	0	0	0	9	98	9.2
Dike pool	0	11	0	0	2	13	15.4
Diked secondary channel	0	0	19	0	1	20	5.0
Adjacent backwater	0	0	0	57	3	60	5.0
Dry land	1	0	4	16	148	169	12.4
Total points	90	11	23	73	163	360	
Omission error (%)	1.1	0	17.4	21.9	9.2		
Overall accuracy							90.0
K-hat							0.85

RESULTS

Habitat designation accuracy

In 1973, the habitat designation accuracy ranged from 82.5 to 90.0% (K-hat = 0.74–0.85) among the three pools (Table II). Dike pool was the aquatic habitat most often overestimated and diked secondary channel and adjacent backwater were the aquatic habitats most often underestimated. In 1999, habitat designation accuracy was 86.4–88.9% (K-hat = 0.80–0.85) among the three individual pools (Table III). Dike pool, diked secondary channel and adjacent backwater tended to be overestimated and dry land underestimated.

Changes in aquatic habitat area

Total surface area of the Arkansas reach of the MKARNS decreased from 42 404 ha in 1973 to 38 655 ha in 1999, which represented a total aquatic habitat loss of 3748 ha (8.8% of the 1973 area) in 26 years[1] (Table IV). Total aquatic area decreased in all pools. The greatest aquatic habitat loss was in Pool 10 (826 ha), and aquatic area losses

[1]Habitat maps are available from the corresponding author.

Table III. Habitat designation accuracy assessment of 1999 satellite imagery

Satellite imagery habitat designation	Aerial photography habitat designation						Total points	Commission error (%)
	Main channel	Dike pool	Open secondary channel	Diked secondary channel	Adjacent backwater	Dry land		
Pool 2								
Main channel	82	0	0	0	0	9	91	9.9
Dike pool	0	16	0	0	0	7	23	30.4
Diked secondary channel	0	0	0	20	0	5	25	20.0
Adjacent backwater	0	0	0	0	42	23	65	35.4
Dry Land	2	1	0	0	2	151	156	3.2
Total points	84	17	0	20	44	195	360	
Omission error (%)	2.4	5.9	0.0	0.0	4.6	22.6		
Overall accuracy (%)							86.4	
K-hat							0.80	
Pool 6								
Main channel	84	0	0	0	0	2	86	2.3
Dike pool	0	30	0	0	0	2	32	6.3
Diked secondary channel	0	0	0	38	0	7	45	15.6
Adjacent backwater	0	0	0	0	25	7	32	21.9
Dry land	6	7	0	5	4	143	165	13.3
Total points	90	37	0	43	29	161	360	
Omission error (%)	6.7	18.9	0	11.6	13.8	11.2		
Overall accuracy							88.9	
K-hat							0.84	
Pool 12								
Main channel	76	0	0	0	0	11	87	12.6
Dike pool	0	11	0	0	0	7	18	38.9
Open secondary channel	0	0	10	0	0	0	10	0
Diked secondary channel	0	0	0	43	0	13	56	23.2
Adjacent backwater	0	0	0	0	58	6	64	9.4
Dry land	1	1	0	0	2	121	125	3.2
Total points	77	12	10	43	60	158	360	
Omission error (%)	1.3	8.3	0	0	3.3	23.4		
Overall accuracy							88.6	
K-hat							0.85	

exceeded 400 ha in Pools 9 and 12. Relative aquatic habitat loss (calculated as a percentage of 1973 area) was greatest in Pool 12 (16.8%), and losses greater than 10% of total aquatic area were measured in Pools 6, 7, 9 and 13.

The main channel decreased 1150 ha (4.3%) throughout the Arkansas reach (Table IV), but the main channel increased from 62.9% of total aquatic area in 1973 to 66.0% in 1999. Changes in main channel area ranged from a gain of 104 ha in Pool 5 to a loss of 818 ha in Pool 10; six of the seven downriver pools (Pools 3–8) gained main channel area, and the four upriver pools (Pools 9–13) lost main channel area. Loss of area exceeded the area attributed to measurement accuracy (i.e., the accuracy bounds did not overlap) in Pool 9.

Dike pool habitat decreased 319 ha (29.1%) from 1973 to 1999 (Table IV). Relative to dike pool area in 1973, dike pool area increased 20.8% in Pool 2 and 100% in Pool 5 and decreased 2.0–100% in the other nine pools. Loss of dike pool area exceeded the area attributed to measurement accuracy in Pools 8, 9, 10 and 12.

Collectively, the off-channel habitats declined by 2279 ha (15.6%) from 1973 to 1999 (Table IV). The area of off-channel habitat increased 0.4% in Pool 10 but decreased 18.3–38.8% among the other 10 pools. Area losses of combined off-channel habitats exceeded 200 ha in Pools 2, 4, 5, 7 and 12.

Except for Pool 8, diked secondary channel and adjacent backwater habitats comprised most (78.7–100%) of the off-channel zone area in 1973 (Table V). Area of diked secondary channels decreased 23.0% reach-wide and

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Table IV. Areas (ha) of main channel, dike pool and combined off-channel habitats in the Arkansas reach of the Arkansas River estimated from satellite imagery in 1973 and 1999

Pool	Main channel			Dike pool			Off-channel			Total			
	1973	1999	Area change	1973	1999	Area change	1973	1999	Area change	1973	1999	Area change	Percentage change
2	2557 (2249–3002)	2523 (2406–2552)	−33	149 (0–178)	180 (62–203)	31	1401	1060	−341	4106	3763	−343	−8.4
3	1161 (1056–1247)	1239 (1193–1258)	79	52 (19–60)	29 (13–36)	−23	327	251	−76	1540	1520	−21	−1.3
4	1292 (1175–1379)	1363 (1312–1383)	71	38 (14–44)	24 (11–30)	−15	1250	982	−268	2580	2368	−211	−8.2
5	1349 (1227–1471)	1452 (1398–1506)	104	38 (14–44)	76 (34–94)	38	1206	946	−260	2592	2474	−118	−4.6
6	1201 (1109–1248)	1218 (1206–1253)	17	182 (117–227)	108 (94–152)	−73	619	425	−193	2001	1752	−250	−12.5
7	2384 (2169–2561)	2474 (2381–2512)	90	218 (80–250)	79 (35–98)	−139	1142	802	−340	3744	3354	−389	−10.4
8	1250 (1137–1343)	1341 (1291–1361)	90	**5** (2–6)	**0**	−5	482	295	−187	1737	1636	−101	−5.8
9	**2417** (2199–2596)	**2072** (1995–2104)	−344	**9** (3–10)	**0**	−9	567	463	−104	2993	2535	−457	−15.3
10	9003 (8190–9671)	8185 (7880–8310)	−818	**31** (11–36)	**0**	−31	5349	5371	22	14 382	13 356	−826	−5.7
12	2727 (2524–2751)	2477 (2340–2492)	−249	**169** (96–169)	**79** (11–94)	−89	1771	1324	−447	4667	3881	−786	−16.8
13	1335 (1214–1434)	1180 (1136–1198)	−155	205 (75–2.35)	201 (90–249)	−4	522	436	−86	2062	1816	−245	−11.9
All	26 674 (24 266–28 653)	25 524 (24 573–25 914)	−1150	1095 (400–1257)	776 (347–961)	−319	14 634	12 355	−2279	42 404	38 655	−3748	−8.8

Off-channel habitat areas are the combined areas of open secondary channel, diked secondary channel, slough, adjacent backwater and remote backwater habitats. Values in parentheses are accuracy bounds. Areas in bold indicate a change in area from 1973 to 1999 that exceeds the accuracy bounds (i.e. the accuracy bounds for 1973 and 1999 do not overlap).

Table V. Areas (ha) of off-channel habitats in the Arkansas reach of the Arkansas River estimated from satellite imagery in 1973 and 1999

Pool	Diked secondary channel			Adjacent backwater			Slough			Remote backwater		
	1973	1999	Change	1973	1999	Change	1973	1999	Change	1973	1999	Change
2	**386** (315–496)	**279** (208–279)	−106	1016 (676–1250)	781 (512–816)	−234	0	0	0	0	0	0
3	117 (103–144)	101 (80–105)	−16	130 (95–199)	120 (89–131)	−10	80	31	−49	0	0	0
4	**1250** (1099–1539)	**982** (781–1021)	−268	0	0	0	0	0	0	0	0	0
5	**1158** (1018–1426)	**913** (726–949)	−245	**48** (35–74)	**32** (24–35)	−15	0	0	0	0	0	0
6	**499** (439–599)	**308** (259–344)	−191	120 (72–241)	118 (81–141)	−2	0	0	0	0	0	0
7	333 (293–410)	335 (267–348)	2	**809** (589–1239)	**467** (348–511)	−342	0	0	0	0	0	0
8	**237** (208–292)	**162** (129–168)	−75	0	0	0	245	133	−112	0	0	0
9	484 (425–596)	441 (351–458)	−43	**13** (9–20)	**7** (5–8)	−5	71	15	−56	0	0	0
10	**359** (316–442)	**284** (226–295)	−75	4410 (3213–6755)	4523 (3367–4946)	113	0	0	0	580	564	−16
12	**721** (679–869)	**493** (395–493)	−228	**1050** (965–1422)	**729** (650–757)	−321	0	0	0	0	0	0
13	**361** (317–444)	**246** (196–256)	−115	135 (98–207)	155 (115–169)	20	0	0	0	26	35	9
All	**5904** (5190–7269)	**4544** (3615–4723)	−1360	7729 (5631–11 838)	6932 (5160–7580)	−797	396	179	−217	605	599	−6

Values in parentheses are accuracy bounds. Areas in bold type indicate a change in area from 1973 to 1999 that exceeds the accuracy bounds (i.e. the accuracy bounds for 1973 and 1999 do not overlap).

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decreases ranged from 8.8 to 38.4% among the pools; only Pool 7 had a gain (0.7%) in area. Loss of diked secondary channel area exceeded the area attributed to measurement accuracy in all pools except 3, 7 and 9.

Adjacent backwater area decreased 10.3% reach-wide. Adjacent backwater habitat was not present in Pools 4 and 8; among the other nine pools, area increased 2.6 and 14.9% in Pools 10 and 13 and decreased 1.7–43.2% in seven pools. Decreases in adjacent backwater area exceeded the accuracy bounds in Pools 5, 7, 9 and 12.

Slough habitat was present in only three pools and remote backwater habitat was present in two pools. Together, these habitat types comprised approximately 2% of the total aquatic habitat area in 1973 and 1999 (Table V), and most of this area was remote backwater habitat in Pool 10. Substantial losses in slough habitat occurred in the three pools where this habitat was present. A small loss of remote backwater habitat was measured in Pool 10, and the area of this habitat type increased in the Arkansas portion of Pool 13.

Only one area of open secondary channel was recognized and this area was present only in 1999 as a result of a sandbar that formed in the main channel after 1973. This habitat was located in Pool 12 and had an area of 102 ha.

Shallow-water area

Among pools, water less than 0.9-m deep (shallow water) was 61–100% of the dike pool habitat area (Table VI). Shallow water was 43–97% of the diked secondary channel habitat area. In contrast, only 27% of the single open secondary channel was less than 0.9-m deep. Shallow water was 38–100% of the adjacent backwater habitat area.

DISCUSSION

Approximately 9% of aquatic habitat has been lost throughout the 477 km Arkansas reach of the MKARNS during the 26-year period beginning 2 years after full operation of the lock-and-dam system. Habitat loss varied among pools with losses exceeding 10% of the aquatic habitat area in five of the seven upstream pools. Habitat loss also varied among habitats, with greatest losses occurring in the dike pool, diked secondary channel, slough and adjacent backwater habitats. Dike pool, diked secondary channel and adjacent backwater habitats were present in most pools in 1973 and areal losses of these habitats occurred throughout the Arkansas reach of the MKARNS.

Sedimentation is a common problem in rivers impounded for navigation (Nielsen *et al.*, 1986), and off-channel habitat losses similar to those in the Arkansas River have occurred in other rivers similarly modified for navigation by impoundment. In the upper Mississippi River, 29 locks and dams were installed throughout 1075 km of river from 1885 to the 1930s. Impoundment initially increased the area of aquatic habitat by 54%, but within 35 years

Table VI. Total area (ha) and percentage of area $\leq$ 0.9-m deep in dike pool, open secondary channel, diked secondary channel and adjacent backwater habitats in Arkansas River navigation pools in 2005

Pool	Dike pool		Open secondary channel		Diked secondary channel		Adjacent backwater	
	Area	Per cent area	Area	Per cent area	Area	Per cent area	Area	Per cent area
2	180	83.5	NP		279	75.1	781	38.7
3	29	99.3	NP		101	53.9	120	99.7
4	24	89.6	NP		982	49.8	NP	
5	39	60.7	NP		949	64.2	32	57.7
6	108	74.5	NP		308	42.6	118	55.7
7	34	71.9	NP		349	73.5	467	70.2
8	NP		NP		162	66.0	NP	
9	NP		NP		441	97.4	7	58.2
10	NP		NP		284	92.8	4523	56.2
12	79	100.0	102	27.2	493	52.7	729	69.7

NP indicates habitat not present.

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after impoundment, the upper Mississippi River lost approximately 25% of its off-channel habitat (UMRBC, 1982). Several early studies forecast extensive loss of off-channel habitat by year 2000 (Simons *et al.*, 1974; Bade, 1980) and Breitenbach and Peterson (1980) predicted almost all backwaters would be dry land within 2 centuries. Although more recent assessments indicate less habitat loss than earlier predicted, they also predict continued habitat loss and 2–4% additional loss of backwater habitat area by 2050 (WEST Consultants, 2000). Although not quantified, extensive losses of off-channel habitat have occurred in the Tennessee–Tombigbee Waterway, a serial lock-and-dam navigation system in northeast Mississippi and southwest Alabama similar to the MKARNS, during the first 20 years after project completion (Hubbard WD, Mississippi Department of Wildlife, Fisheries and Parks, personal communication), and many off-channel habitats continue to fill with sediment (Pugh LL, Mississippi Department of Wildlife, Fisheries and Parks, personal communication). Although sedimentation rates and patterns in other serially impounded river systems will be affected by sediment inputs and hydrology, our results and similar results and observations in other systems forecast substantial loss of off-channel aquatic habitat in serially impounded river systems.

Substantial portions of dike pool, diked secondary channel and adjacent backwater habitats were less than 0.9-m deep. Information was not available to determine sedimentation rates or changes in depth of these habitats since 1973, so it is not possible to conclude that these habitats have changed over time. Nevertheless, the high proportions of shallow water comport with loss of aquatic habitat area and also suggest a vulnerability of these habitats to future sedimentation.

The specific consequences of changes in off-channel habitat have received only limited study (e.g. Sheehan *et al.*, 1990; Bodensteiner and Lewis, 1992; Pitlo, 1992; Knights *et al.*, 1995), but the life histories of many of the fishes prevalent in rivers in the Mississippi River Basin are sufficiently well understood to allow general predictions about the effects of loss of off-channel habitats. Off-channel habitats are productive areas in river ecosystems and are essential for one or more life stages of many species (e.g. Christenson and Smith, 1965; Schramm and Lewis, 1974; Rasmussen, 1979; Holland, 1986; Sheaffer and Nickum, 1986; Grubaugh and Anderson, 1988). Of 137 resident species in the Mississippi River for which sufficient biological information was available to determine habitat requirements, none are expected to reside in the main channel throughout their life cycle, 24 are expected to occupy channel border habitats throughout their life cycle, 50 are expected to reside in one or more backwater habitats throughout their life cycle and 55 require backwater habitats during one or more life stages (Schramm, 2004). Off-channel habitats also support high fish biomass (Schramm, 2004). The consequences of loss of off-channel habitat in the Mississippi River are apparent. Limbird (1993) reports 106 fish species in the Arkansas River in Arkansas, 99 of which also occur in the Mississippi River. Of those 99 species, 44 were categorized as backwater dependent by Schramm (2004). Therefore, a large proportion of the Arkansas River fishes benefit from or depend on off-channel habitats and these fishes can be expected to be adversely impacted if off-channel habitats decline. Furthermore, the ecological value of these habitats is reduced as sediment accumulates (e.g. McHenry *et al.*, 1984; Bhowmik and Adams, 1989; Gent *et al.*, 1995; Knights *et al.*, 1995).

Losses of these habitats can be expected to adversely affect recreational fishing due, directly, to reductions in the area of habitats where anglers fish (Groen and Schmulbach, 1978; Nielsen *et al.*, 1986) and, indirectly, to declines in quantity and quality of sport fishes. The large extent of shallow water also impedes access, thereby diminishing the use of these areas to recreational fishing.

We suggest that these estimates of aquatic habitat area will provide useful baselines for measuring the extent and rate of future habitat changes in the Arkansas reach of the MKARNS. These habitat measurements may also be useful for evaluating relationships between habitat conditions and changes in the fish fauna or population variables that, in turn, may provide insight into effects of habitat change and guidance for habitat management of the Arkansas River and similarly altered systems.

Methodological considerations

Spatial analysis employing satellite imagery is facilitated by the availability of relatively low-cost data. However, the precision of the data (±30 m for recent satellite imagery) is substantially less than for aerial photography (±1 m). Habitat designation accuracy was generally greater than 86% at the pool spatial scale and is probably sufficient for detecting long-term changes in habitat area at the spatial scale of entire pools or larger.

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This aquatic habitat assessment afforded the opportunity to compare aerial photography with satellite imagery. We encountered difficulties with satellite imagery determining the presence of some aquatic habitats, aquatic habitats boundaries, connections of off-channel aquatic habitats with the main channel and whether some aquatic areas (e.g. a fish farm) were actually part of the MKARNS. Furthermore, structures important for habitat designation, such as above-water rock dikes, were not present on satellite imagery. Therefore, we recommend that future assessments of aquatic habitat at the pool-level and smaller spatial scale use aerial photography or high-resolution multi-spectral imagery.

An additional issue in spatial analysis of aquatic habitat is the effect of water level on aquatic habitat area. Depending on the aquatic system, these fluctuations range from centimetres to metres and the changes may be daily, seasonal or multi-annual. Because we used available imagery, we were fortunate that the pool elevations differed by a maximum of 0.31 m between 1973 and 1999 and by a maximum 0.21 m between satellite imagery and the aerial imagery used for accuracy assessment. Although adjustments are possible for imagery obtained at different water surface elevations, all will be constrained by lack of high-resolution bathymetry. The simple solution is to coordinate flight schedules with water elevations.

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REFERENCES

Armantrout NB. 1998. *Glossary of Aquatic Habitat Inventory Terminology.* American Fisheries Society: Bethesda, MD.

Bade G. 1980. *Great River Environmental Action Team: Side Channel Work Group Appendix.* U.S. Fish and Wildlife Service: Rock Island, IL.

Baker JA, Killgore KJ, Kasul RL. 1991. Aquatic habitats and fish communities in the Lower Mississippi River. *Reviews in Aquatic Sciences* **3**: 313–356.

Bertrand BA. 1997. Changes in the Mississippi River fishery along Illinois. *Journal of Freshwater Ecology* **12**: 585–597.

Bhowmik NG, Adams JR. 1989. Successional changes in habitat caused by sedimentation in navigation pools. *Hydrobiologia* **176/177**: 17–27. DOI:10.1007/BF00026540

Bodensteiner LR, Lewis WM. 1992. Role of temperature, dissolved oxygen, and backwaters in the winter survival of freshwater drum (*Aplodinotus grunniens*) in the Mississippi River. *Canadian Journal of Fisheries and Aquatic Sciences* **49**: 173–184.

Breitenbach R, Peterson G. 1980. *Fish and Wildlife Management Work Group Appendix.* GREAT II. Great River Environment Action Team: Rock Island, IL.

Christenson LM, Smith LL. 1965. *Characteristics of Fish Populations in Upper Mississippi River Backwater Areas.* U.S. Fish and Wildlife Service, Circular 212: Washington, DC.

Gent R, Pitlo J, Boland T. 1995. Largemouth bass response to habitat and water quality rehabilitation in a backwater of the Upper Mississippi River. *North American Journal of Fisheries Management* **15**: 784–793. DOI:10.1577/1548-8675(1995)015<0784:LBRTHA>2.3.CO;2

Groen CL, Schmulbach JC. 1978. The sport fishery of the unchannelized and channelized middle Missouri River. *Transactions of the American Fisheries Society* **107**: 412–418. DOI:10.1577/1548-659(1978)107<412:TSFOTU>2.0.CO;2

Grubaugh JW, Anderson RV. 1988. Spatial and temporal availability of floodplain habitat: long-term changes at Pool 19, Mississippi River. *The American Midland Naturalist* **119**: 402–411. DOI:10.2307/2425823

Gutreuter S. 1997. *Fish Monitoring by the Long Term Resource Monitoring Program on the Upper Mississippi River System.* U.S. Fish and Wildlife Service, Environmental Management Technical Center: Onalaska, WI.

Harper DV. 1978. *Transportation in America: Users, Carriers, Government.* Prentice Hall: New York.

Holland LE. 1986. Distribution of early life history stages of fishes in selected pools of the Upper Mississippi River. *Hydrobiologia* **136**: 121–130. DOI: 10.1007/BF00051509

Knights BC, Johnson BL, Sandheinrich MB. 1995. Responses of bluegills and black crappies to dissolved oxygen, temperature and current in backwater lakes of the upper Mississippi River during winter. *North American Journal of Fisheries Management* **15**: 390–399. DOI:10.1577/1548-8675(1995)015<0390:ROBABC>2.3.CO;2

Koel TM. 2004. Spatial variation in fish species richness of the Upper Mississippi River system. *Transactions of the American Fisheries Society* **133**: 984–1003. DOI:10.1577/T03-089.1

Lillesand TM, Kiefer RW, Chipman JW. 2004. *Remote Sensing and Image Interpretation* (5th edn). John Wiley and Sons, Inc.: Hoboken, New Jersey.

Limbird RL. 1993. The Arkansas River; a changing river. In *Restoration Planning for the Rivers of the Mississippi River Ecosystem*, Hesse LW, Stalnaker CB, Benson NB, Zuboy JR (eds). National Biological Survey: Washington, D.C.; 81–94.

McHenry JR, Ritchie JC, Cooper CM, Verdon J. 1984. Recent rates of sedimentation in the Mississippi River. Weiner JG, Anderson RV, McConville DR (eds). *Contaminants in the Upper Mississippi River.* Butterworth Publishers: Stoneham, MA; 99–117.

Moyer EJ, Hulon MW, Sweatman JJ, Butler RS, Williams VP. 1995. Fishery responses to habitat restoration in Lake Tohopekaliga, Florida. *North American Journal of Fisheries Management* **15**: 591–595. DOI:10.1577/1548-8675(1995)015<0591:FRTHRI>2.3.CO;2

Nielsen LA, Sheehan RJ, Orth DJ. 1986. Impacts of navigation on riverine fish production in the United States. *Polish Archives of Hydrobiology* **33**: 277–294.

Pitlo J Jr. 1992. *Mississippi River Investigations.* Iowa Department of Natural Resources, Federal Aid in Sport Fish Restoration, Project F-109-R-4: Des Moines, IA.

Rogala JT, Boma PJ, Gray BR. 2003. *Rates and Patterns of Net Sedimentation in Backwaters of Pools 4, 8, and 13 of the Upper Mississippi River.* United States Geological Survey, Upper Midwest Environmental Sciences Center: LaCrosse, WI; http://www.umesc.usgs.gov/data_library/sedimentation/documents/rates_patterns/page1.html

Rasmussen JL. 1979. *UMRCC Fisheries Compendium* (2nd edn). Upper Mississippi River Conservation Committee: Rock Island, IL.

Schramm HL Jr. 2004. Status and management of fisheries in the Mississippi River. In *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries* (vol. 1), Welcomme R, Petr T (eds). RAP Publication 2004/16: Bangkok, Thailand; 301–333.

Schramm HL, Lewis WL. 1974. *Study of the Importance of Backwater Chutes to a Riverine Fishery.* U.S. Army Corps of Engineers, Waterways Experiment Station, Completion Report (Contract Y-74-4): Vicksburg, MS.

Sheaffer WA, Nickum JG. 1986. Backwater areas and nursery habitats for fishes in Pool 13 of the upper Mississippi River. *Hydrobiologia* **136**: 131–140. DOI:10.1007/BF00051510

Sheehan RJ, Lewis WL, Bodensteiner LR. 1990. *Winter Habitat Requirements and Overwintering of Riverine Fishes.* Southern Illinois University, Federal Aid Project F-79-R Completion Report, Fisheries Research Laboratory: Carbondale, IL.

Sheehan RJ, Rasmussen JL. 1999. Large rivers. In *Inland Fisheries Management in North America* (2nd edn), Kohler CC, Hubert WA (eds). American Fisheries Society: Bethesda, MD; 529–559.

Simons DB, Schumm SA, Stevens MA. 1974. *Geomorphology of the Middle Mississippi River.* U.S. Army Engineer Waterways Experimentation Station, Contract Report Y-74-2: Vicksburg, MS.

Theis LJ, Knox JC. 2003. Spatial and temporal variability in floodplain backwater sedimentation, pool ten, upper Mississippi River. *Physical Geography* **24**: 337–353.

Theiling CH. 1995. Habitat rehabilitation on the upper Mississippi River. *Regulated Rivers Research and Management* **11**: 227–238.

Tyser RW, Rogers SJ, Owens TW, Robinson LR. 2001. Changes in backwater plant communities from 1975 to 1995 in navigational pool 8 upper Mississippi River. *Regulated Rivers Research and Management* **17**: 117–129. DOI:10.1002/rrr.609

UMRBC. (Upper Mississippi River Basin Commission). 1982. *Comprehensive Master Plan for the Management of the Upper Mississippi River System.* Upper Mississippi River Basin Commission: Minneapolis, MN.

USACE (U.S. Army Corps of Engineers). 1992. *Natural Resources Management System (NRMS).* U.S. Army Corps of Engineers: Little Rock, AR.

USACE. (U.S. Army Corps of Engineers). 2003. *McClellan-Kerr Arkansas River Navigation System: Navigation Charts Catoosa, Oklahoma to Mouth of the White River.* U.S. Army Corps of Engineers: Little Rock, AR.

WEST Consultants. 2000. *Final Report: Upper Mississippi River and Illinois Waterway Cumulative Effects Study Volume 1: Geomorphic Assessment.* U.S. Army Corps of Engineers: Rock Island, IL.

Wiener JG, Fremling CR, Korschgen CE, Kenow KP, Kirsch EM, Rogers SJ, Yin Y, Sauer JS. 1998. Mississippi River. In *Status and Trends of the Nation's Biological Resources* (vol. 1), Mac MJ, Opler PA, Puckett Haecker CE, Doran PD. (eds). US Geological Survey: Reston, VA; 351–384.

Winemiller KO, Tarim S, Shormann D, Cotner JB. 2000. Fish assemblage structure in relation to environmental variation among Brazos River oxbow lakes. *Transactions of the American Fisheries Society* **129**: 451–468. DOI:10.1577/1548-8659(2000)129<0451:FASIRT>2.0.CO;2