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HISTORIC CHANGES (1941–2008) IN SIDE CHANNEL AND BACKWATER HABITATS ON AN UNCHANNELIZED REACH OF THE MISSOURI RIVER

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ABSTRACT

Flow regulation has had pervasive effects on aquatic ecosystems within the world's large rivers. While channelization on the lower Missouri River has led to major changes in the river and its floodplain, including the loss of shallow water habitats, effects of upstream dams on unchannelized reaches on the Missouri have not been formally assessed. We quantified changes in the number and size of off-channel habitats, specifically backwaters and side channels, on the 95-km unchannelized reach of the Missouri below Gavins Point Dam (Yankton, South Dakota) using historical (1941, 1983–1985, 2008) aerial imagery. Total and mean areas of side channels declined by 77% and 37% and total and mean length decreased by 79% and 42% from 1941 to 2008. Total area of backwaters increased by 40% from 1941 to 2008, whereas mean area decreased by 36%. Our findings suggest that sharp declines in the area and length of side channels have occurred on this unchannelized remnant reach of the Missouri River, with likely significant impacts on aquatic ecosystem processes. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: flow regulation; dams; channel incision; off-channel habitats

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INTRODUCTION

Large river systems around the world have been greatly altered by human actions and no longer exhibit natural functionality (Sparks, 1995; Bayley, 1995; Nilsson *et al.*, 2005). Dams and channelization have disconnected many large floodplain rivers from their floodplains, reducing ecological diversity and function. The effects of these human alterations are widespread; however, cumulative impacts on the health of these large river systems are rarely recognized, and attempts at remediation rarely begun, until significant or irreversible degradation has occurred (NRC, 2002, 2011).

Off-channel shallow water habitats, such as side channels and backwaters, within river floodplains are formed and maintained by river channel migration and avulsion during peak flood events (Shields *et al.*, 2000; NRC, 2002, 2011). These habitats provide many benefits to aquatic ecosystems, including productive spawning and nursery areas for fish (Junk *et al.*, 1989; Price and Townsend, 2004; USACE, 2008; NRC, 2002, 2011), a refuge from high river velocities for aquatic organisms (Sheaffer and Nickum, 1986a; Price and Townsend, 2004; USACE, 2008) and warmer water for enhanced temperature diversity within the system (Sheaffer and Nickum, 1986a; USACE, 2008). Off-channel habitats increase inputs of organic matter (both autochthonous and allochthonous) to the river ecosystem and provide productive habitat for aquatic invertebrates (USACE, 2008). Benthos abundance and density are often greater within backwaters (Sheaffer and Nickum, 1986b; Angradi *et al.*, 2006) partially because food (primary and secondary production) is more abundant (Sheaffer and Nickum, 1986a). Loss of these unique areas may reduce both the habitat diversity and the productivity of the river ecosystem (Sheaffer and Nickum, 1986a).

Dams and channelization threaten off-channel habitats by disconnecting the floodplain from dynamic river processes (Ward and Stanford, 1995). Levees and bank stabilization directly restrict dynamic river–floodplain connections (Gergel *et al.*, 2002). Dams reduce overbank flooding and may cause degradation of the channel bed, isolating the river from its floodplain and potentially draining oxbows, backwaters, other floodplain wetlands and side channels (Hesse, 1987; Ligon *et al.*, 1995; NRC, 2011). Reconnection becomes even more difficult as alluvial water tables drop with declining river stage and degrading bed level (Schmulbach *et al.*, 1992; NRC, 2011). Furthermore, dynamic river processes that create new side channels and

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backwaters are reduced by flood control and bank stabilization. These physical changes provide significant challenges for ecological restoration of large rivers in general and off-channel habitats in particular (Weeks *et al.*, 2005).

During the mid-20th century, the Missouri River was greatly modified by construction of six large main stem dams and reservoirs along the upper two-thirds of the river and channelization and stabilization of a navigation channel on the lower third (1178 km) of the river (Schneiders, 1999; NRC, 2002; Galat *et al.*, 2005). On the lower Missouri, channelization under the Missouri River Bank Stabilization and Navigation Project (MRBSNP) led to major changes in the floodplain and channel, including near complete loss of 'shallow water' littoral habitats such as backwaters and side channels (chutes) within the channelized river (Funk and Robinson, 1974; Whitley and Campbell, 1974; NRC, 2002). Currently, efforts to recreate shallow water habitats are being implemented along portions of the lower, channelized river (Hamburg and Burke, 1999; Jacobson *et al.*, 2004a, 2004b; USACE, 2008). These efforts have largely been driven by mandates under the Endangered Species Act for recovery of the pallid sturgeon (*Scaphirhynchus albus*) (USFWS, 2000, 2003) and for mitigation of lost habitats. Restoration of shallow water habitat on inter-reservoir and other remnant, unchannelized reaches, however, has not been mandated and remains minimal. Although these reaches retain some natural channel and floodplain features, their flow and sediment regimes have been dramatically altered by upstream dams (Galat and Lipkin, 2000), resulting in disconnection of the floodplain from the channel, reductions in channel meandering and other fluvial geomorphic dynamics and significant degradation of the channel bed (Shields *et al.*, 2000; NRC, 2002, 2011; Galat *et al.*, 2005; Jacobson *et al.*, 2009).

This study assessed historic changes in the number, length, perimeter and area of off-channel habitats, specifically backwaters and side channels, using aerial imagery from pre-dam (1941) and post-dam (1983–1985, 2008) periods within the 59-mile (95 km) segment of the Missouri National Recreational River (MNRR). This segment is the lowermost unchannelized reach of the Missouri River, running from Gavins Point Dam (the most downstream of the six main stem dams), near Yankton, South Dakota to the beginning of channelization structures near Ponca, Nebraska.

METHODS

Study area

The Missouri River (Figure 1) drains approximately one-sixth of the conterminous United States, flowing 3768 km from the Rocky Mountain foothills of eastern Montana,

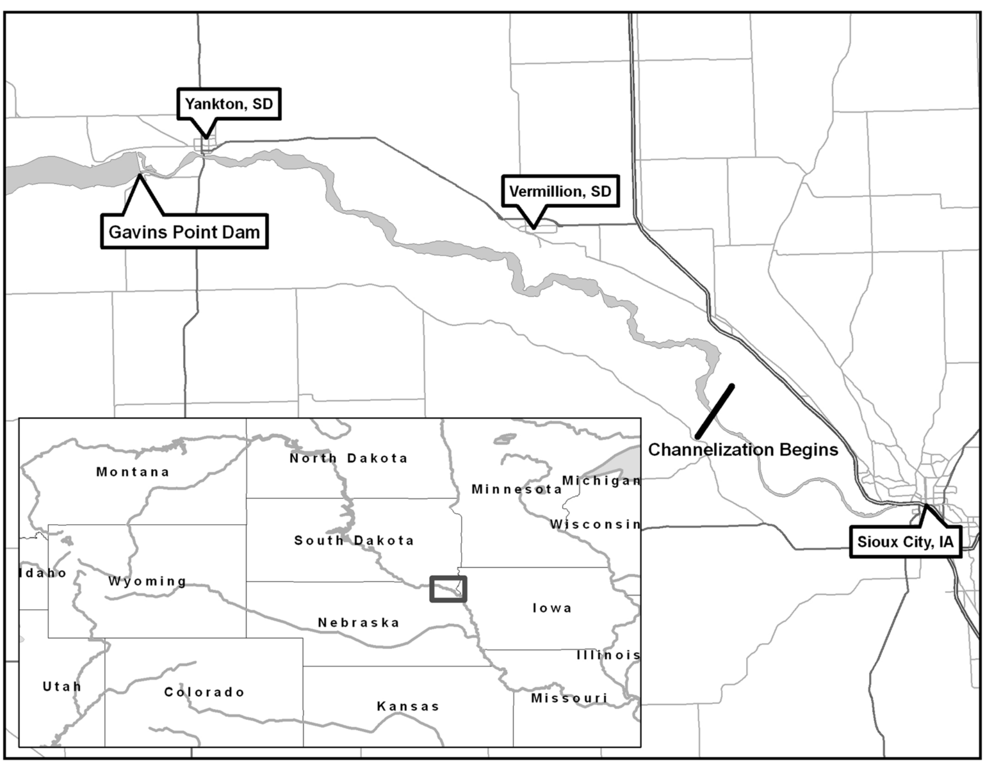

Figure 1. Map of the study area

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through the northern Great Plains and Corn Belt and entering the Mississippi River near St. Louis, Missouri (Galat *et al*., 2005). The pre-regulation Missouri River was a dynamic river, overflowing its banks and meandering through its floodplain (Schneiders, 1999). Side channels, backwaters and floodplain lakes were formed as the channel shifted laterally across its floodplain. This movement of the channel was influenced by two yearly flood pulses, also known as spring rises. The first, often in April, represented local and regional snow melt and rainfall, whereas the second, in June, represented the snow melt from the Rocky Mountains (Galat *et al*., 2005; NRC, 2011).

System-wide regulation of the Missouri began with the construction of Fort Peck Dam in Montana in the 1930s, with five other dams and reservoirs completed in the 1950s and 1960s as part of the Pick Sloan Plan of 1944. The MRBSNP of 1945, along with earlier channelization efforts, led to the channelization of the lower 1178 km of the Missouri River, with the creation of a uniform navigation channel 2.7 m deep and 91 m wide. These two programmes transformed the Missouri River from a natural free-flowing dynamic state to a channelized and impounded river (Schneiders, 1999).

The tail waters of the farthest downstream and smallest of the main stem dams, Gavins Point (completed in 1957), form the most downstream unchannelized segment of river, running from Yankton, South Dakota to Ponca, Nebraska (Figure 1). Under the authority of the Wild and Scenic Rivers Act, this 95-km segment was designated as part of the MNRR (administered by the National Park Service) in 1978 because of its unchannelized nature and historic, scenic and natural qualities. Unlike the channelized river downstream, this segment (known as the 59-mile segment of the MNRR) has a wide and shallow channel with a shifting, meandering current, islands, sandbars and wetland areas (Spegel, 2009). Despite these ‘natural’ qualities, this segment has suffered species and habitat loss (Schmulbach *et al*., 1981), channel degradation (WEST Consultants, Inc., 2002; Jacobson *et al*., 2009) and a greatly altered hydrograph because of flow regulation by upstream dams (Galat and Lipkin, 2000).

Mapping historic change in off-channel habitats

Scanned, georeferenced aerial photographs from 1941 (US Department of Agriculture), 1983–1985 (NHAP1, US Geological Survey) and 2008 (National Agricultural Imagery Program) were used to map historic changes in off-channel habitats. Black-and-white US Department of Agriculture photography from 1941 was used to characterize the pre-regulation river (Table I). Fort Peck Dam in Montana (completed in 1937) was the only main stem dam in operation on the river at the time and had little, if any, influence on floods generated from the Great Plains snowmelt (the early spring rise) but likely did influence flows from Rocky Mountain snowmelt (the June rise). Colour infrared aerial photography for 1983, 1984 and 1985 was from the NHAP1 project of the US Geological Survey. By the early 1980s, all six main stem dams had been completed and in operation for 20 years or more, with the two immediate upstream dams, Gavins Point and Fort Randall, completed in 1957 and 1953, respectively. Imagery for 2008 was from the National Agricultural Imagery Program. Images were true-colour digital orthorectified county mosaics with a pixel size of 1 m.

Table I. Dates, location and recorded daily discharge for all aerial imagery. US Geological Survey gauge numbers are provided in parentheses

Image Date	Image location (river km)[a]	Discharge ($m^3 s^{-1}$) Yankton, South Dakota (06467500)	Discharge ($m^3 s^{-1}$) Sioux City, Iowa (0648600)
10/8/1941	1305–1271	583	549
1/9/1941	1236–1199	603	643
7/10/1941	1275–1236	575	609
23/5/1983	1242–1196	725	878
24/10/1984	1275–1239	1348	1393
23/5/1984	1297–1255	663	813
18/5/1985	1305–1292	810	886
1/7/2008	1305–1181	368	498
2/7/2008	1305–1233	283	501
3/7/2008	1305–1267	283	444
8/8/2008	1234–1181	623	651

[a]Correspond to river km from the mouth of the Missouri.

Comparisons of backwater and side channel area by date were complicated somewhat by differences in flow between aerial photography dates (Table I). Reservoir levels were at record lows in 2008, with daily flows during the 2008 photograph dates lower than on both the 1980s and the 1941 imagery dates. Flows on 2008 photograph dates averaged 34% less at Yankton and 13% less at Sioux City than flows on the 1941 imagery dates. Flows averaged higher on the 1983–1985 photograph dates than in the 1941 and 2008 imagery, by 33% and 56%, respectively, at Yankton and 40% and 47%, respectively, at Sioux City. Flows on one date, 24 October 1984, were substantially higher (1348 $m^3 s^{-1}$ at Yankton; 1393 $m^3 s^{-1}$ at Sioux City) than those on the other 1983–1985 imagery dates (663–810 $m^3 s^{-1}$ at Yankton; 813–886 $m^3 s^{-1}$ at Sioux City). On the basis of provisional field records, these discharge differences translate into stage differences of 1.3 m at Yankton and 1.2 m at Sioux City between the days of highest and lowest discharge during the period. Such differences could impact and possibly inflate estimates of off-channel habitat area and numbers of features for the 1980s images. However, only 11 km (out of the 95 km) of our study reach was covered

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exclusively by imagery taken on this date of exceptionally high flow, with few off-channel features measured on that subreach. Overall, we consider potential influences of flow differences to be minor compared with the magnitude of changes in habitat area observed over the time series, particularly for the 1941 versus 2008 comparisons.

Using historic and recent imagery, we interpreted all recognizable off-channel habitats and digitized them as polygon features in ArcGIS 9.3 (ESRI Inc., Redlands, California), at a scale of 1:10 000. Off-channel habitats were defined as 'bodies of water adjacent to the main channel that have surface water connections to the main river channel' (Landers *et al*., 2002). Only water features were digitized, and these were generally separated from the main channel by adjacent vegetated surfaces or large, relatively stable sandbars. We classified each polygon of off-channel habitat as either a backwater or a side channel and determined the area, perimeter and length (longest axis) of each off-channel feature in each image year. Side channels were flowing off-channel habitats with both an upstream and downstream connection to the main river channel (Landers *et al*., 2002). Although the two terms are sometimes synonymous, we distinguished between secondary channels and side channels and only mapped the latter. Features defined as side channels were narrower (<100 m) than the main or secondary channel and received less flow (often with exposed sand) than the main channel (Figure 2). We defined a backwater as a body of water with a downstream connection to the main channel and with little to no upstream connection at normal (nonflood) flows (Figure 2). Other authors have also referred to these bodies of water as 'alcoves' (Landers *et al*., 2002) or 'backups' (Schmulbach *et al*., 1981).

We were unable to determine water depth or velocity from recent and historical aerial imagery and hence could not evaluate to what degree our off-channel habitats were synonymous with shallow water habitats, as defined by the US Fish and Wildlife Service (depth < 1.5 m, velocity $< 0.6\,\mathrm{m\,s^{-1}}$). Shallow water habitats are a focus of mitigation and restoration efforts to restore spawning and nursery areas for rare benthic fish along the lower Missouri (USFWS, 2000, 2003).

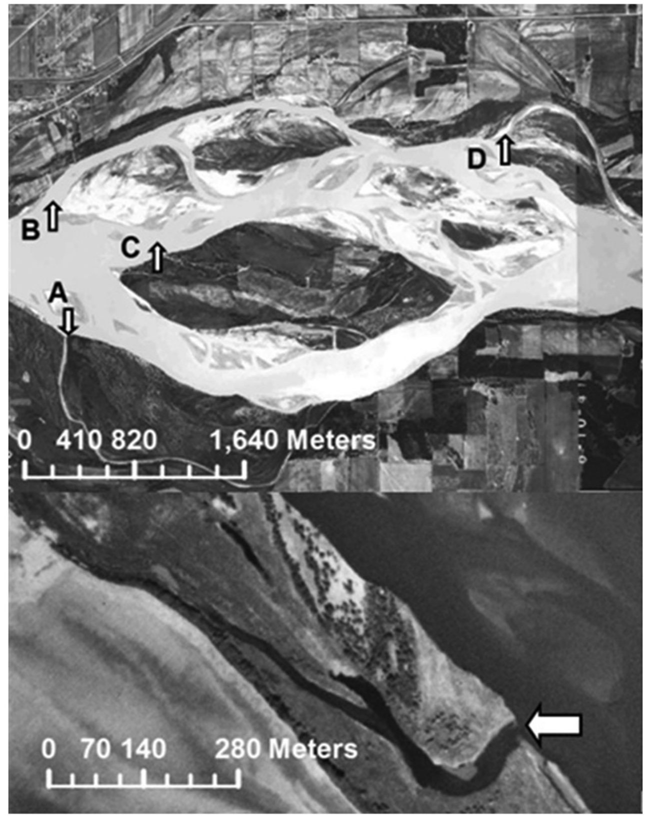

Figure 2. Aerial imagery from 1941 (top) and 1985 (bottom), depicting main channel, secondary channel, side channel and backwater features. In the top image, features 'A' and 'D' are side channels. They are narrow (<100 m wide), have exposed sand and maintain both upstream and downstream connections to the main channel. Features 'B' and 'C' are secondary channels. They are wide (>100 m) and maintain a direct connection to the main channel. The arrow in the bottom image denotes a backwater, characterized by a downstream connection to the main channel but no upstream connection

Statistical analysis

We tested for differences in mean characteristics of off-channel habitats (e.g. length, perimeter, area) and river flows between dates using two-sample *t*-tests with unequal variances, using the Microsoft Excel® Analysis ToolPak (Microsoft Corporation, Redmond, Washington). The chi-square test for independence was used to assess changes across dates in the relative numbers of backwaters and side channels. For all statistical tests, we considered *p*-values ≤ 0.05 to represent strongly significant differences, whereas values between 0.05 and 0.10 were considered weakly significant. Means are reported with standard errors. All results, unless specifically stated, represent natural off-channel features only as our goal was to assess how changes in fluvial geomorphic processes because of dam operations have influenced development and persistence of off-channel habitats. Data for three human-restored backwaters (constructed 2004–2008) in the study area are shown separately (Table II).

RESULTS

Total area, length, perimeter and number of natural off-channel habitats (backwaters and side channels) declined through time within the study area (Table II). Total area of off-channel habitats declined by 56% between 1941 and 1983–1985 and by 32% from 1983–1985 to 2008, for a net loss of 70% (65% if restored backwaters included) over 1941–2008. Total length and perimeter of off-channel

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Table II. Historic changes in the number, length, area and perimeter of off-channel habitats within the study reach

Imagery date	Feature type	Total number	Total length (m)	Mean length (m)	Total area (ha)	Mean area (ha)	Total perimeter (m)	Mean perimeter (m)
2008	Restored backwater	4	4723	1181 (483)	21.2	5.3 (1.7)	10 789	2697 (986)
	Natural backwater	11	6874	625 (121)	31.0	2.8 (0.7)	18 317	1665 (374)
	Side channel	9	12 567	1396 (184)	80.0	8.9 (2.4)	30 325	3369 (407)
	All natural features	20	19 441	972 (136)	111.1	5.6 (1.3)	48 642	2432 (331)
1983–1985	Backwater	15	9823	655 (98)	27.0	1.8 (0.3)	23 853	1590 (216)
	Side channel	20	29 390	1470 (356)	135.9	6.8 (1.9)	74 230	3711 (867)
	All features	35	39 213	1120 (216)	162.9	4.7 (1.2)	98 083	2802 (530)
1941	Backwater	5	3692	738 (293)	22.2	4.4 (2.8)	8086	1617 (606)
	Side channel	25	60 033	2401 (545)	350.5	14.0 (5.1)	129 611	5184 (1,112)
	All features	30	63 725	2124 (469)	372.6	12.4 (4.3)	137 698	4590 (960)

For means, standard errors are reported in parentheses.

features also declined sharply over 1941–1980s (38% and 29%, respectively), 1980s–2008 (50% for both) and cumulatively across the whole time period (69% and 65%, respectively; 62% and 57% if restored backwaters included). The total number of off-channel features increased slightly from 1941 (30) to 1983–1985 (35) but decreased strongly by 2008 (20).

Strong shifts in the relative and absolute numbers of natural backwaters and side channels occurred over time (Table II), with a progressive decline in the number of side channel habitats and a shift in the ratio of side channels to backwaters. In 1941, prior to the construction and operation of nearby upstream dams, 83% (25 of 30) of the identified off-channel features were side channels. By 1983–1985, the ratio of side channels to backwaters had changed markedly ($\chi^2 = 5.202$, d.f. = 1, $p = 0.023$) as the number of side channels declined (from 25 to 20) and the number of backwaters increased (from 5 to 15). The number of side channels and natural backwaters both declined from 1983–1985 to 2008, with particularly strong declines in side channels (from 20 to 9), although shifts in the relative proportion of side channels to backwaters were not significant ($\chi^2 = 1.663$, d.f. = 1, $p = 0.197$). Cumulative changes from 1941–2008 showed a significant shift in the numbers of side channels relative to backwaters ($\chi^2 = 8.104$, d.f. = 1, $p = 0.004$), with a sharp decline in the number of side channels (from 25 to 9) and an increase in the number of natural backwaters (from 5 to 11).

Changes in the total and relative areas of natural side channels and backwaters were similar to the trends observed for feature numbers (Table II). The total area of side channels decreased by 61% from 1941 to 1983–1985 and by 41% from 1983–1985 to 2008, for an overall decline of 77% over 1941–2008. Total area of natural backwaters increased by 22% from 1941–1980s and 15% from 1980s–2008, for a total increase of 40% from 1941–2008 (135% if restored backwaters included). The proportion of the total off-channel habitat area comprised of side channels declined from 94% in 1941 to 83% in 1983–1985 and 72% in 2008 (60% if restored backwaters included). The mean areas of individual side channels and natural backwaters declined from 1941 to 1983–1985 (51%, $p = 0.099$ and 59%, $p = 0.056$, respectively) but increased slightly (not significant for side channels) between 1983–1985 and 2008 (31%, $p = 0.254$ and 56%, $p = 0.073$, respectively).

Side channel mean length declined significantly ($p = 0.046$) between 1941 (2401 ± 545 m) and 2008 (1396 ± 184 m), with most of the change occurring by 1983–1985 (Table II). Similar changes occurred for mean perimeter, with a 28% decline from 1941–1980s and a 9% decline from 1980s–2008, for a 35% decline from 1941–2008. Total side channel length decreased by 51% from 1941 to 1983–1985 and again by 57% from 1983–1985 to 2008, for an overall decrease of 79% from 1941 to 2008. Backwater total length nearly tripled from 1941 to the 1980s but decreased by 30% from the 1980s to 2008. Despite some declines between the 1980s and 2008, total number, length, perimeter and area of natural backwaters were all higher in 2008 than in 1941, whereas side channel number, length, perimeter and area were greatly reduced.

DISCUSSION

Impacts of flow regulation on off-channel habitats

Flow regulation by upstream dams (e.g. Garrison and Fort Randall completed in 1952 and 1953, respectively; Gavins Point in 1957) has dramatically altered both flow and sediment regimes within the 59-mile segment of the MNRR (Galat and Lipkin, 2000; Jacobson *et al*., 2009; NRC, 2002, 2011), impacting the processes necessary for formation and maintenance of dynamic floodplain and channel features. Mean annual peak flows declined significantly in magnitude at the Sioux City, Iowa gauge (i.e. by 67%, $t = 5.097$, d.f. = 17, $p < 0.0001$), from 4477 (± 570) $m^3 s^{-1}$ over

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1929–1953 to 1471 (±64) $m^3 s^{-1}$ over 1954–2010, with no flows exceeding 3000 $m^3 s^{-1}$ between 1953 and 2010 (Figure 3). Upstream reservoirs have dramatically reduced sediment loads downstream from Gavins Point Dam, with an estimated 99.8% decline in sediment loads at Yankton, South Dakota (from 125 to 0.25 metric tonnes/year) (Jacobson *et al*., 2009). On the basis of a geographic information system analysis of the study reach, Dixon *et al*. (in review) found reductions in geomorphic dynamism in terms of lateral erosion (70% decline) and accretion rates (27% decline), a reduction in active channel area of 28% and an 81% decline in unvegetated sandbar habitat from 1955–1956 to 2006. Most notably, the near cessation of downstream sediment transport from Gavins Point Dam has contributed to substantial channel bed degradation since the 1950s, with declines in river stage of 3.5 m directly below the dam (Jacobson *et al*., 2009) and an average of more than 2 m throughout the entire reach (Figure 4, WEST Consultants, Inc., 2002). The combination of these factors has led to increasing disconnection of the river channel from the floodplain and from former shallow water and off-channel habitats (Elliott and Jacobson, 2006; NRC, 2011). Flow regulation has largely eliminated large, avulsive flows that formerly formed new side channels or restored old ones, whereas channel bed degradation has further isolated river flows from off-channel habitats, simplified channel structure and drained former wetland and shallow water habitats (NRC, 2011).

Although the study area is not part of the MRBSNP, 33%–40% of the reach has been stabilized (National Park Service, unpublished data) by local landowners and state and federal agencies, including a stabilization demonstration project by the US Army Corps of Engineers in the late 1970s. Stabilization on the 59-mile segment of the MNRR is composed of individual sites with rock revetments (rip-rap) designed to stop local bank erosion, rather than the system of wing dikes and other structures designed to form and stabilize a reach-wide navigation channel on the lower Missouri. As such, bank stabilization on the study reach has likely had some influence on channel bed degradation and reduced channel migration but has not been a mechanism by which entire backwater or side channel habitats have been cut off from the river channel and eliminated.

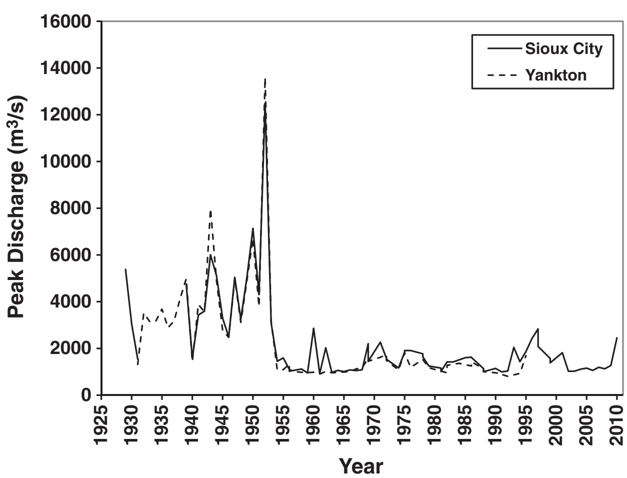

Figure 3. Historic changes in annual peak river discharge on the Missouri River at the Yankton, South Dakota (#06467500) and Sioux City, Iowa (#0648600) US Geological Survey gauges. Adjacent upstream dams at Fort Randall and Gavins Point were completed in 1953 and 1957, respectively

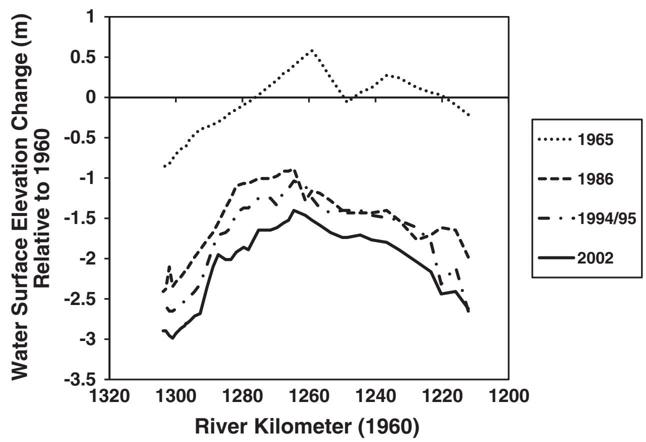

Figure 4. Changes in water surface elevation relative to 1960 for flows at 849.5 $m^3 s^{-1}$ within the study reach (on the basis of data from WEST Consultants, Inc., 2002)

Historic changes within our study area suggest a progressive response of off-channel habitats to flow regulation and channel bed degradation (Figure 5), with sharp declines in total and average length, perimeter and area of off-channel features and a decrease in the relative proportion of side channels (Table II). An initial increase in the number of side channels between 1941 and 1983–1985 may reflect conversion of former secondary channels to narrower, shallower side channels as peak flows declined, and the channel bed progressively degraded. Historic declines in the number, size and length of side channels, moderate increases in backwater number and area and an overall increase in the ratio of backwaters to side channels suggest a process of conversion of side channels to backwaters through loss of the upstream channel connection from channel downcutting, sedimentation and vegetation expansion. Although such a process seems logical, direct evidence of side channel to backwater conversions is lacking in our data, perhaps because of habitat changes that are rapid relative to the 23–44 year intervals between photograph dates or to different mechanisms for backwater formation. Instead, the dominant changes that we observed were complete losses of individual off-channel features (side channels or backwaters) between dates, through conversion to terrestrial

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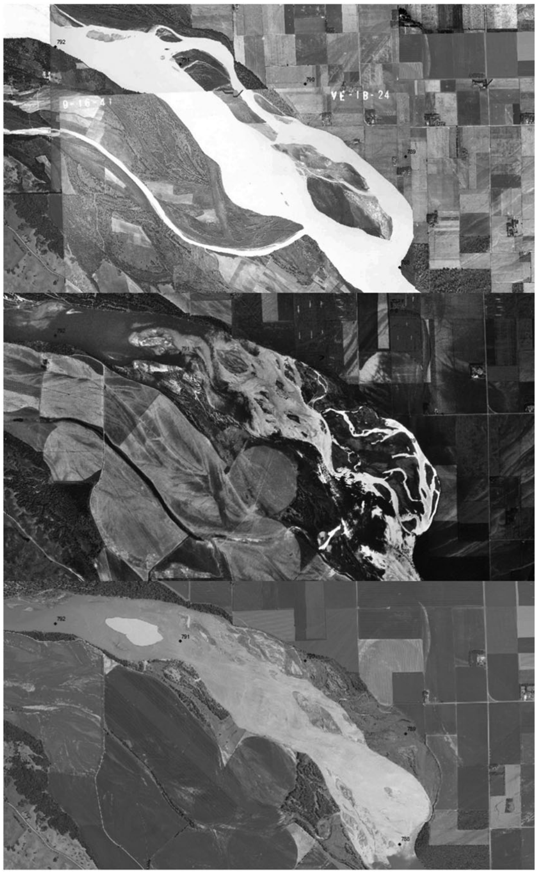

Figure 5. Changes in off-channel habitats are visible from 1941 (top) to 1983–1985 (middle) and 2008 (bottom) for a portion of the study reach (St. Helena Island area, south-east of Yankton, South Dakota)

land cover or, in some cases, to river channel because of shifts in the main channel (Yager and Dixon, personal observation). Analysis of additional, intervening photography dates (and hence shorter time intervals) may be necessary to elucidate the actual sequence of habitat changes that led to net losses in off-channel habitat area, perimeter and length.

Other studies (Morris *et al.*, 1968; Volesky, 1969; Schmulbach *et al.*, 1981; Elliott and Jacobson, 2006) have also estimated areas of off-channel habitats within the study area. Each concluded that the area or number of side channel and backwater habitats has declined, although none took a time series approach to document these changes. Elliott and Jacobson (2006) mapped side channel chutes, defined as secondary channels much narrower than the main or primary channel, from 1941 imagery. Although they used a definition very similar to ours for side channels, Elliott and Jacobson were presumably less inclusive and identified 13 side channel chutes with an average length of 3670 m, 1269 m longer than the average length that we calculated from the 1941 imagery. Our definition included many shorter side channels, resulting in a smaller average length and a greater number of identified features. Morris *et al.* (1968) and Volesky (1969) estimated that backwaters (referred to as backups and marshes) alone represented approximately 5% of the area between high water marks (estimated at 7367 ha by Schmulbach *et al.*, 1981) within the study area in the late 1960s or approximately 368 ha. This estimate is comparable to our estimate of total off-channel habitat for 1941 but is much larger than our estimates from 1983–1985 for backwaters (27 ha) and total off-channel habitat (163 ha) (Table II). Schmulbach *et al.* (1981) used 1979 aerial photography and ground-truthing to estimate that chutes/side channels constituted 273.78 ha or 3.72% of the area between the high water mark, whereas backwater habitat (including backups and marshes) was limited to 0.83% and 61.21 ha. His estimates are approximately two times larger than our 1983–1985 estimates of side channel (136 ha) and backwater area. Differences in how off-channel habitats were defined in each study make direct comparisons with our estimates difficult, however. For example, Schmulbach's definition of a chute (or side channel) included any 'subsidiary' channels, generally with depths <2 m and a mean current velocity of $<0.75\,m\,s^{-1}$ (Schmulbach *et al.*, 1981), with parts of the main channel that were in a 'transitory' stage also placed within the chute/side channel habitat.

Management implications

Efforts to restore or recreate shallow water, off-channel habitats (Hamburg and Burke, 1999; Jacobson *et al.*, 2004a, 2004b; USACE, 2008) on the Missouri River have focused on the lower, channelized river between Sioux City, Iowa and St. Louis, Missouri because of federal mandates to protect the endangered pallid sturgeon (USFWS, 2000, 2003), with little attention to unchannelized segments upstream. Extensive channelization and bank stabilization under the MRBSNP has resulted in the loss of approximately 67 987 ha of natural channel, 143 258 ha of meander belt and 50% of the river's surface area on the channelized lower 1178 km of river. Stabilization has caused nearly 90% loss of off-channel and shallow water habitats while nearly eliminating sandbars, islands, oxbows and backwaters (Funk and Robinson, 1974; USGS, 1998).

Our findings show that significant losses of off-channel habitats have occurred on an unchannelized upstream segment of the Missouri as well, with particularly steep declines in side channel number, length, perimeter and area. Declines in these habitats have likely led to decreased productivity in the river ecosystem. Nearly 67% of off-channel benthic insect production was estimated to have been lost in conjunction with channelization on the Missouri River (Morris *et al.*, 1968). Within our study area, Mestl and Hesse (1993) found that secondary production declined

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nearly 61% between 1963 and 1980. In 1963, off-channel areas provided 37% of the secondary production; yet, by 1980, these habitats only contributed 19%. Biomass of insects produced by these habitats also dropped 80% from 1963 to 1980. This decline in aquatic insects may also have contributed to the loss of native fish species within the Missouri River (Hesse, 1987; Weeks *et al*., 2005). With continued steep declines in natural off-channel habitats from the 1980s to present, levels of productivity have likely continued to decline as well.

Some restoration or recreation of backwater habitats has occurred recently on the 59-mile MNRR, with three backwaters created or restored between 2004 and 2008 (Yager, 2010). These backwaters were constructed in conjunction with excavation of sediment to create sandbar nesting habitat for two threatened and endangered birds, Interior Least Tern (*Sternula antillarum athalassos*) and Piping Plover (*Charadrius melodus*), as part of the Emergent Sandbar Habitat programme of the US Army Corps of Engineers (USFWS, 2003; USACE, 2011; NRC, 2011). These new backwaters have, at least in part, helped to counteract some of the losses of natural off-channel habitats, although historic losses have been primarily of side channels. Initial monitoring suggests that these recreated habitats are being used by a diversity of fish species (Stukel *et al*., 2009, 2010) and are showing evidence of other off-channel habitat characteristics and functions (Yager, 2010). These findings, in combination with the historic losses of off-channel habitats documented in our study, suggest that mandates for off-channel habitat restoration should be expanded to include upstream, unchannelized reaches such as the 59-mile segment of the MNRR. In addition, given the disproportionately greater losses of side channels in comparison to backwaters, we recommend that future efforts prioritize side channel restoration.

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