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FLOOD EFFECTS PROVIDE EVIDENCE OF AN ALTERNATE STABLE STATE FROM DAM MANAGEMENT ON THE UPPER MISSOURI RIVER

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ABSTRACT

We examine how historic flooding in 2011 affected the geomorphic adjustments created by dam regulation along the approximately 120 km free flowing reach of the Upper Missouri River bounded upstream by the Garrison Dam (1953) and downstream by Lake Oahe Reservoir (1959) near the City of Bismarck, ND, USA. The largest flood since dam regulation occurred in 2011. Flood releases from the Garrison Dam began in May 2011 and lasted until October, peaking with a flow of more than 4200 $m^3 s^{-1}$. Channel cross-section data and aerial imagery before and after the flood were compared with historic rates of channel change to assess the relative impact of the flood on the river morphology. Results indicate that the 2011 flood maintained trends in island area with the loss of islands in the reach just below the dam and an increase in island area downstream. Channel capacity changes varied along the Garrison Segment as a result of the flood. The thalweg, which has been stable since the mid-1970s, did not migrate. And channel morphology, as defined by a newly developed shoaling metric, which quantifies the degree of channel braiding, indicates significant longitudinal variability in response to the flood. These results show that the 2011 flood exacerbates some geomorphic trends caused by the dam while reversing others. We conclude that the presence of dams has created an alternate geomorphic and related ecological stable state, which does not revert towards pre-dam conditions in response to the flood of record. This suggests that management of sediment transport dynamics as well as flow modification is necessary to restore the Garrison Segment of the Upper Missouri River towards pre-dam conditions and help create or maintain habitat for endangered species. Published 2016. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS: dam effects; channel morphology; alternate stable state; deltas; flood effects

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INTRODUCTION

Dams associated with major reservoirs alter the flow of sediment and water in rivers across the world, substantially impacting channel morphology, flood patterns and riverine ecosystems. Negative consequences of river damming have been documented, including loss of river form and function, floodplain disconnection and the loss of habitat for threatened and endangered species (Richter *et al*., 2003; Jansson *et al*., 2000; Grant *et al*., 2003). The effects of dams have been extensively documented (Brandt *et al*., 2000; Grant *et al*., 2003; Schmidt and Wilcock, 2008; Skalak *et al*., 2009) and will not be thoroughly reconsidered here. The magnitude of the perturbation from a dam depends on the characteristics of the watershed (e.g. underlying geology, bedrock control and precipitation) and the dam itself (e.g. size, type and flow release; Grant *et al*., 2003; Skalak *et al*., 2009). Where dams have created a highly altered flow and sediment regime, it is possible that the geomorphology and ecology have also been fundamentally changed, resulting in an alternate stable state. Perturbations to fluvial systems resulting in alternate stable states have been proposed elsewhere such as the 'floodplain large-wood cycle hypothesis' where loss of large trees can result in state change (Collins *et al*., 2012) as well as land use changes that result in the inability for headwater streams to retain large wood and can cause a state change (Wohl and Beckman, 2014).

Ecologists are gathering increasing empirical support for the idea that communities can be found in one of the several possible alternate stable states (Beisner *et al*., 2003). Two perspectives have been developed to describe how communities shift from one stable state to another. The first perspective assumes a constant environment with shifts in variables such as population density, and the second assumes changes to underlying parameters or environmental drivers. In the case of the damming of rivers, we believe that changes in river geomorphology and flow conditions involve the second perspective for the creation of an alternate stable state. It has been hypothesized that a return to the pre-dam (original)

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state requires the return of natural water and sediment flow dynamics throughout the system. Complete removal of dams is not feasible or recommended in many major reservoir systems because of continued need or high cost, and therefore, it is likely that unintended consequences will persist or even worsen, despite best management efforts. Current available ecosystem restoration strategies include targeting and managing specific components such as flood restoration or modification of structures to pass sediment or allow fish passage (Richter and Thomas, 2007). For example, the Grand Canyon Monitoring Research Center has conducted high flow experiments to correspond with seasons of peak tributary sediment loads to maximize downstream delivery of sediment to replenish sandbars (Grams *et al*., 2010). Wohl *et al*. (2015) hypothesized that the restoration of the 'natural flow regime' (Poff *et al*., 1997) will likely only be successful with inclusion of the 'natural sediment regime'. However, as Yang (2006) and Jacobson *et al*. (2009) point out, the six large dams (moving from the headwaters downstream in order, the dams are as follows: Fort Peck, Garrison, Oahe, Big Bend, Fort Randall and Gavins Point) on the Missouri River were not constructed to permit sediment bypass, and retrofitting them for this purpose is not feasible.

Recent historic flooding on the Missouri River and extensive historical data on the Garrison Segment of the river (Figure 1) provided an opportunity to assess whether high-magnitude floods on managed rivers could restore pre-dam form and function and benefit threatened species. The largest flood since dam regulation (1953) occurred in 2011. Although this flood was different in character to a pre-dam flood (see Figure 2 for a comparison between a pre-dam flood in 1947 and the May 2011 event), it resembled and even exceeded any realistic flood release that managers would perform and provided a unique opportunity to assess whether flood flows could restore some geomorphic and ecological functionality to the landscape.

Pre-dam flows on the Missouri River included a double-peaked annual flood pulse, with high flows in the early

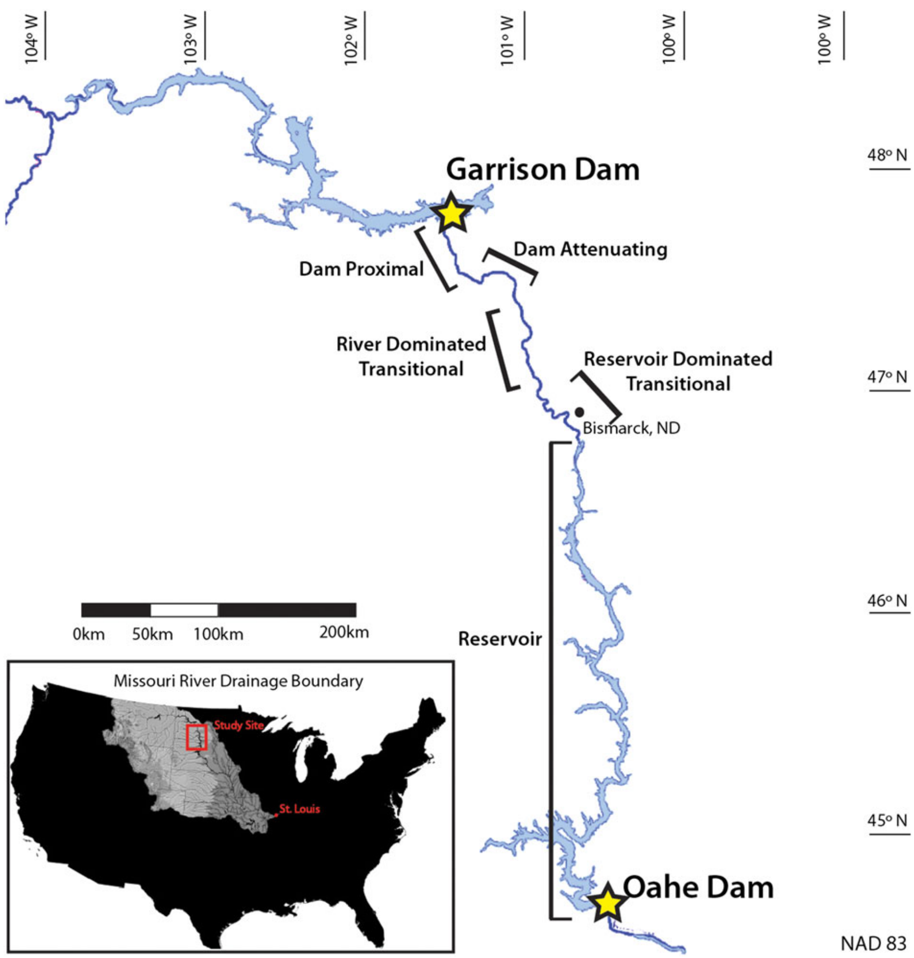

Figure 1. Map of the study site. The stars indicate the location of the Garrison Dam and Oahe Dams. The Garrison Segment of the river is the reach between the Garrison and Oahe dams. The labelled reaches are the zones described by Skalak et al., 2013. [Colour figure can be viewed at wileyonlinelibrary.com]

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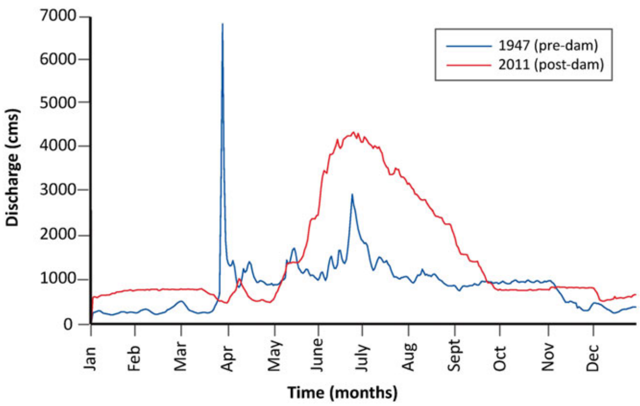

Figure 2. The effects of dam regulation on a flood hydrograph. The blue line is the pre-dam flood from 1947, and the red line is the 2011 flood. Data are from USGS Gage 06342500. [Colour figure can be viewed at wileyonlinelibrary.com]

spring from Great Plains rainfall and snowmelt, and a larger, longer duration flood pulse in later spring or early summer from the Rocky Mountain snowmelt. The six dams resulted in reduction of peak flows, flow stabilization, navigation, power generation, flood control and recreational uses. Downstream from the dams, water releases still retain substantial sediment-transport capacity, but have lost the natural supply of sediment to reservoir trapping (Galloway *et al.*, 2013). Prior to main stem dam construction, sediment loads were estimated to be 270 to 326 $Mg \times 10^6 yr^{-1}$ depending on the river segment. Dam emplacement resulted in a 0.2% to 17% load reduction (Jacobson *et al.*, 2009). The Missouri River's pre-regulated channel form was dynamic, with considerable potential for lateral channel migration (Galat *et al.*, 2005; Dixon *et al.*, 2012; Dixon *et al.*, 2015).

A series of distinct geomorphic transitions occurs on the segment of the Missouri River bracketed by the Garrison and Oahe Dams, documented by Skalak *et al.*, 2013. For clarification, the segment between the two dams is referred to as the Garrison Segment (or generally segment). The word ‘reach’ is used in a general sense to refer to a generic length of river, shorter than the segment. Skalak *et al.* (2013) described five geomorphic zones termed as inter-dam sequence: Dam Proximal, Dam Attenuating, River Dominated Transitional, Reservoir Dominated Transitional and Reservoir. The Dam Proximal zone experienced channel degradation through bed incision, channel widening and near total loss of island and sandbar area through erosion and deflation. Downstream in the Dam Attenuating zone, the islands became metastable (shifting locally but with little net change) while the channel banks eroded and channel capacity continued to expand. Farther downstream, the backwater effects of the lower reservoir appeared in the River Dominated zone; the channel banks and capacity stabilized, and island morphology changed from primarily small in-channel, low-lying, unvegetated islands to large, vegetated, bank-attached features separated from the shore by a shallow, narrow channel, which may be ephemeral. In the Reservoir-dominated zone, the bed aggraded, forming a delta and lowering channel capacity. Deposition also occurred in the Reservoir zone, but sedimentation was uniform; no aggradation occurred, and channel form remains relatively stable. The transition from River to Reservoir-dominated zones is spatially variable, shifting up to 100 km (along the entire 512 km segment) as reservoir levels and river discharge fluctuate seasonally and annually. The geomorphic pattern created by dam interaction is intensified by sediment supply reduction and artificial bank stabilization in many locations; as much as 25% of the shoreline is stabilized in this reach primarily around Bismarck (Angradi *et al.*, 2004).

The dam-induced geomorphic conditions represent a new, alternate stable state on the Missouri River. This geomorphic template (as described by Skalak *et al.*, 2013) has substantially altered the hydrogeomorphic processes, which has direct implications for ecology, flooding characteristics and channel form. Within the Garrison Segment, the presence of dams has been linked to a loss of channel islands and sandbars, vital habitat for the endangered Interior Least Tern (*Sternula antillarum*) and threatened Piping Plover (*Charadrius melodus*). Additionally, recent work suggests a subpopulation of the endangered Pallid Sturgeon (*Scaphirhynchus albus*) was negatively impacted by anoxic zones in the headwaters of the Fort Peck Reservoir (Guy *et al.*, 2015). Pallid Sturgeon requires long, uninterrupted river reaches of high flow for the larvae to mature (Kynard, *et al.*, 2007; Braaten *et al.*, 2008), and reservoirs could be affecting upstream populations by fragmenting these reaches. The largest wild subpopulation surviving (6000 members) occurs below the Gavins Point Dam and is unaffected by downstream reservoirs, supporting theories that populations upstream of reservoirs are affected by reduced consistency of high flow (because no downstream reservoir exists to impact this subpopulation). Losses of riparian forest species such as willow and cottonwood have been documented along the Missouri River and linked to the presence of the dams (Dixon *et al.*, 2012; Dixon *et al.*, 2015).

In this study, we document island loss and bank attachment, analyze cross-sectional area changes, track thalweg migration through time and develop a metric to quantify channel planform change to show that dam regulation has created an alternate geomorphic stable state in which historic flooding does not revert towards pre-dam conditions. The analyses we present facilitate discussion about how these geomorphic changes have impacted the ecology of this system resulting in a shift to an alternate stable state for biological communities as well.

STUDY SITE

In 2011, the Missouri River Basin experienced near-record peak streamflow. The flooding was caused by a combination

DOI: 10.1002/rra

of above normal snowpack in headwater regions in the Rocky Mountains of Montana and Wyoming, near-record snowfall and wet soil conditions on the plains and record rainfall in May across the upper Missouri River Basin (Grigg *et al*., 2011). Total volume of runoff into all six Missouri River main stem reservoirs in 2011 was the largest since record keeping began (1898), forcing releases of record high-magnitude discharges from several of the main channel dams operated by the U.S. Army Corps of Engineers (USACE; Grigg *et al*., 2011). The releases at the Garrison Dam were more than 4247 m^3 (150 000 $ft^3\,s^{-1}$) at the peak of the flood. Although this is the largest event on record, the rarity of its occurrence can only be properly emphasized by calculating the return interval of the flood runoff. Runoff estimates in the basin have been calculated by the U.S. Army Corps of Engineers since 1898 and can serve as a proxy for discharge in absence of natural flow because of dam regulation of discharge. Typical runoff for the basin is 12 km^3 (10 million acre-ft), but in 2011, 30 km^3 (24 million acre-ft) of runoff entered the reservoir, which the U.S. Army Corps of Engineers considered a 500-year event (USACE, 2011).

Channel morphology

The Missouri River begins in the Rocky Mountains in southwestern Montana and flows southeast for 3768 km until it enters the Mississippi River, north of St. Louis, Missouri (Figure 1). We use the recent classification scheme by Carling *et al*., (2013) to describe the river, which we prefer because of its process-based consideration of planform. The free flowing sections of the Missouri River, according to this system, are braided channels that alternate between single and multi-thread depending on island height and vegetation development. Islands are defined as vegetated landforms that are subaerial and completely surrounded by water during managed flow conditions (typically range between 283 and 991 $m^3\,s^{-1}$). Features that do not have vegetation and are bare sand (during the same flow condition) are considered sandbars. However, we did not differentiate between these features in our analysis and therefore refer to them as a lumped category ‘islands’ in subsequent discussion. As a result of loss of sediment from damming, island extent has been severely diminished. Williams and Wolman (1984) reported changes in mean-bed elevation ranging from −3.26 to 0.20 m in the 87 km below the dam between 1954 and 1976; however, the rate of channel bed degradation has slowed substantially since the mid-1970s (Skalak *et al*., 2013) and is approaching a state of dynamic equilibrium (Biedenharn *et al*., 2001; Skalak *et al*., 2013).

Ecology

The development of the Missouri River basin has resulted in three species becoming endangered or threatened: the Least Tern (*Sternula antillarum*), Piping Plover (*Charadrius melodus*) and Pallid Sturgeon (*Scaphirhynchus albus*; Whitmore and Keenlyne, 1990; National Research Council, 2002). The Least Tern and Piping Plover populations, which utilize sandbars for breeding season habitat, have declined as dams have diminished sediment loads causing a loss of islands (Lott *et al*., 2013). The decline of the Pallid Sturgeon, once abundant along the Missouri, has been attributed to the loss and modification of its habitat by human activities, which have blocked fish migration, destroyed spawning areas, reduced food sources, altered temperature and flow of water and reduced sediment loads and turbidity (Keenlyne and Evenson, 1989, Pegg *et al*., 2003; Steffenson *et al*., 2013). Subpopulation declines in the Fort Peck reach have been linked to the large reservoir, which interrupt downstream drift of the larvae and create zones of reduced dissolved oxygen resulting in larval mortality (Guy *et al*., 2015).

Hydrology

The study segment in Upper Missouri River extends 512 river kilometres from the Garrison Dam in North Dakota to the Oahe Dam in South Dakota (Figure 1) with only two minor tributaries in the study segment with mean daily discharges of 15 and 8 $m^3\,s^{-1}$ (USGS streamgages 06340500 and 06349000).

Garrison Dam was completed in 1953, and the Oahe Dam was completed in 1959 with the Lake Oahe Reservoir taking around 4 years to fill. Post-dam, the mean discharge in the Garrison Segment (the reach between the Garrison and Oahe dams), is approximately 623 $m^3\,s^{-1}$ at the USGS stream gauge in Bismarck, ND, USA (USGS ID: 06342500). Two major floods have occurred since dam regulation. The largest flood occurred in 2011 with a peak discharge of 4390 $m^3\,s^{-1}$ (Figure 2). The next largest flood (1975) was approximately one-half the discharge of the 2011 flood, with a peak of 1954 $m^3\,s^{-1}$ (Schenk *et al*., 2014). The largest pre-dam flood in the gauging record occurred in 1947 and had a much higher peak (discharge of 6781 $m^3\,s^{-1}$) and shorter duration (3 days) than the 2011 flood (Figure 2).

METHODS

We analyzed channel morphology and floodplain modification using repeat cross-sectional surveys and aerial photographs. Post-dam morphologies, both preceding and following the flood, were compared with historical trends observed by Skalak *et al*. (2013).

Photo analysis

The change in island area and inundation extent because of the flood was determined by delineating zones of vegetation,

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sand and water along the Missouri River using Geoeye imagery (<50 cm resolution) compiled by the USGS Northern Prairie Wildlife Research Center (Strong 2012). We used this information to identify islands and shorelines from images collected on 8 June 2010 ($487\,m^3\,s^{-1}$) and 9 May 2012 ($742\,m^3\,s^{-1}$) and quantified the change during this time period. The difference in discharge between these two data sets is relatively high for this type of analysis and therefore likely underestimates the island area in 2012. However, this limitation was unavoidable because discharges during 2012 were higher than 2010 for the entire year, and these were the best images available for the analysis. Consequently, our results should be interpreted as maximum estimates of island change. Inundation area was compiled by measuring all 2010 derived land areas, which were in the flooded area measured in 2011.

Cross-sectional analysis

The U.S. Army Corps of Engineers conducted repeat lateral cross-sectional surveys from river terrace to opposite terrace every few river kilometres downstream of the Garrison Dam (77 cross sections over 253 km). Surveys were reoccupied every 1 to 8 years from 1946 to present, but different sections of river were not always surveyed in the same year, providing an extensive, but temporally unsynchronized, record of the river morphology. We used data from 1953 to present to examine post-dam trends and use the survey in 1946 as a pre-dam reference. We analyzed a total of 802 surveys for changes in cross-sectional area and minimum bed elevation. We used the elevation of the highest recorded water level during the survey period at-a-station to calculate channel depth for each survey point (Equation 1). The river is heavily managed for flood control, and since the dam was constructed only one event (May 2011), it has overtopped the banks (Schenk *et al*., 2014). Therefore, it can be assumed that the highest recorded water height prior to 2011 [H, Equation (1)] at each cross section approximates bankfull conditions during normal dam operations.

$$\Delta E_i = H - E_i \tag{1}$$

where H is bankfull height (m), $E_{(i)}$ is survey elevation (m) at survey location i along a cross section and $\Delta E_{(i)}$ is the calculated elevation difference at survey location i. The channel capacity or cross-sectional area for each year was determined using this fixed height [Equation (2)].

$$A = \sum_{i=1}^{n} \left(\left(D_{(i+1)} - D_{(i)} \right) * \left(\left(\Delta E_{(i+1)} + \Delta E_{(i)} \right) / 2 \right) \right) \tag{2}$$

where D_i is the location (m) of the point i along a cross section and $D_{(i+1)}$ is the next measured location in the cross section, such that $D_{(i+1)} - D_{(i)}$ yields the width between consecutive points along the cross section. A is the cross-sectional area (m^2). We use the percent change in cross-sectional area between years for each cross section to compare cross-sectional change at different locations along the river. This was calculated by subtracting the pre-dam cross-sectional area from the relevant year measurement and by dividing the pre-dam measurement.

Dam management has occurred over a period of decades. We divided the total capacity change for a defined period of time by the time increment to normalize for the varying number of repeat surveys and calculate an average annual change in channel capacity. Skalak *et al*. (2013) demonstrated that bed elevation was dynamic from 1953 to 1975 and reaches a quasi-steady state by approximately 1975. In order to determine deviation of the 2011 flood from current trends, we compared calculated flood effects with trends observed from 1976 to the present.

Two river-wide surveys were conducted before and after the flood: 2007 and 2012. To correct for the 4 years of normal river conditions, we use the average annual change in channel capacity to estimate how much of the cross-sectional change we would normally expect during this time period. Any excess change was attributed to the flood. For example, if we expect the channel capacity at a cross section to increase 5% in 5 years but between 2007 and 2012, it increases only 1%; Figure 6b will indicate a 4% decrease from the expected change. We determined the effects of long-term dam management on channel migration by assessing the thalweg location through time. The thalweg was identified as the maximum depth in each cross section from each year a survey was conducted. Movement between surveys is calculated by measuring the change in cross-channel location of the thalweg in each survey divided by the number of years between the surveys.

Shoal metric

Classification of channel planform as either single or multi-thread is typically achieved by simply counting the number of channels, which can lead to qualitative and subjective measurements in complex river systems. Carling *et al*. (2013) suggest that existing planform metrics are not robust enough and require improved quantification based on process metrics. Shallow water locations in large rivers contain unique and ecologically important habitats, which cannot be completely described by counting the number of channels. One such habitat is the floodplain also referred to by Junk *et al*. (1989) as an aquatic/terrestrial transition zone (ATTZ) because it alternates between aquatic and terrestrial environments. Flood pulses create a dynamic edge as the 'moving littoral', or shoreline, traverses the ATTZ with changing river stage. Tracy-Smith *et al*. (2012) suggest that the ATTZ

DOI: 10.1002/rra

also includes the margins of islands and sandbars whose locations, areas and morphologies are constantly changing with the river's stage and sediment dynamics. These landforms are important for many species of turtles, fish and birds including Tern and Plover, which use the shoreline and delta deposits for habitat (Catlin *et al*., 2011). Additionally, shifts in shallow water locations have important navigational and infrastructural implications, especially in the deltaic region entering the Lake Oahe Reservoir, which continues to grow and migrate (Skalak *et al*., 2013).

To calculate the shoal metric, we determined the total width of the channel at bankfull conditions for each cross-section time period by identifying areas inundated at this water level. We approximated the minimum water level by using the lowest water elevation recorded at each cross section during channel surveys. Although these numbers do not represent absolute minimum or maximum flow depth, measured discharge values during surveys were typical of managed flow conditions, which are set by reservoir guidelines. In this study, we define shoals as locations where the elevation is between bankfull water level and minimum water level minus 0.9 m (3 ft; Figure 3). This elevation range was selected as it represents areas, which may experience different flow characteristics and ecologic function (Tracy-Smith *et al*., 2012). The shoal metric is calculated as the ratio of shoal width to the total width of the channel, representing the percentage of the river channel, which experiences shoal conditions. A ratio of 1 would indicate the entire channel is a shallow section less than 0.9 m (3 ft) in depth while a ratio of 0 indicates a single, deep, steep-sided channel with no shallow areas. Shoal metrics for each geomorphic zone were calculated from 1953 to 2007. We calculated the linear slopes of the shoal metric trends through time at each cross-section location by least-squares regression. These data indicate whether a location is increasing in shallow area with a positive slope or decreasing in shallow area with a negative slope and allows us to examine longitudinal trends in channel morphology. The data for the cross sections and shoal metric were made available from the U.S. Army Corps of Engineers and have not been published. The GeoEye imagery was provided by USGS Northern Prairie Wildlife Research Center and published by Strong (2012).

RESULTS

Skalak *et al*., 2013 identified a gradation of five geomorphic zones that occur as a result of an interaction between two dams in series: Dam Proximal, Dam Attenuating, River Dominated Transitional, Reservoir Dominated Transitional, and Reservoir, which comprise an Inter-dam Sequence. The Dam Proximal zone is immediately below the Garrison Dam and is net erosional. The Dam Attenuating zone has metastable islands, but the bed and banks are eroding. The River Dominated Transitional zone has an increase in islands and bars, which have shifted to become bank-attached sandbars. The Reservoir Dominated Transitional zone has aggrading islands and bars and flooded meander bends. Morphologically, the Reservoir zone is highly stable with net aggradation. Those data were collected during normal dam operations between 1953 and 2009. The data collected post-flood were utilized for our analysis of how channel morphology (as measured by channel capacity, island area, bank erosion and stability, thalweg migration and shoal to channel ratios) and floodplain functions (as measured by floodplain size) were changed by the flood. Ecological adjustments documented in recent research on riparian forest decline (Dixon *et al*., 2015), ecosystem health (Johnson *et al*., 2015) and native species decline (Catlin *et al*., 2011; Anteau *et al*., 2012; Guy *et al*., 2015) are discussed within the context of geomorphic change.

Island area

Changes in island area following the flood accelerated historical trends in each geomorphic zone. Erosion of islands in the Dam Proximal Zone (where substantial island loss had already occurred) was exacerbated as a result of the flood; 40% of the remaining islands in the reach were lost

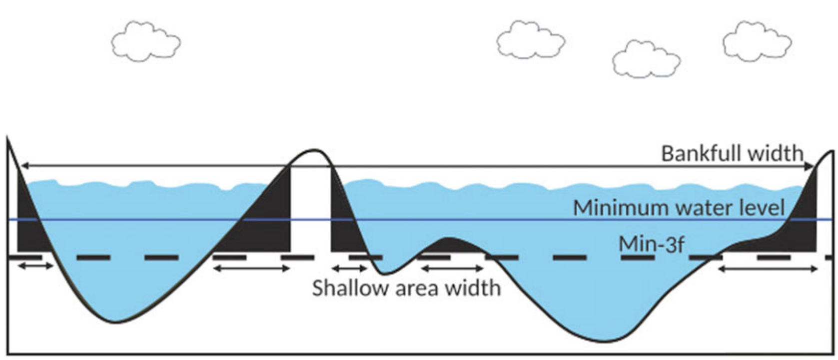

Figure 3. Schematic of methodology for deriving shoaling metric. [Colour figure can be viewed at wileyonlinelibrary.com]

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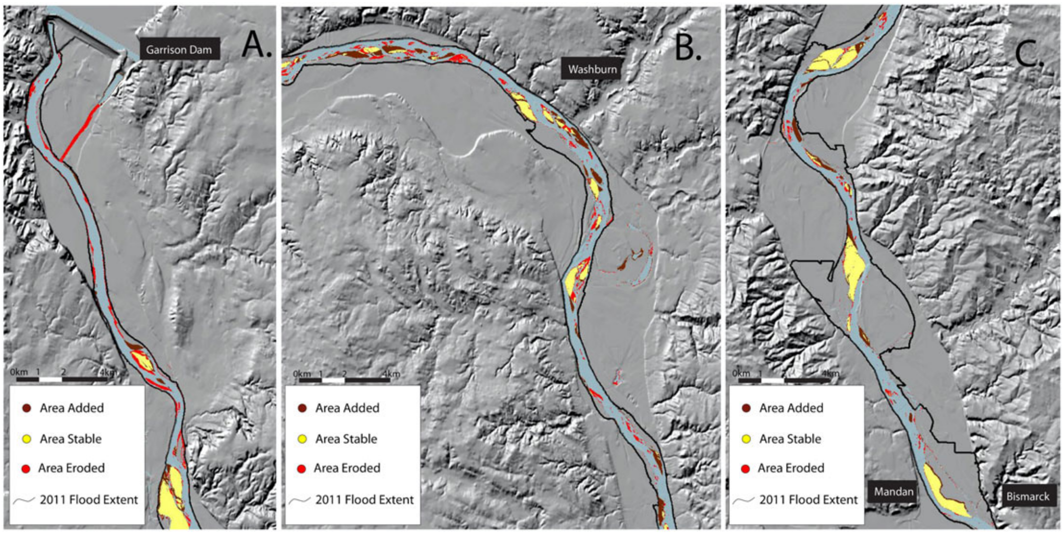

Figure 4. Island area eroded, deposited (area added) and maintained (area stable) during the 2011 flood event. The panels are selected representative portions of each geomorphic zone (A = Dam Proximal, B = Dam Attenuating, C = River-Dominated). [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 4, Table I). Over the dam management period, islands in the Dam Attenuating zone have been metastable (16% increase in island area; Figure 4, Table I), and modest gain in island area occurs as a result of the flood (increase of 13%; Figure 4, Table I). Island area increases in the River Dominated Transitional zone. During the dam management period, island area increased by 150% and many islands became bank attached. As a result of the 2011 flood, the islands continue to increase in this zone by 25% (Figure 4, Table I). The Reservoir zone is completely inundated and does not contain any islands, therefore is excluded from this analysis.

Table I. Comparison of average yearly trends to flood trends for geomorphic parameters in each zone.

	Average yearly rate (% year^{-1})	Estimated flood effect (%)	Number of years of work performed by the flood
Island area*			
Dam Proximal	−0.9	−40.0	44
Dam Attenuating	0.3	13.0	43
River Dominated	3.1	25.0	8
Reservoir Dominated	NA	NA	
Channel capacity change			
Dam Proximal	1.1	−4.4%	−4
Dam Attenuating	0.5	12.9	25
River Dominated	0.0	15.0	Changes a previously stable system
Reservoir Dominated	−0.4	−7.2	18
Thalweg stability			
Dam Proximal	−1.9	21.2	−11
Dam Attenuating	0.3	5.7	Changes a previously stable system
River Dominated	−3.0	9.1	−3
Reservoir Dominated	−2.9	18.9	−7
Shoal metric			
Dam Proximal	−0.8	7.0	−9
Dam Attenuating	−1.0	−1.3	1
River Dominated	−0.8	−23.7	29

*Island data are from 1950 to 1999, and flood change is from difference from 2010 to 2012.
All other yearly rate is calculated from 1976 to 2007 data.

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The cumulative island area change, presented in Figure 5, shows that there are substantial shifts in trends associated with each of the geomorphic zones. There is no change in the first 10 km, but then a rapid loss in the next 10 km related to the degradation of the last large island located near the mouth of the Knife River tributary as it enters the Missouri River. Losses continue within the Dam Proximal reach until about 30 river kilometres downstream. In the Dam Attenuating zone, the islands generally appear to maintain their area or demonstrate moderate loss or gain longitudinally (up to 0.2 km^2) until area starts decreasing around 60 km at the end of the zone (a loss of more than 0.4 km^2 between 56 to 58 river kilometres). The River Dominated transitional zone has greater fluctuations in island area. For example, from 104 to 107 km downstream of the dam, there is a loss of island area of more than 1.1 km^2, and from 114 to 117 km, there is a gain in island area of approximately the same magnitude (1.1 km^2). Substantial losses and gains are associated with large bank-attached islands that have completely connected to the shore and have a much greater spatial extent relative to mid-channel islands upstream.

Channel morphology

We revisit the work on the effect of dams on channel morphology to establish the alternate stable state conditions and demonstrate the level of change that occurred as a result of the flood. Channel morphology data include metrics related to islands, banks, thalweg position and shallow shoal areas. We examined the capacity of the channel at different locations along the river (Figure 6a,b). The annualized capacity change from 1976 to 2007 has been associated with trends observed in the island area (Figure 6a). Historically, the channel is increasing in capacity over most of the segment, but decreases when the backwater of the Oahe Dam is reached. The estimated capacity change from the flood does not uniformly enhance or retard the trends created by the dam or cause uniform erosion or deposition (Figure 6b). Although the channel was significantly reworked by the flood, the average conditions may not reflect that because of spatial variability of morphological changes within each zone. Analysis of the time interval with the flood shows less channel erosion in the Dam Proximal zone, more erosion in the Dam Attenuating zone, significantly more erosion in the River Dominated zone and enhanced deposition in the Reservoir Dominated zone than would be expected based on trends derived from pre-flood data (Figure 4, Table I). A similar change analysis for other time intervals for which data were available was conducted to determine if any subset of time during normal conditions showed similar, or any, trends such as those of the flood (analysis not shown). No consistent trends were found for the other periods.

Thalweg changes were examined relative to historical trends. The data show a general trend of decreasing thalweg migration since 1956 with migration of the thalweg stabilizing by the mid-1970s (Figure 7) at the same time as incision rates stabilized (Skalak *et al*., 2013). The 2011 flood had little effect on the stability of thalweg migration in any of the zones (Figure 7) and did not cause incision rates to change (data not shown).

The historical trend for the shoal metric over the period of record (1946 to 2012) versus distance downstream of the Garrison Dam indicates a high degree of variability (Figure 8); however, average trends indicate a decrease in shoaling in the upstream zones. The shallow areas that represent portions of submerged bars (and therefore a proxy for multiple thalwegs and braiding) have been reduced. This indicates a planform change from braided to single-thread. The change in shoal metric approaches zero in the central portion of the segment (River Dominated zone and Reservoir Dominated zone) indicating channel stability. The slope of the shoal metric becomes primarily positive 161 river kilometres (100 river miles) below the Garrison Dam, indicating an increase in shoaling over time (an increase in the number of thalwegs and channel complexity). In addition to quantifying a change

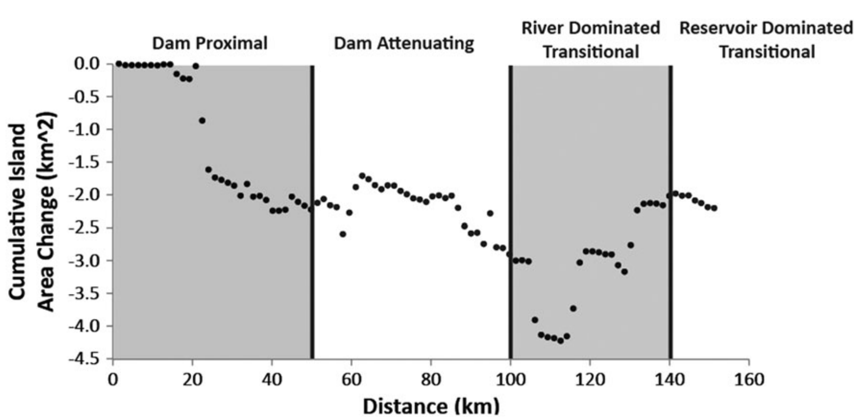

Figure 5. Cumulative island area change versus distance downstream of the Garrison Dam. The geomorphic zones identified by Skalak et al., 2013 are labelled for reference

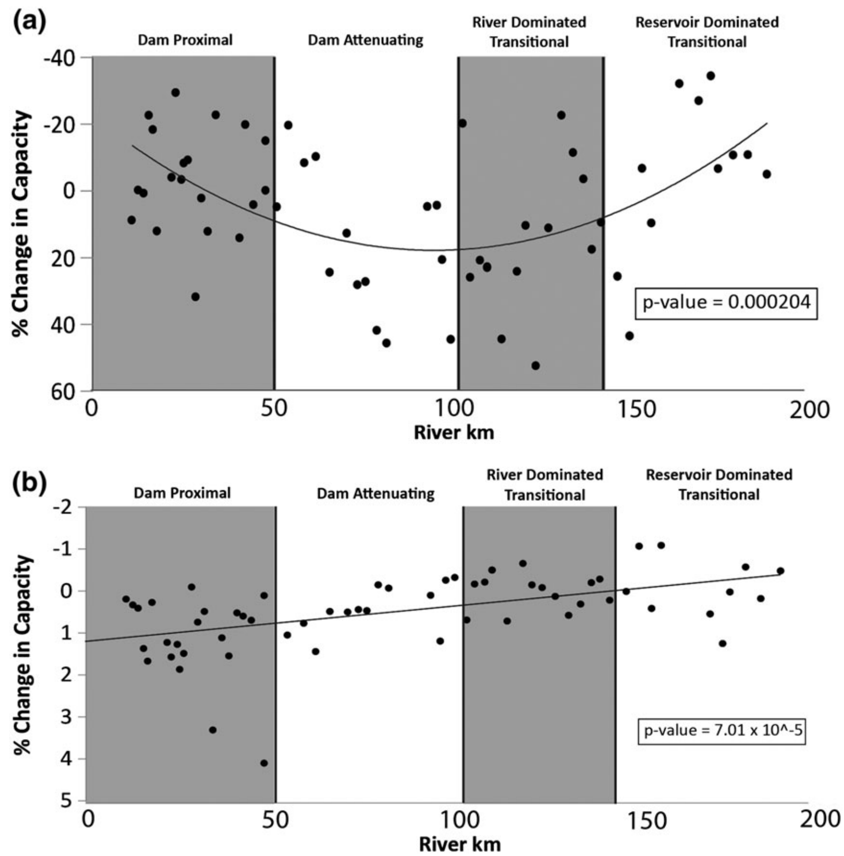

Figure 6. Annualized channel capacity changes from 1976 to 2007 compared with estimated changes that the flood would generate if annualized trends were to continue

in planform, there is ecological significance to the shoaling areas or ATTZ, which is further considered in the discussion.

Floodplain connectivity

The analysis of cumulative area of land inundated by the 2011 flood between the Garrison Dam and the delta (Reservoir Dominated zone in Figures 1 and 9) indicates significant shifts in inundation area that generally correspond to the locations of the geomorphic zones. The shape of the slope line indicates areas of inundation with steep slopes representing large areas of inundation, and shallow slopes represent areas that had little inundation. The 20 km

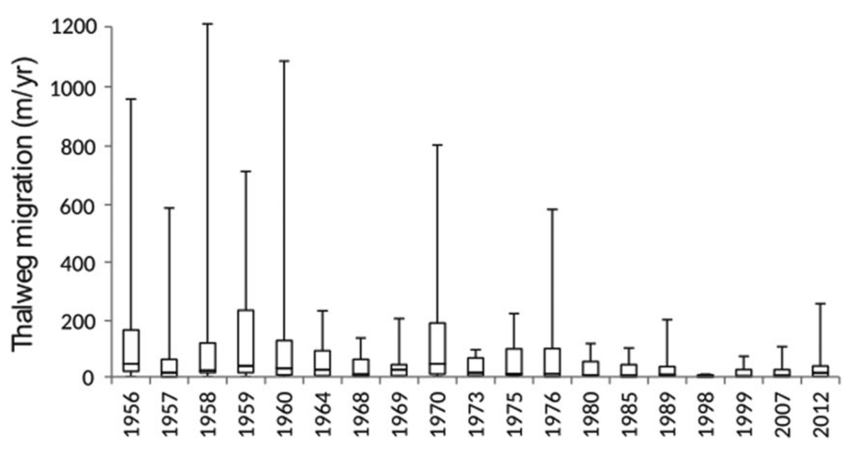

Figure 7. Lateral movement of the channel through time in the Dam Proximal Segment. High values indicate that the river thalweg has shifted locations significantly while low values indicate that the river thalweg has remained in place

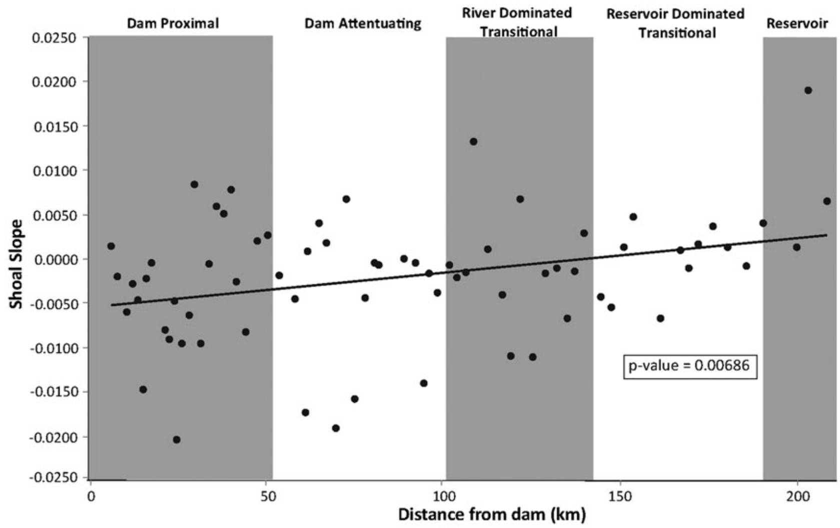

Figure 8. Slope of the shoal metric for the period of record (1946 to 2012) versus distance from the Garrison Dam

immediately below Garrison Dam has virtually no inundated surfaces and can be attributed to island loss and river incision. The steep slope around 30 km is related to a large island associated with a tributary input. The increase in inundated land in the Dam Attenuating zone can be mostly attributed to channel islands, which remained metastable during dam management. In the River Dominated zone, there was a large increase in inundation area as large point bars have developed (many of which were islands, which have become completely bank attached).

DISCUSSION

Long-term effects of dams

Dams result in fundamental changes in landscape and fluvial conditions through the loss of previous governing processes, creation of new transport regimes or transition from one regime to another. Sediment supply has been virtually cut off

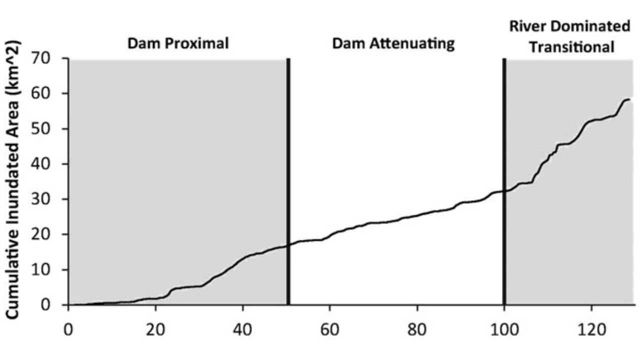

Figure 9. Cumulative inundated land from Garrison Dam to the Oahe Delta

(Jacobson *et al*., 2009) and flow is heavily managed (Skalak *et al*., 2013). As expected, dams have reduced floodplain connectivity as a result of flow management, but there has also been a longitudinal shift of floodplain connectivity when flooding does occur as a result of sediment redistribution in the reach (erosion below the Garrison Dam, deposition above the Oahe Dam), bank stabilization through the reach (approximately 25% of the reach length) and change in island morphology (Figure 9; Skalak *et al*., 2013). During pre-dam conditions, flooding caused avulsion, which resulted in substantial changes in the location of the channel (Johnson *et al*., 2015). Currently, lateral migration of the thalweg has been restricted (Figure 7) by incision below the dam, armoring of the banks, the restriction of upstream sediment supply and the shift towards a single-thread channel in the upper portion of the reach. Additionally, aeolian transport has emerged as a potentially important component of the sediment budget, following the creation of terraced surfaces by the 2011 flood, (Benthem *et al*., 2014, December) and is the subject of additional study. Finally, the transition from lotic to lentic processes within the Reservoir has been documented by others (Junk *et al*., 1989).

There are two significant consequences from alteration of fluvial processes. The first is a fundamental change in the landscape structure through the loss of pre-existing landforms and the creation of new landforms. In the case of the Garrison Segment, channel islands are eroded completely in the Dam Proximal zone. Two new landforms identified in the Garrison Segment are the delta in the Reservoir Dominated zone (which is the subject of additional research) and the creation of large, bank-attached islands, which may become connected to shoreline during low flows in the River Dominated and Reservoir Dominated Transitional zones, the effects of which can be seen in

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Figures 4 and 5 of the current study and in Skalak *et al.* (2013).

The second consequence is a change in state of the channel planform. On the Missouri River, the planform has shifted from a braided system with islands to a single-thread system in the Dam Proximal zone and has become more braided in the Reservoir Dominated zone as a delta forms into Lake Oahe. We believe this change to a single-threaded system drives thalweg stability and limits lateral migration of the river. This is documented in Skalak *et al.*, 2013 and Figure 7 of the present study.

The effect of the 2011 flood on the Missouri River

During the historic flood of 2011, the Garrison Segment of the Missouri River experienced increased discharge and sediment loads (Figure 2; Galloway *et al.*, 2013) that significantly modified river geomorphology locally, but did not result in a return to pre-dam conditions. Long-term shifts in island area (such as losses in the Dam Proximal zone and gains in the Reservoir Dominated zone) were accelerated by the flood (Figures 4 and 5, Table I). The thalweg generally remained stable both vertically and laterally (Figure 7, Table I; Skalak *et al.*, 2013). Changes in channel capacity and shoal area varied longitudinally, and in some reaches, the trends from dams continued, and in others, the trends were reversed (Figure 6a,b, Table I). Johnson *et al.*, (2015) and Dixon *et al.* (2015) assert that the flow release in 2011 provided an unplanned opportunity to assess whether pulsed floods would be adequate to restore a measure of ecological functionality to the Missouri River with respect to riparian vegetation communities. However, because of the ‘geomorphic legacy’ created by dams, they found that this type of flow would be insufficient to restore these communities to pre-dam functionality. Our results confirm that large hydrologic pulses, such as the 2011 flood, do not revert the geomorphic template created by the Garrison Dam nor do they uniformly impact the different river zones or geomorphic features. We believe that other dammed rivers may have similar responses to floods and that their geomorphology will likely not revert towards pre-dam conditions.

Alternate stable state of the Missouri River

Water and sediment supplied to and transported by rivers are the fundamental drivers of a river's state or condition (Wohl *et al.*, 2015). The importance of flow regime on river's ecology and functionality has been well documented (Poff *et al.*, 1997; Poff *et al.*, 2010 and references therein); however, sediment regimes are critical to aquatic and riparian ecosystems as well (Wohl *et al.*, 2015). The geomorphic template created by the interaction between water and sediment largely determines the physical habitat template (Southwood, 1977) and habitat dynamics. The Inter-dam Sequence, identified by Skalak *et al.* (2013), exemplifies a fundamental change in state from a free-flowing river to a dam-regulated system, resulting in a distinct set of geomorphic features. It is valuable to consider the geomorphic change of a dammed river in the context of an alternate stable state as this perspective directly links change in geomorphic form and process to change in ecological functionality and provides a potential future management framework. The present interaction between the geomorphology and ecology has resulted in a unique and stable system that is fundamentally different from the one that existed before dam emplacement. Our results indicate that a 500-year flood event on a managed river with multiple dams does not revert the system towards a pre-dam geomorphic state. We hypothesize that this current condition will likely remain as long as both sediment dynamics and hydrologic conditions remain altered. We also speculate that the current, altered geomorphic conditions will modify the river's response to any short-term restoration of flow and/or sediment, such that the river will not uniformly return towards pre-dam conditions. We believe that similar conditions may also be expected in other river systems impacted by dams.

Ultimately, a change in conditions other than high-magnitude flooding will be required to return the Missouri River to its pre-dam condition or restore the ecosystem to a self-maintaining state. A balanced sediment regime will likely also be required (Wohl *et al.*, 2015). Sufficient conditions may involve either dam removal (not feasible because of agricultural water demand and flood risk abatement) or an altered flow regime from both the Garrison Dam and Lake Oahe water levels accompanied by sediment augmentation. Sediment management alternatives for the Missouri River at Gavins Point Dam have been explored and deemed largely infeasible such as sediment bypass (Yang, 2006; Jacobson *et al.*, 2009) and sediment mining from the upstream reservoir (Coker *et al.*, 2009; Jacobson *et al.*, 2009). It is possible for sediment to be mined from other deposits such as the delta or the floodplain. Floodplain mining has been evaluated on the Platte River, and critical challenges remain, such as the disturbance to the floodplain relative to the volume of material mined (The Flatwater Group, 2014). Restoration of flow, sediment and ecosystem function while maintaining requirements for dam operation remains an exceedingly complex undertaking with no simple solutions.

Ecological effects of an alternate stable state

The faunal response to a changed geomorphic state on the Missouri River has been an overall decline in native bird, fish and plant populations. Historically, channel islands have been a critical habitat for the Interior Least Tern and the Piping Plover to nest. They prefer bare sand patches of medium, well-sorted sand (Catlin *et al*., 2011; Anteau *et al*., 2012; Buenau *et al*., 2014). Skalak *et al*. (2013) demonstrate that channel islands are being eroded in the reach immediately below the dam. Although island area is increasing in the River Dominated zone, most of the increase is a result of an increase in large, vegetated islands, which are only separated from the shore by small, shallow ephemeral channels, which may not provide the same ecologic habitat. This change in island type is a result of the backwater effects of Lake Oahe influencing sedimentation patterns. It has also been documented that the bank attachment allows predators from the floodplain to access the habitat, which would not be possible if the islands were mid-channel and separated by flow (Catlin *et al*., 2011; Anteau *et al*., 2012; Lott *et al*., 2013). Fish populations have also been impacted by changes in geomorphology; research has directly linked dam-induced changes to the decline of the Pallid Sturgeon as a result of loss in spawning habitat, reduction in food supply, altered temperature and flow of water and reduced sediment loads and turbidity (Keenlyne and Evenson, 1989, Pegg *et al*., 2003; Steffenson *et al*., 2013). Declines in the Fort Peck reach's subpopulation have been linked to the large reservoirs, which create zones with reduced dissolved oxygen resulting in increased larval mortality (Guy *et al*., 2015). In addition, the reduction in shoaling areas has implications for the in-channel ATTZ, which has ecological significance for riverine fauna. The 'moving littoral' along the channel margins, islands and sandbars, created by changing water levels, determines the disturbance regime of many riverine species including soft-shelled turtles, shorebirds, riverine fishes and fish-eating birds (Tracy-Smith *et al*., 2012).

The vegetation has responded to the altered geomorphic state through declines (50% or greater) in riparian forest, shrubland and grassland and a sixfold increase in agricultural area along seven reaches of the Missouri River (Dixon *et al*., 2012). In addition, the age distribution of cottonwood stands has matured with relatively little new recruitment as they depend on flooding (Dixon et al., 2012). The 2011 flood removed most of the vegetation that colonized after high flows in 1993. The 2011 flooding spanned the entire recruitment season of that year, and no cottonwood was able to recolonize (Dixon *et al*., 2015). Growth of the following year was limited to lower elevation surfaces, not the high flood deposits from the prior year because flow could not access them in 2012 and provide the seeds for germination (Dixon *et al*., 2015). Cottonwood recolonization was ultimately limited spatially, and the riparian area that was lost from the flooding is much larger than the new areas of regrowth. Because of the change in the geomorphic template and management restricting large flows, the river is not permitted to inundate the floodplain regularly. The historic littoral habitat, which depends on these conditions, will decrease. In order to fully understand the transition of both floral and faunal communities along the Missouri River as a result of dam operations and changes in geomorphology, a state transition model could have potential. State transition models have been invoked to explain the dynamics of individual ecological sites as well as identify 'states' that may exist at a site and how other site characteristics might change with them (Van Dyke, 2015).

CONCLUSIONS

We have presented evidence that dams have created an alternate stable state on the Garrison Segment of the Upper Missouri River with respect to both the geomorphology and ecology. The 500-year flood did not significantly alter the post-dam geomorphic state and did not return the river towards pre-dam conditions. Some geomorphic features reverted towards their original state, and other post-dam trends were enhanced. This new alternate stable state has created a number of different geomorphic changes: the loss of pre-existing landforms, gain of new landforms, a change in the river planform, loss of historic flow and sediment transport conditions and the fractionation of sediment transport processes. These geomorphic and hydrologic changes have resulted in the declines of native species of flora and fauna. Our results suggest that flow restoration through river pulsing would likely be insufficient to restore pre-dam conditions.

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