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Large dams and alluvial rivers in the Anthropocene: The impacts of the Garrison and Oahe Dams on the Upper Missouri River☆

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ABSTRACT

The Missouri River has had a long history of anthropogenic modification with considerable impacts on river and riparian ecology, form, and function. During the 20th century, several large dam-building efforts in the basin served the needs for irrigation, flood control, navigation, and the generation of hydroelectric power. The managed flow provided a range of uses, including recreation, fisheries, and habitat. Fifteen dams impound the main stem of the river, with hundreds more on tributaries. Though the effects of dams and reservoirs are well-documented, their impacts have been studied individually, with relatively little attention paid to their interaction along a river corridor. We examine the morphological and sedimentological changes in the Upper Missouri River between the Garrison Dam in ND (operational in 1953) and Oahe Dam in SD (operational in 1959). Through historical aerial photography, stream gage data, and cross sectional surveys, we demonstrate that the influence of the upstream dam is still a major control of river dynamics when the backwater effects of the downstream reservoir begin. In the "Anthropocene", dams are ubiquitous on large rivers and often occur in series, similar to the Garrison Dam Segment. We propose a conceptual model of how interacting dams might affect river geomorphology, resulting in distinct and recognizable morphologic sequences that we term "Inter-Dam sequence" characteristic of major rivers in the US.

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1. Introduction

One of the greatest modifications of the fluvial landscape in the Anthropocene is the construction of dams. Approximately 800,000 dams have been constructed worldwide (Gleick, 1998; Friedl and Wuest, 2002). On a global scale, river damming has increased the mean residence time of river waters from 16 to 47 days and has increased the volume of standing water more than 700 percent (Friedl and Wuest, 2002). The timescale of major dam-building was contemporaneous globally, with an extreme acceleration in activity in 1950 and a peak in 1968 (Petts and Gurnell, 2005). More than 80,000 dams are currently in the United States with a quarter of these built in the 1960s (Graf, 2005).

Dams provide valuable services such as irrigation, hydroelectric power, navigation, flood protection, and recreational opportunities (Collier et al., 1996; Graf, 1999), but they have had a dramatic effect on river form and function. Dam effects on river morphology and fluvial processes have become increasingly important to watershed management during recent decades. Flow regimes, channel morphology, sediment transport, and ecological processes such as the quality of riparian and aquatic habitats have been influenced by dams (Heinz Center, 2002).

The downstream impact of dams is well documented (Williams and Wolman, 1984; Brandt, 2000; Fassnacht et al., 2003; Grant et al., 2003; Graf, 2005, 2006; Petts and Gurnell, 2005; Schmidt and Wilcock, 2008; Hupp et al., 2009). Several authors have developed generalized conceptual models of the downstream effects of dams on rivers (Brandt, 2000; Grant et al., 2003; Schmidt and Wilcock, 2008). The fundamental cause of channel change is the imbalance between sediment supply and stream flow, leading to post-dam sediment deficit or surplus and channel change that can persist for hundreds of kilometers downstream (Schmidt and Wilcock, 2008). Because of the differing degree of these imbalances (due to varying watershed, climate, and dam characteristics), channel adjustments

☆ The "Anthropocene" is not formally recognized by the U.S. Geological Survey as a geochronologic or chronostratigraphic unit. We use it here informally. Zalasiewicz (2012) discuss the origins of the term.

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downstream of dams are often complex. Previous work emphasizes the variability of downstream channel response which include bed degradation and narrowing, changes in channel bed texture or armoring, bed aggradation, bar construction, channel widening (Williams and Wolman, 1984; Brandt, 2000), or no measurable change (Fassnacht et al., 2003; Skalak et al., 2009). Bed degradation, in some instances, can persist for decades and extend spatially from a few kilometers to as far as 50 km or more (Williams and Wolman, 1984). Bed degradation downstream of the Hoover Dam extended more than 120 km thirty years after dam closure (Williams and Wolman, 1984). Hupp et al. (2009) also suggest that impacts on channel morphology on the Roanoke River are measurable 150 km downstream of the dam. A wide variety of controls have been identified that create a diverse range of geomorphic responses for channels downstream of dams (Grant et al., 2003).

Previous research suggests that sediment loads downstream of dams require long distances to recover. Williams and Wolman (1984) state that the North Canadian River required more than 182 km and possibly as much as 500 km of channel distance to provide enough sediment to have pre-dam concentrations. On the Missouri River (8 km downstream from Gavins Point dam), post-dam sediment load is 1% of pre-dam conditions; 1147 km downstream of Gavins Point dam the post-dam load is only 17% of pre-dam loads (Jacobson et al., 2009; Heimann et al., 2011). Data for the Nile River in Egypt show that 965 km downstream from the dam, post-dam loads are only 20% of pre-dam conditions (Hammad, 1972). Dams exert considerable control upstream in addition to the myriad of downstream channel impacts, with large dams generally retaining sediment with trapping efficiencies near 100% (Syvitski and Milliman, 2007; Williams and Wolman, 1984). Considerable research has been conducted on the upstream effects of dam installation, particularly sedimentation of reservoirs. The principal sedimentation processes in reservoirs is deposition of coarser sediment in the delta and deposition of fine sediment in the reservoir through either stratified or homogenous flow (depending on reservoir geometry and sediment concentration). Other processes such as landslides and shoreline erosion also play a role in reservoir dynamics. Reservoir sedimentology and governing geomorphic processes forming various zones (headwater deltas, deep water fine-grained deposits, and turbidity currents) are generally well-characterized (Vischer and Hager, 1998; Annandale, 2006), and quantified (Morris and Fan, 1998; Annandale, 2006).

Despite significant advancements in the knowledge of downstream and upstream impacts of dams, they are often considered independent of one another. The current governing hypothesis is that the effects of dams attenuate in space and time both upstream and downstream of a dam until a new equilibrium is reached in the system. But given the extremely long distances required for attenuation this gradual attenuation may frequently be interrupted by other dams. Our GIS analysis of 66 major rivers in the US shows, however, that over 80% have multiple dams on the main stem of the river. The distance between the majority of these dams is much closer than the hundreds of kilometers that may be required for a downstream reach to recover from an upstream dam (Williams and Wolman, 1984; Schmidt and Wilcock, 2008; Hupp et al., 2009). For example, Schmidt and Wilcock (2008) metrics for assessing downstream impacts predict degradation of the Missouri River near Bismark, ND, but aggradation has occurred because of backwater effects of the Oahe.

We hypothesize that where dams that occur in a longitudinal sequence, their individual effects interact in unique and complex ways with distinct morphodynamic consequences. On the Upper Missouri River, the Garrison Dam reduces both the supply and changes the size composition of the sediment delivered to the delta formed by the reservoir behind the Oahe Dam. Conversely, the backwater effects of the Oahe Dam cause deposition in areas that would be erosional due to the upstream Garrison Dam and stratifies the grain size deposition. These effects are further influenced by large changes in water levels and discharge due to seasonal and decadal changes in dam operations.

This study introduces the concept of a distinct morphological sequence indicative of Anthropocene Streams, which is referred to as an Inter-dam sequence. Merritts et al. (2011) used the term 'Anthropocene Stream' to refer to—a stream characterized by deposits, forms and processes that are the result of human impacts. We use the Garrison Dam Segment of the Upper Missouri River as a case study to outline a model of morphologic progression between dams. We propose this Inter-dam sequence is simultaneously impacted both in the downstream direction by a dam upstream and in the upstream direction by a dam downstream. Our study also shows that this Inter-dam Sequence is likely prevalent on most large rivers in the U.S. and potentially common across the world.

2. Study site

The Missouri River is the longest river in the United States and is historically important as a major route for settlement of the American West. The River rises in the southwestern part of Montana in the Rocky Mountains and flows east and south for 3768 km until it enters the Mississippi River, north of St. Louis, Missouri (Fig. 1). The basin drains more than 1,300,000 km^2 including portions of ten states and two Canadian provinces and encompasses approximately one-sixth of the conterminous United States. The watershed is semi-arid and has a low discharge relative to its basin area.

2.1. Geology

The Missouri River meanders through a wide alluvial valley bottom in the Great Plains and flows over the Ogallala Group (material eroded off the Rocky Mountains formed during Miocene). The valley bottom is defined by the bluffs and slopes from Tertiary sandstone and glacial deposits (Kume and Hanson, 1965). The current course of the river is largely controlled in the upper reaches by the late-Wisconsinan glacial margin (Kume and Hanson, 1965). The Upper Missouri River displays a largely meandering main stem characterized by extensive mid-channel and lateral sand bars with islands defined as vegetation-stabilized sandbars (Angradi et al., 2004). The Missouri River is predominately sand-bedded.

The Garrison Dam Segment lies at the boundary between the glaciated and unglaciated Northwestern Great Plains. The alluvial valley bordering the Garrison Dam Segment ranges in width from $<$1.6 km near Garrison Dam to $>$11 km south of Bismarck. In many locations the river channel lies at the margin of the alluvial plain and has eroded into Tertiary sandstone bedrock and inset glacial deposits that form bluffs bordering the river. The channel is characterized as meandering in this segment with a sand bed and extensive mid-channel and lateral sand bars that vary in elevation and vegetative development. Most islands are vegetation stabilized sand bars, not typically formed by avulsive processes.

2.2. Human alterations of the Missouri River

During the 20th century, the Missouri River basin was extensively engineered for irrigation, flood control, navigation, and the generation of hydroelectric power. Fifteen dams impound the main stem of the river, with hundreds more on tributaries. The Missouri River contains the nation's largest reservoir system with over 91 km^3 (73 million acre-feet) of storage for irrigation, urban use, and flood abatement storage (Galat et al., 2005; Elliott and

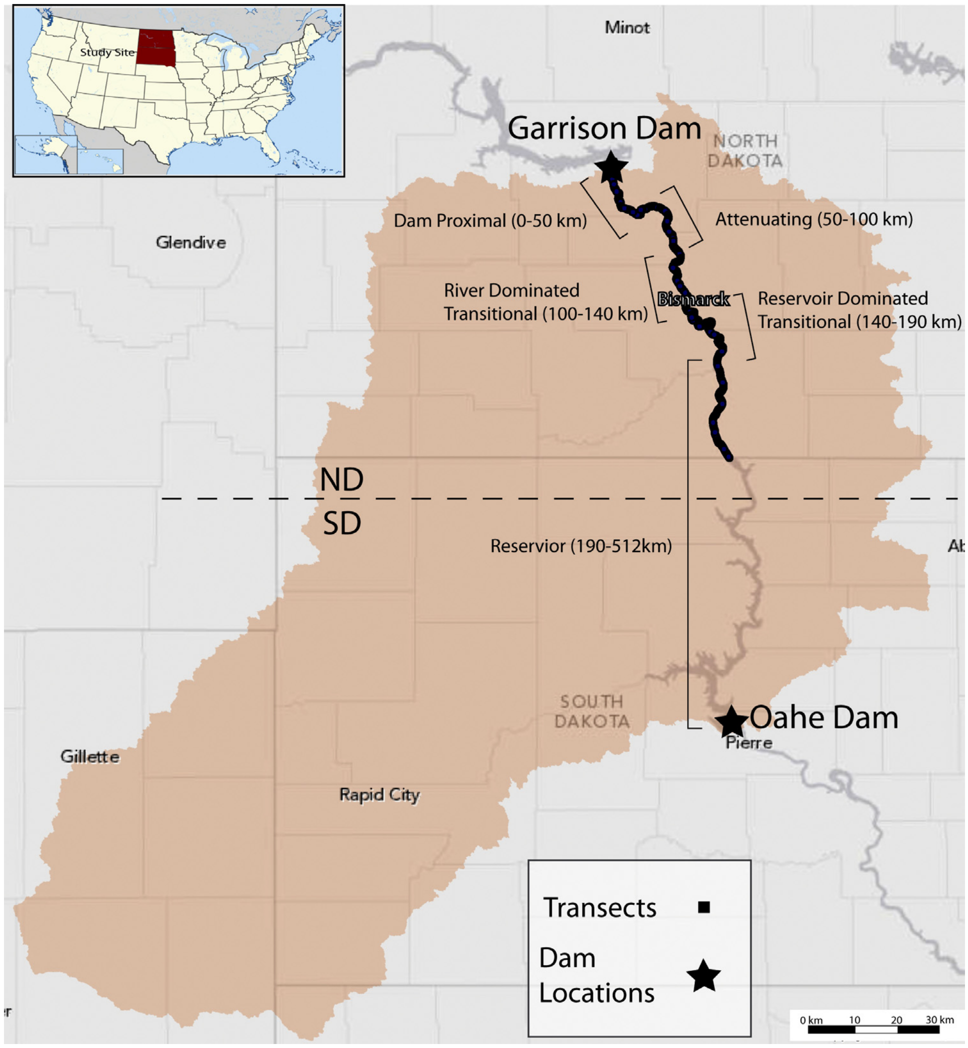

Fig. 1. Map of the study site. In the map of the United States, North and South Dakota are in red. The highlighted region shows the reach extent from the Garrison Dam to the Oahe Dam. The geomorphic zones are also indicated.

Jacobson, 2006; Jacobson et al., 2009). Meanders have been cut off and the river channelized reducing its length by almost 320 km (200 miles) from pre-development times. Before human development, the Missouri River transported more than 298 million metric tons of sediment per year (Jacobson et al., 2009; Heimann et al., 2011). Anthropogenic impacts have reduced this transport to 55 million metric tons in the present day. It is estimated that reservoirs along the Missouri trap roughly 33 million metric tons of sediment each year (USACE, 2000). Human alterations and their impacts on the system's ecology have been considerable. The development of the Missouri River basin has ultimately resulted in many endangered or threatened species of flora and fauna (Whitmore and Keenlyne, 1990; National Research Council, 2002). The conservation organization, American Rivers, listed the Missouri River as North America's fourth most endangered river in 2012 because of flow regulation and management practices (http://www.americanrivers.org/assets/pdfs/mer2012/2012-compiled.pdf, accessed 2/5/2013).

2.3. Garrison Dam segment

The study segment in Upper Missouri River extends 512 river km from the Garrison Dam in ND and the Oahe Dam in SD (Fig. 1). The free-flowing (but regulated) segment is approximately 129 river km (80 miles) long with over 81 additional river kms of variability (50 miles) dependent on reservoir levels at Lake Oahe. At low reservoir levels the free-flowing segment of river ends near the SD border while at high levels the free-flowing segment of the river may end near Bismarck, ND. Two primary tributaries contribute to the free-flowing segment: the Knife River enters the Missouri River near Stanton, ND and the Heart River joins the Missouri immediately downstream of Mandan, ND.

The river segment is used for recreation, irrigation, flood control, water supply, fisheries, and habitat for threatened and endangered species including the Least Tern (Sternula antillarum), Piping Plover (Charadrius melodus), and Pallid Sturgeon (Scaphirhynchus albus). The Least Tern and Piping Plover utilize sand bars for breeding season habitat, which has resulted in extensive efforts to characterize the patterns and trends of these features in addition to habitat management by plant removal and sand replenishment efforts.

Construction of the Garrison Dam began in 1946, and was completed in 1953. Releases for the production of hydroelectricity began in 1956. The Oahe Dam was completed in 1959. The impact on hydrology of the Garrison Dam is typical of large dams: reduction in peak discharges and increases in baseflow (Fig. 2). The river discharge varies several m^3/s daily due to demand for power generation and seasonally to accommodate technical, environmental, and navigational needs. Mean annual peakflow prior to dam construction was 3398 m^3/s. The peak of record occurred

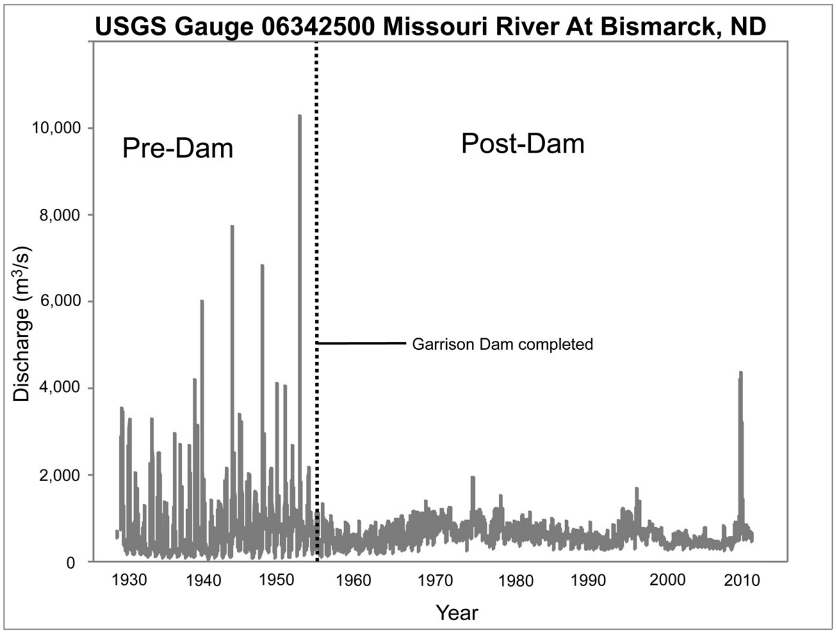

Fig. 2. Hydrograph for the stream gage at Bismarck (USGS 06342500). The year the Garrison Dam was completed is indicated separating pre- and post-dam flows. There is an increase in baseflows and decrease in peakflows as a result of the dam.

immediately before dam completion in 1953 with a peak discharge of 10,279 m^3/s (Fig. 2). Mean baseflow prior to dam construction (1928–1953) was 121 m^3/s.

Post-dam, the mean monthly discharge in the Garrison Segment is approximately 623 m^3/s at the USGS streamgage in Bismarck, ND (USGS ID: 06342500). Flow inputs by the Knife and Heart Rivers tend to peak in the spring with snow melt, occasionally briefly peaking above 850 m^3/s, but decreasing to nearly 0 m^3/s during the late summer and fall. The mean discharge is 15 and 8 m^3/s for the Knife and Heart Rivers, respectively (see USGS streamgage 06340500, and 06349000 for information on the Knife and Heart Rivers, respectively). Two major floods have occurred since dam regulation: the largest flood, which is the subject of additional studies, occurred in 2011 with a discharge of 4390 m^3/s (Fig. 2). The other major flood in 1975 had a discharge of 1954 m^3/s.

Previous studies on the Garrison Dam segment of the Missouri River provide a useful context and data for this study (Biedenharn et al., 2001; Berkas, 1995). Berkas (1995) published a USGS report on the sources and transport of sediment between 1988 and 1991. Grain size data presented in Fig. 8 of this report is presented from Schmidt and Wilcock (2008) along with data collected during this study to document textural changes in the bed downstream of the dam.

3. Methods

The interaction of the effects of the Garrison Dam and Oahe Dams were estimated using two primary sets of data: (1) historic cross-sections from the U.S. Army Corps of Engineers (USACE) from various years between 1946 and 2007, (2) aerial photos for the segment between Garrison Dam and the city of Bismarck from 1950 and 1999.

3.1. Analysis of cross-sections

USACE has surveyed repeat cross-sections every few river kms downstream of the Garrison Dam for a total of 77 cross sections over 253 km. Different sections of the river are surveyed every 1–8 years from 1946 to present offering an extensive but often temporally unsynchronized snapshot of the river. A total of 802 surveys were entered into a database and analyzed for changes in cross-sectional area and minimum bed elevation. Cross-sectional areas were calculated using the elevation of the highest recorded water level during the survey period at-a-station (Eq. (1)). The river is heavily managed for flood control and since dam construction only one event (May 2011) has overtopped the banks. Therefore, it can be assumed that the highest recorded water height prior to 2011 (*H*, Eq. (1)) at each cross-section approximates de facto bankfull conditions during normal dam operations.

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

where *H* is bankfull height (m), *E* is survey elevation (m), *i* is a location at a cross-section, and ΔE is the calculated elevation difference. Cross-sectional area for each year was determined using this fixed height (Eq. (2)).

$$\Sigma\left(\frac{(\Delta Ei + \Delta Ei + 1)}{2}\right) \times (Di - +Di + 1) = A \tag{2}$$

where *D* is the cross-stream distance (m) and *A* is the cross-sectional area (m^2).

The percent change in cross-sectional area, was calculated by subtracting the cross-sectional area from the oldest measurement from the relevant year measurement and divided by the oldest measurement. Not every cross-section was surveyed each year thus the oldest time frame can vary from 1946 to 1954. The free-flowing section of the river was most recently surveyed in 2007. Surveys taken in the reservoir at Lake Oahe (190+ km) have surveys over a shorter time frame (1968–1989). Despite the shorter time frame the trends in reservoir channel change are still considered applicable.

The rate of change in the thalweg bed elevation was calculated as a function of downstream distance and year by determining the minimum elevation of each cross-section (or the maximum depth of the channel), subtracting it from the minimum elevation of the cross-section for the next available year of data, then dividing by the time interval between the two measurements (Eq. (3)).

$$\frac{\mathrm{BE}\,t1 - \mathrm{BE}\,t2}{t1 - t2} \tag{3}$$

where BE is the minimum bed elevation (m) and *t* is time (years).

Channels vary naturally through space and time. To attribute a geomorphic change to an anthropogenic disturbance, it must be outside the range of the natural variability and should be statistically significant. This was calculated using the Williams and Wolman (1984) method; ergodically assuming that longitudinal variation in a single year can approximate at-a-station variability through time. The mean pre-dam channel cross-sectional area along the entire segment (irrespective of the defined geomorphic zones) and standard deviation was calculated. The study included all cross sectional data available from 1946, which is the only year of the survey data before the dam was completed. The spatial standard deviation was used to approximate natural variability and compared to the changes at each cross sections.

3.2. Analysis of historical aerial imagery

Historical photos from 1950 and 1999 were used to compare change in island area. Photos were georectified using ArcGIS version 10.1. The channel banks and islands were delineated for each year and the aerial difference between the channel and island boundaries were determined. Water levels along the river vary due to seasonal and annual weather patterns, dam operations, tributary influx, and reservoir levels. This consideration is particularly germane with respect to sand bars as the area exposed (and therefore quantified) depends largely on flow depth. The 1999 photo set provides the best comparison to the pre-dam photos (1950) due to similar discharge rates from the Garrison Dam (841 and 835 m^3/s respectively or $\sim$0.7%) and stage gage at Bismarck, ND. All other historical imagery available was collected with discharge differences of 10% or greater related to the pre-dam 1950 images. The spatial extent of the aerial photo analysis ranged from the Garrison Dam to the upper section of Lake Oahe (approximately 130 km downstream of the Garrison Dam); this is the farthest downstream extent of the 1950 images.

Image quality of historical aerial photography is often poor, and distortion and clarity are common issues. The aerial photos from 1999 provided by USACE were orthorectified. These orthorectified images were used as a baseline to georectify the 1950 photo set. A minimum of 10 control points per 5 km of river were used. Points were selected as close to the river's edge as possible and evenly distributed along the stream length in the photos. Georectification was performed in ArcGIS "Adjust" transformation, which utilizes a combination polynomial least fitting square transformation with a triangular irregular network interpolation. Given the georeferencing algorithms and the fact that the photos were taken in an overlapping series, delineation was limited on each frame to areas internal to the distribution of control points. Common control points were building corners, road intersections, bridges, uniquely identifiable trees, and distinct morphologic features such as bedrock outcrops.

3.3. Inter-dam sequences

Interacting dam effects were analyzed using distance criteria related to sediment loads and geomorphic adjustment determined from previous research. Williams and Wolman (1984) indicate bed degradation can persist up to 50 km, Hupp et al. (2009) and Schmidt and Wilcock (2008) indicate that geomorphic effects can persist for more than 100 km and sediment loads can require more than 1000 km to recover (Williams and Wolman, 1984; Jacobson et al., 2009). Results from previous work on individual dams incorporate a temporal component cannot be adequately applied in this study due to the number of dams in place, the temporal difference in dam completion along the river, and unknown downstream dam impacts. Additionally dam impact distances are highly dependent on physiography, river hydrology, and dam type. Therefore, a conservative estimate of impact distances are used: significant geomorphic effects are predicted up to 25 km from the dam, discernible impacts are predicted up to 100 km from the dam, and minor impacts are predicted up to 1000 km from the dam. This distance range is used to estimate the prevalence and impact type of interacting dams in the United States.

A GIS analysis of 66 major rivers within the contiguous United States was conducted. Rivers were chosen based upon Benke and Cushing (2005) regional watershed lists. Dams were identified using USACE National Inventory. For each river, only the main river stem was considered and river distanced delineated in ArcGIS to the nearest km. We used grain size data previously published by others for the Upper Missouri River (Berkas, 1995) combined with bed sediment data collected in 2012 to generate a hypothetical stratigraphic section for an Inter-Dam Sequence. 2012 sediment data was collected along the thalweg using a grab sampler (USGS BM60) and samples were dry sieved using a Ro-tap shaker and separated into bins. An inverse Phi-scale (Krumbein, 1938) was used to illustrate grain size. Longitudinal trends were identified using a standard regression analysis.

4. Results

4.1. Geomorphic units downstream from Garrison Dam

The Garrison Dam exerts considerable morphological control on the channel until the backwater effects of the Oahe Dam and reservoir begin to influence the channel. Analysis of historic cross-sections (Figs. 3 and 4, Appendix A) and channel planform (Fig. 5) produced a series of geomorphic classifications along river. The segment between the Garrison and Oahe dams was divided into five geomorphic reaches termed: Dam Proximal, Dam-Attenuating, River-Dominated Interaction, Reservoir-Dominated Interaction, and Reservoir. The divisions are based on changes in cross-sectional area, channel planform, and morphology, which are often gradational.

The Dam Proximal reach of the river is located immediately downstream of the dam and extends 50 km downstream. The cross-sectional data and aerial images suggest that the Dam Proximal reach of the river is eroding the bed, banks, and islands (Fig. 5). The standard spatial deviation of cross sectional area for all cross sections on the river in 1946 was 269 m^2. All 22 sites examined in the Dam-Proximal reach (Appendix A) experienced an increase in cross-sectional area that is greater than this natural variability. As an example, Fig. 3A is a typical cross-section in the Dam Proximal reach and has lost 1364 m^2 of cross-sectional area between 1954 and 2007 (Fig. 3A, Eq. (2)). The thalweg elevation at the transect decreased by as much as 1.5 m between 1954 and 2007, evidence that much of the material scoured from the channel in this location came from the bed (Fig. 3A). Laterally, the banks scoured as much as 45 m in other areas. The aerial images shown in Fig. 5A also indicate that most of the islands in the area have eroded away (red areas). The historical aerial photo analysis indicates that the island surface area lost is approximately 35,000 m^2. The areal extent of islands in 1999 was 43% of what is was in 1950.

The Dam-Attenuating reach extends from 50 to 100 km downstream of the dam. The islands in this reach are essentially metastable (adjusting spatially but with no net increase or decrease in areal extent). The reach itself has experienced net erosion with respect to the bed and banks, but to a lesser extent than the Dam Proximal reach. Twelve of the 14 cross sections in the Dam-Attenuating reach show an increase in cross-sectional area greater than the 1946 natural variability (269 m^2). Fig. 3B is representative of the reach and has had an increase in cross-sectional area of 346 m^2. The reach gained a net of 3300 m^2 in

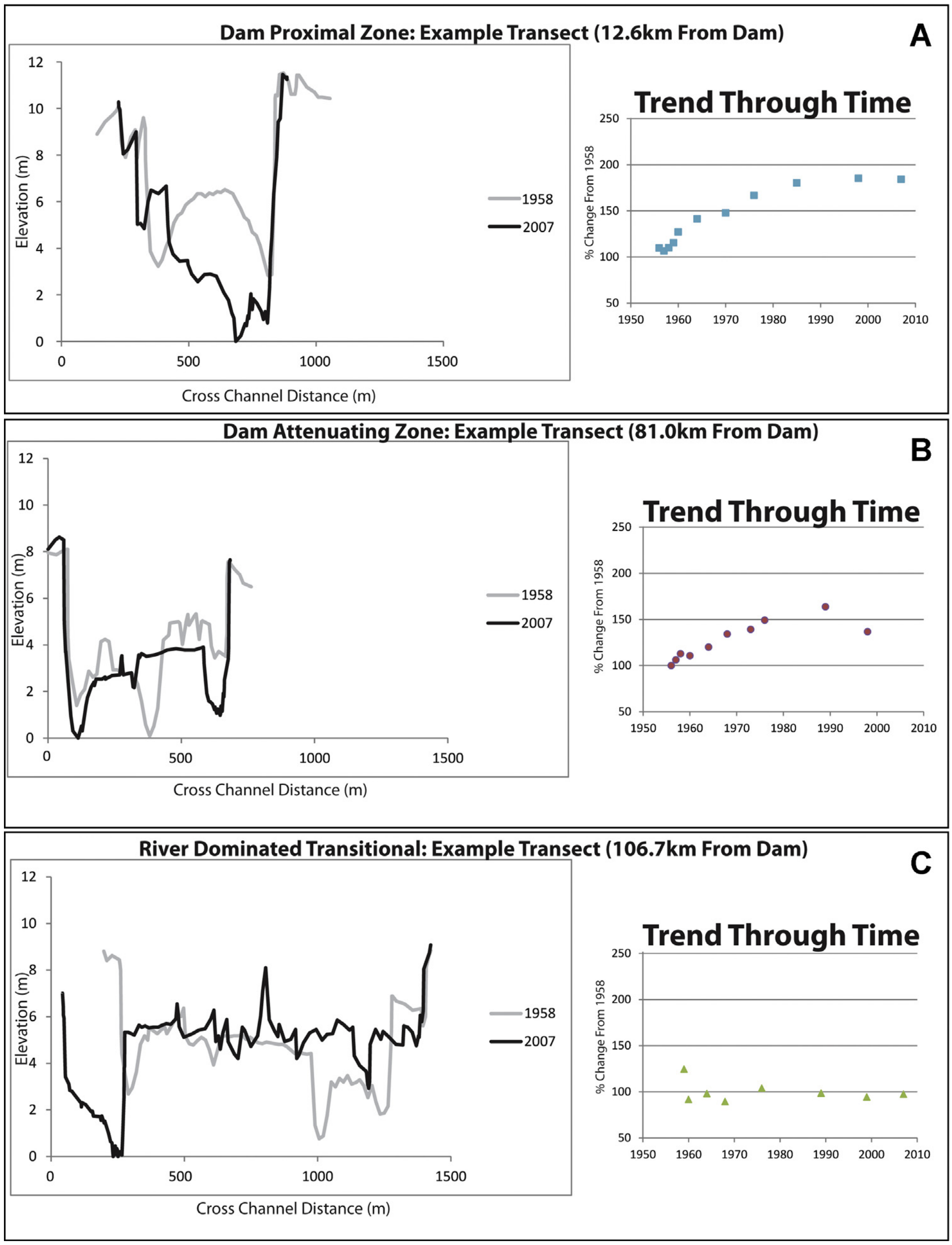

Fig. 3. Channel cross-sections for individual transects. (A) The Dam Proximal zone is eroding through time and there is a clear loss of a channel island or sand bar. The trend is attenuating through time. (B) The Dam Attenuating zone is eroding through time although that trend is less than the Dam Proximal zone. (C) The River Dominated Transitional zone is mostly stable through time.

island area from 1950 to 1999 which represents a 16% increase. All major islands present in 1950 were still present in 1999 with similar geometries and distribution (Fig. 5B).

4.2. Geomorphic units from longitudinal dam interactions

The River-Dominated Interaction reach extends from 100 to 140 km downstream of the dam. This reach is characterized by an increase in islands and sand bars and minimal change in channel cross-sectional area. 4 of the 11 sites have erosion greater than the natural variability (269 m^2) and 5 of the 11 sites are depositional. The cross-section in Fig. 3C is typical of this reach and has a relatively small decrease in the cross-sectional area between 1958 and 2007 (25 m^2), less than the natural variability. However, the banks widened more than 518 m (Fig. 3C). Channel widening due to dam influence can result from several factors. An increase in islands and lateral sand bars in the reach is also shown in Fig. 5C. Analysis indicates that the reach gained 23,600 m^2 of island area in 40 km of reach (the length of the reach is limited by the extent of the aerial photos). The areal extent of island area in 1999 was 150% greater in 1950. Additionally, the island morphology has shifted from in-channel islands (indicative of the pre-dam river) to large islands attached to the outside of meander bends with distinctive distributary channels running through them. These are essentially former islands that have become attached to the banks as a result of excess sediment cutting off side channels.

The Reservoir-Dominated Interaction reach is located 140–190 km downstream from the Garrison Dam. Reservoir effects vary both annually and seasonally due to changing reservoir levels creating a recognizable deltaic morphology. The Reservoir-Dominated Interaction reach is characterized by aggrading islands, sand bars, and the flooded meander bends (former meanders that

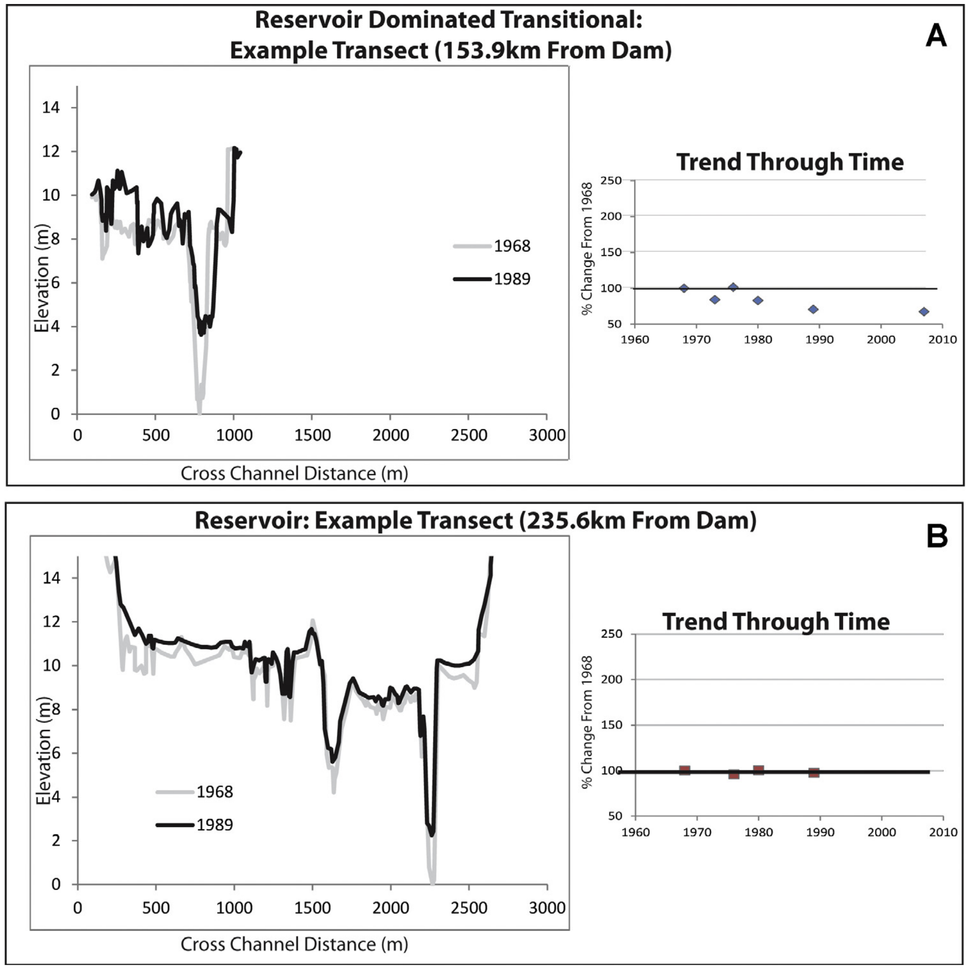

Fig. 4. Channel cross-sections for individual transects. (A) The Delta zone shows a decrease in cross-sectional area from 1968 to 1989. The data indicates deposition is attenuating through time. (B) The Reservoir zone shows relatively little change from 1968 to 1989 and the trend through time is essentially a straight line.

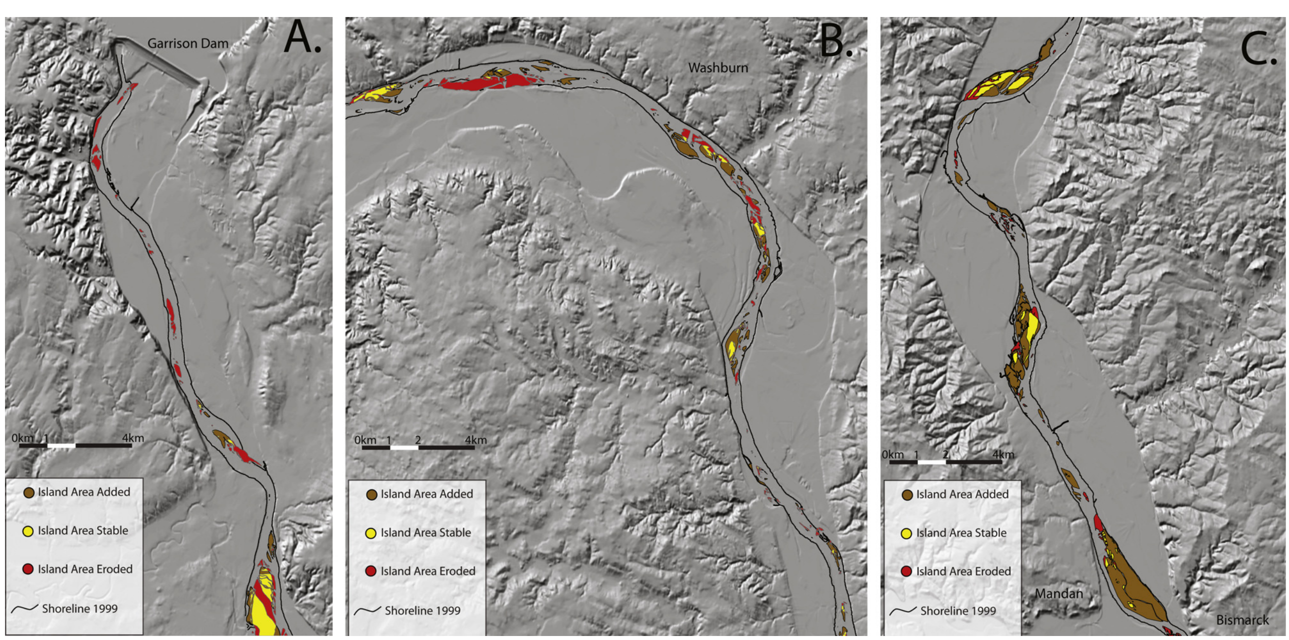

Fig. 5. Island delineations from 1950 to 1999 for: (A) the Upper zone, (B) the Middle zone, and (C) the Lower zone. Eroded areas are shown in red, stable areas are shown in yellow, and depositional areas are shown in green.

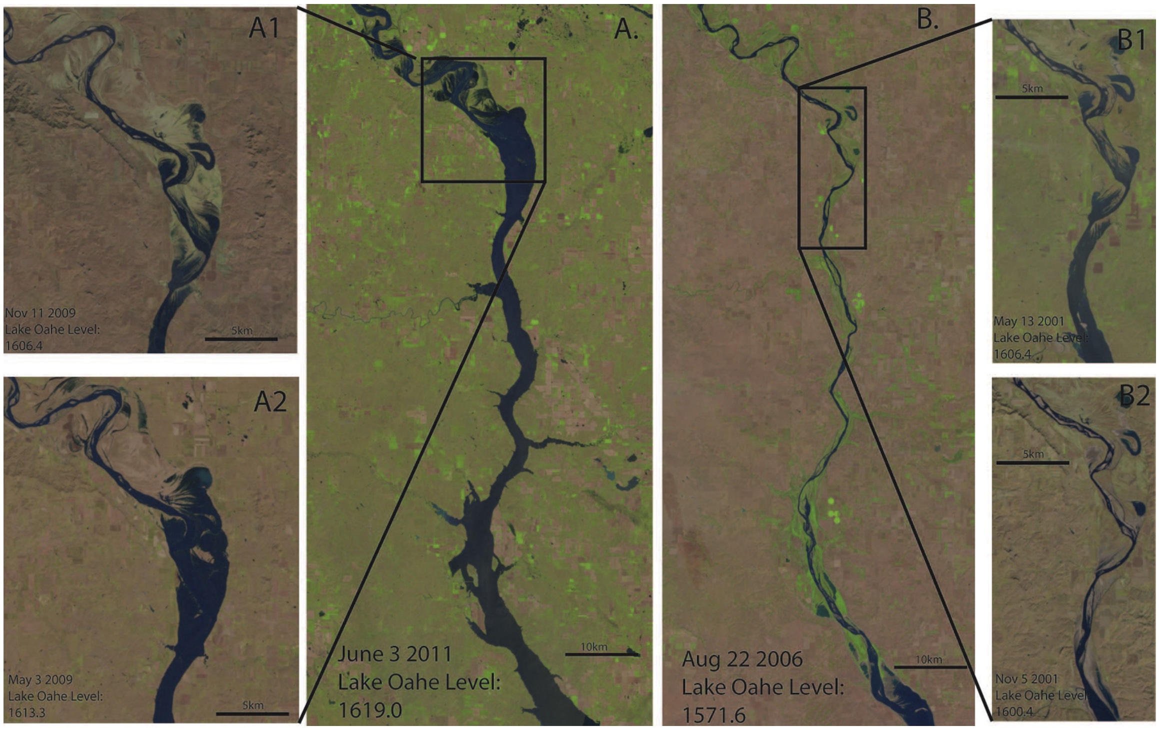

Fig. 6. Aerial images of the Delta zone through various points in time demonstrating the temporal variability in reservoir levels for the maximum (A) June 2011, and minimum (B) August 2006, and variation within a single year (A1) November 2009 and (A2) May 2009 and (B1) May 2001 and (B2) November 2001.

have been flooded by the reservoir). 9 of 11 sites indicate deposition greater than the natural variability (269 m^2). Fig. 4A is typical of cross sections in this area and shows al decrease in cross-sectional area of 411 m^2. No suitable historic aerial imagery was available for this section of the river but current conditions indicate higher levels of low elevation sand bars than other sections of the river. The active extent of this reach can migrate drastically from year to year depending on the reservoir level (as much as 160 km longitudinally, Fig. 6). Although the 50 km reach encompasses most of the delta in a typical discharge year, changes in releases from either dam can substantially change the active extent of the reach. Consequently, the depositional morphology and ultimately the Reservoir-Dominated Interaction reach can have a broader spatial distribution (Fig. 6A and B) than can be accounted for by a single year (insets A1 and A2, B1 and B2). Although the lake level and backwater effects are highly spatially and temporally variable, the most recent set of aerial photos indicate the area of maximum deposition encompasses only this 50 km section of river. The morphology of this reach changes with varying lake levels. Islands, flooded meander scrolls, and deltaic splays are alternatively exposed and flooded. A large numbers of dead trees from flooding and those washed downstream litter the landscape and are present in channel.

4.3. Geomorphic units upstream of the Oahe Dam

The Reservoir reach (Lake Oahe) is remarkably stable. This reach extends from approximately 190 km to just upstream of the Oahe Dam; 512 km downstream from Garrison Dam. Cross-sections in this section extend into the first 100 km into this reach. All 12 cross sections in the Oahe reach shows deposition greater than natural variability from 1963 to 1989 (269 m^2). It should be noted that because the lower floodplain is impounded (unlike other sections of the river), the deposition that occurs is spread out laterally rather than vertically. Thus, even though the cross-sectional area for the surveyed sample transect in this reach has changed by 1353 m^2, the overall change in channel capacity is only 2.5%. General channel morphology, as shown in Fig. 5B, remains stable and all pre-dam islands in this reach are submerged under several meters of water.

4.4. Spatial trends in geomorphic adjustment

The river has experience the most erosion near the dam (Dam Proximal which diminishes downstream through the Dam-Attenuating reach (Figs. 7 and 8, Appendix A, Table 1). Upon reaching the River-Dominated Interaction reach the cross sectional area is stabilizes and begins to be depositional in the Reservoir-Dominated Interaction reach. Deposition occurs in the reservoir reach but due to increased water level and area this deposition has had little effect on the channel morphology (Figs. 4 and 8). Banks experienced erosion in the upper section of the Garrison Dam Segment which decreases downstream eventually becoming stable or depositional (Table 1).

Longitudinal island trends post-dam show a similar pattern of erosion near the dam and deposition near the reservoir but with significantly different transitional locations relative to cross sectional area and banks. The islands immediately downstream of the Garrison Dam in the Dam Proximal reach have eroded away (Fig. 5A, Table 1). The surficial area and configuration of pre-dam islands are retained in the Dam-Attenuating reach of the river even as the river channel erodes in this section (Fig. 5B, Table 1). In the River-Dominated Interaction reach (Fig. 5C) the islands have grown substantially in area and the morphology of bank attached sand bars have changed, creating a distinct distributary stream (Fig. 6, Table 1). No pre-dam aerial photos were available for the Reservoir-Dominated Interaction reach or the Reservoir reach but the main channel is flooded and all historic islands are below current water level. All current islands in this stretch appear to be the tops of flooded meander scrolls.

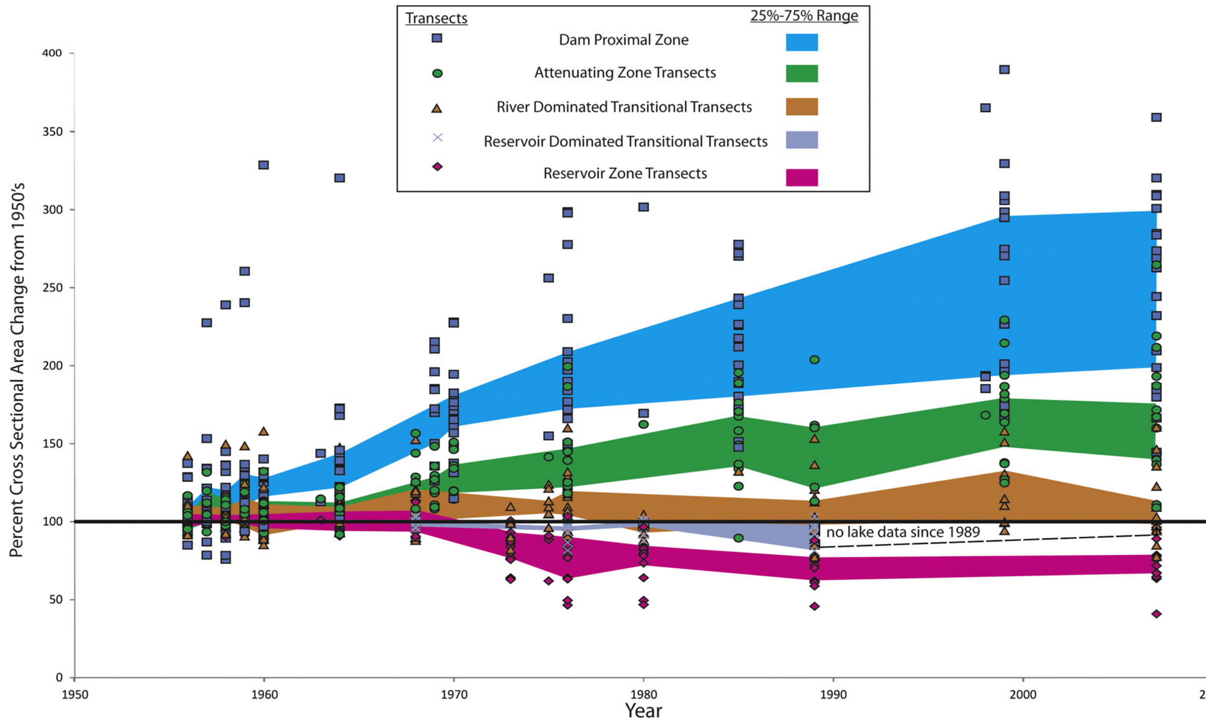

Fig. 7. Percent change in cross-sectional area at an individual cross-section through time. The shaded regions represent the 25–75% data range of the various geomorphic zones described in Section 4. The blue band is the Dam Proximal zone and indicates the greatest increase in cross-sectional area through time. The green band is the Dam Transitional zone which is still erosional (although less than the Dam Proximal zone). The orange band is the River Dominated Transitional zone which shows no real net change through time. The pink band is the Reservoir Dominated Transitional zone and indicates a decrease through time. The light blue band is the Reservoir zone and has little vertical growth.

Longitudinal patterns in bed sediment data indicate that grain size decreases with distance from the Garrison Dam (Table 2). The linear regression has a $r2$ of 0.32 with a p-value of 0.07 (Equation, Inverse Krumbein Phi Scale = 0.0194 × River Miles-21.728).

4.5. Temporal trends in geomorphic adjustment

Temporally, the data suggest that individual cross-sections within each study reach are approaching a steady state (inset panels in Figs. 3 and 4). Erosion rates in the Dam Proximal and Dam-Attenuating reaches decrease exponentially. The Reservoir-Dominated Interaction reach and Reservoir are both depositional. Channel capacity in the Reservoir, however, is relatively small and the trend is decreasing. The general patterns for each reach are similar to the data at individual stations, but demonstrate greater variability through time (Fig. 7).

The rate of change for the thalweg bed through time for the upper (Fig. 9A, Appendix B) and lower (Fig. 9B, Appendix B) parts of the river indicate a difference in the temporal response to the dam. Each line in Fig. 9 represents the minimum bed elevation

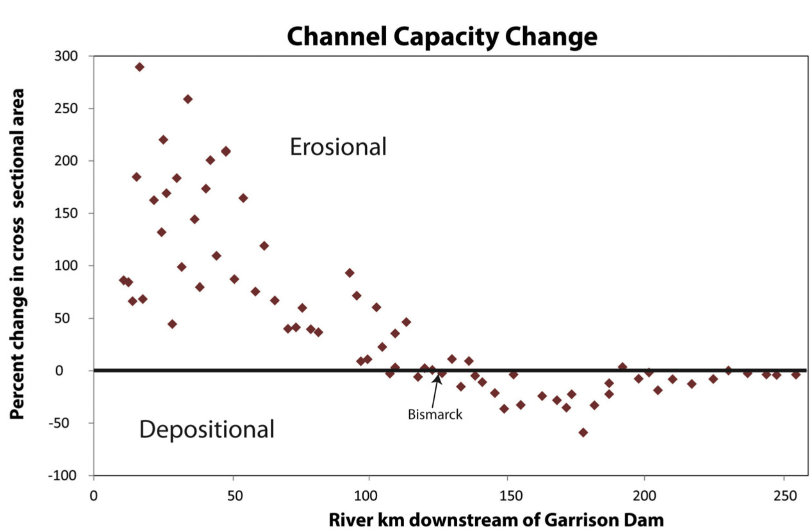

Fig. 8. Percent change in cross-sectional area from 1950s to the present versus distance downstream from the Garrison Dam. Erosional and Depositional areas are indicated. An arrow indicates the location of the city of Bismarck, ND. A dashed line indicates the hypothetical attenuation of erosion downstream of the dam. Diversions from this trend are hypothesized to be from the impact of the Oahe Dam.

Table 1
Spatial trends in bank erosion and deposition and percent change in island area.

Distance downstream from Garrison Dam (km)	1950 islands area (km²)	1999 islands area (km²)	Distance from dam (Army Corp Miles)	% island change	Bank erosion area (km²)	Bank deposition area (km²)	Net change area (km²)
0–8.06	0.33	0.00	0–5	−100.00	1.20	0.32	−0.88
8.23–16.13	0.30	0.21	5–10	−28.80	0.08	0.67	0.59
16.29–24.19	2.04	1.96	10–15	−3.94	0.27	0.76	0.49
24.35–32.26	1.87	0.17	15–20	−90.83	2.01	0.85	−1.16
32.42–40.32	1.65	0.40	20–25	−76.07	2.17	1.24	−0.93
40.48–48.39	0.43	0.71	25–30	65.95	0.57	2.11	1.54
48.55–56.45	1.18	0.40	30–35	−66.02	0.48	1.13	0.65
56.61–64.52	0.77	1.03	35–40	32.88	0.01	1.06	1.05
64.68–72.58	0.30	0.61	40–45	105.95	0.03	0.91	0.89
72.74–80.65	0.35	0.60	45–50	74.38	0.72	1.62	0.91
80.81–88.71	0.24	0.75	50–55	214.58	0.01	1.74	1.73
88.87–96.77	0.91	1.61	55–60	77.75	0.00	0.91	0.91
96.94–104.84	0.12	0.25	60–65	103.23	0.43	1.28	0.85
105.00–112.90	0.58	4.25	65–70	630.01	0.26	0.73	0.47
113.06–120.97	0.54	5.75	70–75	967.35	No data	No data	No data
121.13–129.03	0.15	0.62	75–80	308.58	No data	No data	No data

through time for an individual cross-section within the reach. The upstream channel has adjusted to the new hydrologic regime of the dam over a few decades. Fig. 9A shows the bed essentially stabilized by about 1975. The upper section of the river shows no change from the 1975 flood (1956 m^3/s in Bismarck, ND). The lower section has not achieved a new equilibrium following dam completion. The maximum depth of the thalweg did not stabilize until the mid-1990s in the River-Dominated Interaction reach and remains more active than the Dam-Proximal reach (Fig. 9B).

4.6. Prevalence and spatial distribution of Inter-Dam sequences in the US

Of the 66 major rivers analyzed, 404 dams were located on the main stem of 56 of the rivers. Fifty of these rivers had more than one dam on the river creating a total of 373 possible Inter-Dam sequences. The average distance between these dams is 99 km (median less than 50 km and the range is 1 to more than 1600 km). Thirty-two percent of the Inter-Dam sequences had lengths of 25 km or less, 41% were less than 100 km, and 26% of the dams

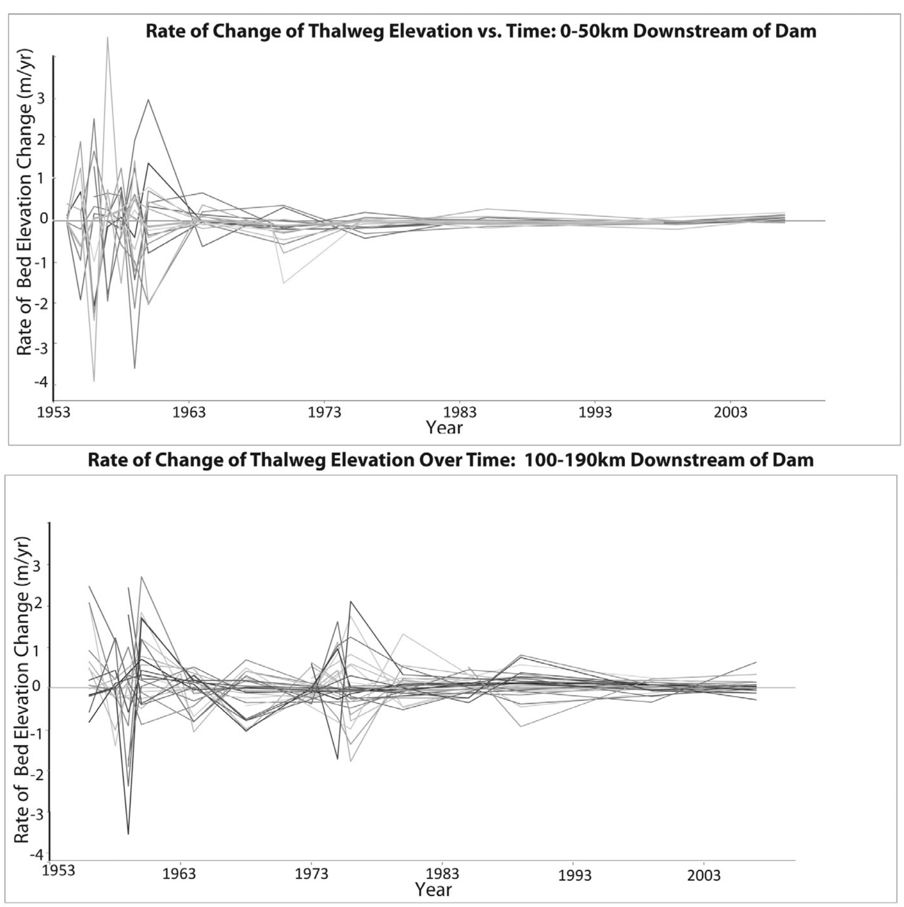

Fig. 9. (A) Rate of change of the thalweg elevation through time for the Upper zone (50 km downstream of the dam). (B) Rate of change of the thalweg elevation through time for the lower zones (100–190 km downstream of the dam).

Table 2
Grain size of bed sediment versus river km downstream of Garrison Dam.

Distance downstream of Garrison Dam (km)	Inverse Phi Scale
27	3.5
28	3
44	3.6
49	3.9
64	4
73	3.9
78	6
93	4.7
114	3.2
144	4.6
205	6.6

were within 1000 km of one another. Only one Inter-Dam Sequence was identified to be longer than the 1000 km. These results suggest that there are numerous large dams occurring in sequence on rivers in the US.

5. Discussion

Results of this study suggest that the two dams in the Garrison Dam Segment interact to shape the river morphology, although it is important to distinguish the interaction does not control the entire segment, and some sections only respond to one dam. Five geomorphic gradational zones were identified in the segment between the Garrison Dam and the Oahe Dam and three are influenced by this interaction. The major impacts on channel processes downstream of the Garrison Dam are identified: (1) erosion from the bed and banks immediately below the dam as a result of relatively sediment-free water releases, (2) localized deposition farther downstream as a result of material resupplied to lower reaches from mass wasting of the banks, tributary input, and bed degradation, and (3) the capacity for large floods and episodic transport of material has been limited. Similarly, the predicted upstream responses of the Garrison Segment to the Oahe Dam are: (1) the creation of a delta in a fining upwards sequence that migrates longitudinally both upstream and downstream. (2) The sorting by sediment size as velocities decrease in the reservoir. Previous studies on dam effects suggest that these effects will propagate and dissipate (downstream or upstream respectively) until a new equilibrium is achieved. In the Garrison Dam Segment, the downstream impacts reach the upstream impacts before the full suite of these anticipated responses occur. As a result, there are a unique set of morphologic units in this reach.

The Dam-Proximal and Dam-Attenuating reaches are not affected by any dam interaction. Sediment-free water leaving the dam has scoured the pre-existing islands and sandbars in the Dam-Proximal reach; these effects attenuate downstream as local sediment is introduced to the system. As predicted by the standard dam model, erosion continues downstream of the dam until a new stable channel form is achieved (Williams and Wolman, 1984). This new equilibrium will be based on a number of factors such as vegetation, bedrock controls, bed armoring, or other local control. As such, the eventual stable state of the river will be highly variable and dependent on location. In the Dam-Attenuating reach net channel erosion continues but is reduced and islands and sand bars are metastable in geometry. The disconnect between channel erosion and island stability is likely due to flow regulation by the dam. Dam regulation lowers peak floods and enhances baseflow discharges which can result in a stable channel thalweg (Fig. 3B). Initially, the channel will excavate the bed, but if the thalweg does not migrate that process is ultimately limited both vertically and

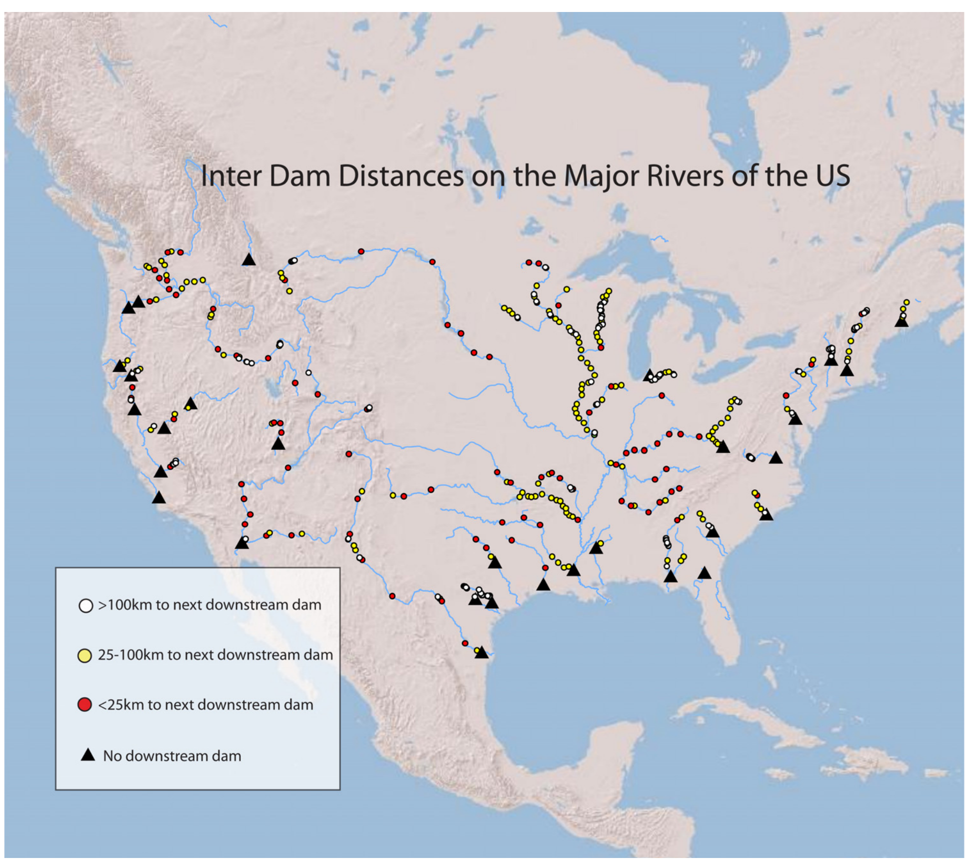

Fig. 10. Map of potential interacting dams based on the distance criterion described in Section 3. Dams within 25 km upstream of another dam are shown in red circles. Dams within 100 km of another are shown in yellow. Dams greater than 100 km apart are shown in green.

horizontally. Consequently, capacity increases because of bed and bank erosion, but islands remain stable laterally. Flows do not often overtop the islands and therefore vertical erosion does not occur.

In the River-Dominated Interaction reach the river experiences the beginning of backwater effects of the Oahe Dam. Water velocity slows and the coarsest material is deposited. With peak discharges reduced due to dam operations, this material is not transported and is deposited on the outside of the main river channel (forming bank-attached islands). Further downstream, large amounts of sediment accumulate in the Reservoir-Dominated Interaction reach and fills in the historical thalweg resulting in accumulation on the flooded banks (Fig. 4). The inundation, in turn, then causes additional backwater effects upstream resulting in additional infilling. The exact location of these processes can shift substantially longitudinally due to fluctuating reservoir levels and upstream dam discharges. Many of the features found in this reach are the result of the creation of deltaic deposits during one season and the subsequent modification as the active process in the location shifts. The Reservoir reach (Lake Oahe) is depositional but, given the lateral extent of the channel due to impoundment, the vertical bed accumulation is small and the morphology remarkably stable through time (Figs. 4 and 5). Reservoir and delta sedimentation in this reach is reduced significantly due to the trapping of sediment in the upper reservoir (Lake Sakakawea above the Garrison Dam) and regulated dam flows limit storm induced transport. This has the effect of magnifying the sediment sorting, limiting the dynamic response of the delta, and potentially stabilizing its location (relative to a delta without an upstream dam).

5.1. Interaction over time

While the river below the dam appears to have reached a new equilibrium in each of the reaches, the effects of the Garrison Dam will continue to migrating downstream over time while at the same time the effects of Oahe migrate upstream by shifting the boundaries of the reaches.

The initial response to the dam closure appears to have occurred. In the Dam-Proximal reach, channel adjustment has been largely achieved a steady state with respect to minimum bed elevation (Fig. 9A) and the cross-sectional area rate of change has lessened (Fig. 7). In the River-Dominated Interaction reach (Fig. 9B), the minimum bed elevation continues to change through time which indicates it has not completely stabilized. However, the historical trend indicates that the rate of change in cross-sectional area is decreasing for all sites (Fig. 7). This suggests that the river in the River-Dominated Interaction reach has not yet achieved its new equilibrium, though the rate of change in the reach has decreased relative to the first two decades following installation of the dam.

Although each reach could be achieving stability, the boundaries of the different reaches will likely continue to migrate. The Dam-Proximal reach will continue to migrate downstream into the

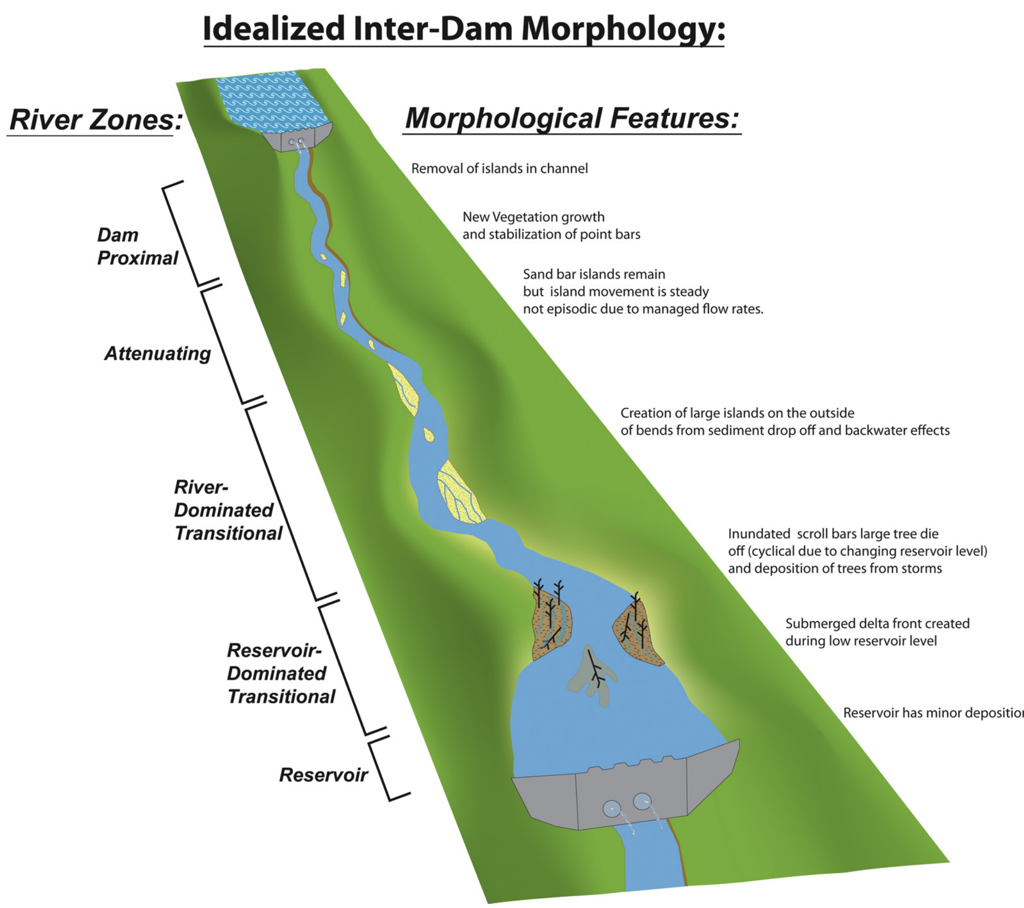

Fig. 11. Conceptual model of channel morphology that results from dam interaction along a river reach. Removal of islands occurs just below the dam in the Dam Proximal zone (bed degradation and bank erosion are also likely). The eroded sediment may be locally deposited in new islands and sand bars downstream. These sand bars and islands are stable in the Dam attenuating zones but erosion and deposition are likely less episodic due to the controlled releases from the dam. In the Transitional reaches all sediment that has not been locally deposited will accumulate here. This results in large distributary islands and deposition of large wood. Finally, in the downstream reservoir, the historic channel is completely submerged.

Dam-Attenuating reach as upstream sediment supply continues to be limited. Islands in this reach will be eroded and channel capacity will continue to increase from bed and bank erosion. Fines are transported farther downstream than coarse material and will ultimately end up in the reservoir. The coarser sediment from the islands and bed will be transported downstream (likely into the next reach), which will extend the River-Dominated Interaction reach upstream. The Reservoir-Dominated Interaction reach will continue to extend longitudinally both upstream and downstream from sediment transported from upstream as well as the reduced velocity from the Oahe Dam. The timescale of this adjustment is unclear and ultimately depends on the limit of bed degradation (when the channel reaches bedrock control, for example), the limits of bank erosion (which could result from vegetation or from bank armoring), and the hydrology (which depends on flow management and climate change).

5.2. Implications for management

Important management consequences can arise as a result of the interaction between the two dams in the Garrison Dam Segment. The first is the continued loss of islands, which are habitat for endangered Least Tern and Piping Plover and are currently actively managed to mitigate the impacts from the Garrison Dam. If the Dam-Proximal reach continues to migrate downstream, islands will continue to be lost and more active management may be required. The second consequence is the growth of the Interaction reaches near the city of Bismark. The increased accumulation of sediment in this reach has significant implication for the management of infrastructure and flooding risk due to ice jamming. Third, navigational issues in the lower reach of this segment will likely continue and will increase in extent both downstream into Lake Oahe, as well as upstream into the city of Bismarck.

5.3. A generalized model for Inter-Dam Sequences

Many other rivers in the US have dams which are proximal longitudinally and are likely interacting in a similar way as the Garrison and Oahe Dams (Fig. 10). Of the 404 sequence of dams, 73% are closer than 100 km to each other. Results show that the 512 km between the Garrison and Oahe Dam is not enough distance to consider these dams separately. We propose a conceptual model of how a sequence of interacting dams might impact river geomorphology (Fig. 11) based on our results. We call this morphologic sequence the Inter-Dam Sequence, and we present a simplified model based on the Upper Missouri River that could be easily adapted to other river reaches.

Although the morphologic sequence is a useful conceptualization, there are clear limitations to these results. This model is likely only applies to large dams on alluvial rivers. Dams on rivers that are controlled by bedrock or where morphologic adjustment is limited by vegetation or cohesive banks may respond completely different than the model presented here. Similarly, the downstream effects of small dams will likely attenuate over much shorter distances. However, this framework is a helpful advancement in our understanding of longitudinal responses to multiple dams.

6. Conclusions

One of the greatest influences that humans have had on the fluvial landscape is the construction of dams. Despite significant advancements in the study of the downstream and upstream impacts of dams, they are often considered separately from each other. The Garrison and Oahe Dama on the Missouri River are used to demonstrate that the effects of an upstream dam maintains significant geomorphic control over river morphology as the backwater effects of downstream reservoir begin to occur. The upstream–downstream interaction of multiple dams overlap to create a distinct morphologic sequence. Five unique geomorphic gradational reaches were identified for the Garrison Reach, two of which are controlled solely by the upstream dam and three of which are controlled by the dam interaction termed: Dam Proximal, Dam-Attenuating, River-Dominated Interaction, Reservoir-Dominated Interaction, and Reservoir. A conceptual model was developed of a morphologic sequence of downstream dam impacts and dam interaction which can be adapted to other rivers. The current distribution of dams on the major rivers in the U.S. indicates that more than 80% of large rivers may have interacting between their dams. Given this widespread occurrence, we describe a generalized morphologic sequence termed the Inter-Dam Sequence and suggest it should be the focus of additional research.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ancene.2013.10.002.

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