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Flood disturbance, recovery, and inter-flood incision on a large sand-bed river

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ABSTRACT

The lower 800 km of the Missouri River has been incising for decades. However, the 2011 flood scoured more sediment than the previous 12 yr combined. The river rebounded in the following two years, re-depositing over 70% of the sediment scoured during the 2011 flood. Historic evidence suggests that past Missouri River floods may have followed similar scour-rebound patterns. This paper analyzes 16 channel surveys from 1987 to 2014, including 50,723 total cross sections to document the morphological history of the lower 800 km of the Missouri River over the last thirty years, including flood disturbance and long-term trends. The last thirty years on the Missouri River included two basic morphologic regimes: steady incision during low-to-moderate flow periods and rapid scour-rebound responses to floods. Surveys collected during the 2011 flood demonstrate that the river scoured throughout the flood (including the falling limb) and did not begin a rebound phase until after the flood. The analysis also identifies sediment sinks associated with each of these scour regimes (flood scour and incision between floods) that exceed the total volume eroded from the bed during those periods. Results suggest that floodplain deposition may induce the supply limitation that drives flood scour on this large sand-bed river. Additionally, aggregate mining removes substantially more sediment than the total river incision between floods and the reaches with maximum scour during the 1993 and 2011 floods correspond to the zones of aggregate mining.

1. Introduction

Flood disturbance and recovery are critical components of river morphology (Schumm, 1976; Wolman and Gerson, 1978; Lewin, 1989; Knighton, 1998; Simon and Rinaldi, 2006; Phillips and Dyke, 2016) and ecology (Resh 1982; Ward and Stanford, 1983; Lake, 2000). Fluvial form and lotic communities reflect the influence of periodic, powerful events separated by extended periods of low-to-moderate flows. Rivers respond to disturbance events in a variety of ways, on multiple time scales. Additionally, river responses to disturbance-recovery cycles can be complicated by a variety of natural and anthropogenic influences driving long-term incision (e.g., Downs et al., 2013). Parsing transient disturbance-recovery impacts from long-term morphological trends can be particularly challenging on large sand-bed rivers, where noise from rapidly-migrating bedforms can drown out the signal of actual morphological change at individual cross sections. Moreover, remote sensing technologies such as LiDAR, photogrammetry, and structure from motion cannot detect morphological change under meters of turbid water. Currently, only underwater sonar can measure bed shape and change in these deep, turbid systems, which is time consuming and costly over large spatial domains.

Because of the difficulty of large scale morphological studies on large sand-bed rivers, these systems are underrepresented in morphological literature (Hudson, 2002), including the disturbance-recovery literature, despite growing suspicion that their morphologic behaviors differ from those documented in smaller rivers (Latrubesse, 2008). Repeated surveys on the Missouri River present an opportunity to investigate the relative importance of disturbance-recovery cycles and long-term incision on a large sand-bed river.

The Missouri riverbed is actively incising (USACE, 2017a). This incision (persistent, reach-scale channel lowering) caused the low discharge water surface elevations through Kansas City, Missouri, to drop as much as 3.7 m since the 1940s (USACE, 2015), including 2.5 m since 1974 (USACE, 2017b). Bed incision is not a phenomenon unique to the Missouri River. Rivers worldwide are incising, particularly highly engineered rivers with major dams and in-channel mining (Kondolf, 1997). Bed incision can affect infrastructure and ecosystems (Rinaldi et al., 2005) associated with large sand-bed rivers. Persistent channel incision can undermine infrastructure (e.g., main stem and tributary

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bridges) or strand public works (e.g., water intakes and sewer outfalls). Missouri River incision has damaged or impaired water intakes, levees, floodwalls, bridges, and river training structures (USACE, 2017b). Additionally, incising sand-bed rivers reduce emerging sand-bar habitat (Buenau et al., 2014), perch backwater ecotones that can affect vulnerable aquatic species (Jacobson and Galat, 2006), and drain riparian wetlands.

This paper analyzes eight surveys of the lower 800 km of the Missouri River, with 50,000 total cross sections, to parse multi-year and multi-decadal trends on a large sand-bed river. This analysis quantifies disturbance-and-recovery on two scales: a full river (800 km) multi-decadal scale including floods and between flood periods, and a sub reach (255 km) flood disturbance and recovery scale that measures the river response during and immediately after the historic 2011 Missouri River flood. The paper also examines bed change in the thalweg and channel bars separately to analyze disturbance-recovery response on the sub-cross section scale.

These data contribute to three main research questions:

1. What is the basic disturbance-recovery response to floods on the lower 800 km of the Missouri River? (e.g., erosion-deposition, deposition-erosion, etc.)
2. What are the relative contributions of flood scour (and rebound) and incision during moderate-flow periods between floods to long-term incision on the Missouri River?
3. What sediment sinks could contribute to incision during floods and between events?

2. Background

The Missouri River is a large sand-bed river that drains 1.37 million km^2 of North America, comprising approximately 46% of the Mississippi watershed. The study reach, including the downstream 800 km of the Missouri River, includes approximately a third of the total river length, from Rulo, Nebraska, to St. Louis, Missouri (Fig. 1). The reach has a very consistent, mild gradient (0.0002) and is confined by levees along most of its length. The study reach substrate is mostly medium and fine sand, which coarsens downstream (Gibson et al., 2016). This reach of the Missouri River is actively incising. Stage trends indicate as much as 3.7 m of stage lowering at Kansas City since 1940 (USACE, 2012).

The river erodes on two temporal scales:

1. “Acute” flood disturbance – rebound events that scour the channel bed and then deposits in the years immediately following the event.
2. “Chronic” incision between floods, scouring the channel during low-to-moderate flow periods between major floods.

2.1. Flood disturbance and rebound

Wolman and Miller (1960) recognized the role of moderate magnitude, moderate frequency events on channel form. They argued that morphologically significant events must include sufficient magnitude *and* frequency to shape the channel over time. The role of large, infrequent floods has been more controversial (Lewin, 1989).

In different contexts, large, rare floods can cause minor adjustments, transitory effects that quickly rebound to previous conditions, or catastrophic channel change. Wolman and Gerson (1978) argued that large events often make minor contributions to channel form because they are infrequent and followed by recovery periods. Recovery or rebound processes following high-magnitude, low-frequency disturbances reduce the morphological impact and move the system back towards equilibrium. Other studies also recognized relatively minor (or transitory) impact of large events (Costa, 1974; Magilligan et al., 1998; Fryirs et al., 2015). However, others found that large events drive channel form, and “catastrophic” or “threshold” events can substantially change the system form and function (Gupta and Fox, 1974; Magilligan, 1992; Schook et al., 2017) even driving it to a new stable state or quasi-equilibrium (Karcz, 1980; Phillips, 2014).

Additionally, while rivers generally respond to large flood events through disturbance and rebound phases, disturbance and rebound can affect different rivers in different (or even opposite) ways. Floods

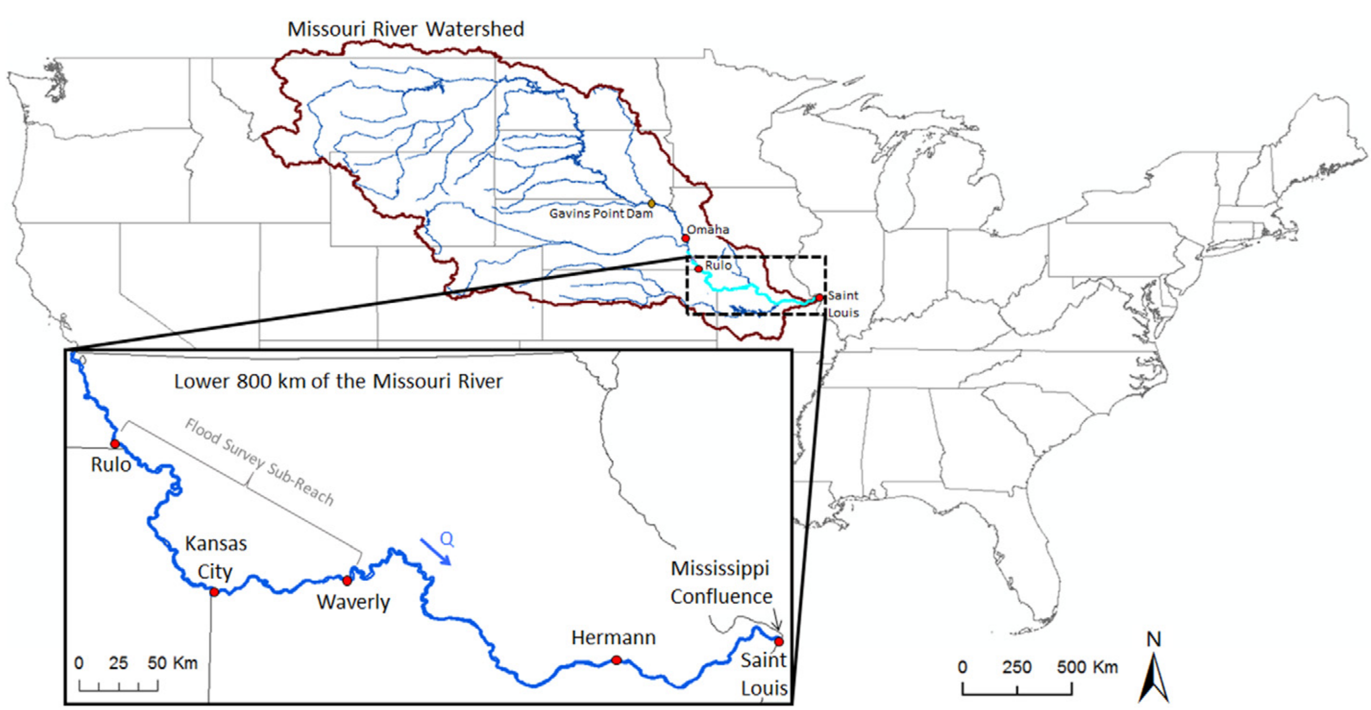

Fig. 1. Missouri River with its watershed, including the 800 km study reach (detailed inset). The sub-reach with multiple surveys during the 2011 flood (between Waverly and Rulo) is indicated in the inset.

can erode or aggrade the channel; they can widen the channel or build channel bars; they can deposit or strip the floodplain; or they can combine several of these processes. Flood widening, followed by narrowing during the post-flood recovery period (through bench or bar building) seems to be the most widely documented response (Costa, 1974; Gupta and Fox, 1974; Wolman and Gerson, 1978; Moody and Meade, 2008; Dean and Schidt, 2013; Downs et al., 2013; Nelson and Dubé, 2016). However, channel scour followed by deposition (Wang et al., 2014; Nelson and Dubé, 2016) as well as channel deposition followed by erosion (Thompson and Croke, 2013; Calle et al., 2017) have also been observed. Floods also store sediment in floodplain and overbank areas (Gibson and Nelson, 2016; Nelson and Dubé, 2016) or strip floodplain deposits and introduce them back into the channel (Nanson, 1986).

However, most disturbance-recovery studies tend to focus on small to moderate-sized systems with gravel bed material. Morphological change is easier to measure on smaller, coarser systems where it manifests as widening or can be computed from remotely sensed data including LiDAR, and aerial photos. Morphological change can be more difficult to measure on large sand-bed rivers (Hudson, 2002; Gupta, 2007), which can lead to inappropriate extrapolation of processes observed on smaller and coarser systems (Latrubesse, 2008; Naylor et al., 2017).

Large sand-bed rivers are not as laterally active as smaller, coarser systems, and tend to transfer energy into vertical bed and bar evolution for two reasons: (1) the bed-to-bank ratio of the wetted perimeter is larger and (2) anthropogenic bank stabilization has halted or slowed lateral migration on many of these rivers. These vertical bed changes also follow deposition-erosion or erosion-deposition patterns of disturbance-recovery processes. Navigators report that river crossings on the Mississippi (Heath, personal communication) and Madeira (Creech et al., personal communication) deposit during floods and erode after floods and Schenk et al. (2014) report flood deposition and post-flood erosion at Missouri River stations (Bismarck, North Dakota) affected by reservoir backwater. Alternately, supply limited reaches, downstream of dams, including the Colorado River (Mueller et al., 2014), Yangtze River (Li et al., 2017) and upper reaches of the Missouri River (upstream of our study reach) (Skalak et al., 2017) tend to scour the channel and build river bars during natural or managed flood pulses.

Further, sand-bed rivers rebound on various temporal scales, including intra-event rebound (e.g., on the falling limb of the hydrograph) or multi-decadal scour and rebound. The textbook (Skinner and Porter, 2000), large river, flood response scours on the rising limb and deposits on the falling limb. The rising-limb scour, falling-limb recovery is also demonstrated or assumed in much of the bridge scour literature (Richardson and Davis, 1995). However, sediment load hysteresis commonly delivers higher loads on the rising limb of the hydrograph than similar flows (i.e., shear stresses, stream powers, and transport capacities) on the falling limb, which could drive deposition-erosion intra-flood disturbance-recovery models.

Gage data and anecdotal evidence suggest the Missouri River fits the erosion-deposition model of flood disturbance and recovery. USACE (1994, 2017a) indicate that the floods of 1951, 1952, 1987, 1993, 2007, and 2011 scoured the Missouri riverbed, and were each followed by periods of bed recovery. USACE (2017b) reports this scour-rebound effect at the Kansas City gage (RKM 589.3) when flows exceed 6230 m^3/s (annual exceedance probability between 20% and 10% or a 5 to 10 yr recurrence interval). In most cases, the river recovered within six months of the flood.

2.2. Missouri River incision and influences

Bed incision on the Missouri River is not limited to major floods. The river also erodes during moderate-to-low flow periods between floods. Three major system modifications affect or have affected the lower Missouri River sediment balance: upstream dams, in-channel navigation projects, and aggregate mining. Each of these processes provided partial hypotheses for past and current incision drivers. However, long-term (chronic) incision trends are complicated by short-term (acute) channel responses to flood flows, which can be substantial.

2.2.1. The Missouri dams

Six mainstem dams regulate flows and trap sediment generated in the upper 53% of the Missouri River watershed. These dams have trapped over 4.6 trillion m^3 of sediment (NRC, 2011) and reduced the suspended sediment load from around 300 million tons per year to 55 million tons per year at Hermann, MO, about 161 km upstream from its confluence with the Mississippi River (Jacobson et al., 2009; Meade and Moody, 2010). These dams trap nearly all the sediment upstream of river kilometer (RKM) 1305, the location of Gavin's Point, the downstream dam. The final mainstem dam was finished in 1963. Gavin's Point Dam was constructed in 1957. The river has incised the bed as much as 4.3 m directly downstream of Gavin's Point dam. The dam-induced incision decreases downstream of the dams, fully tapering off approximately 32 km downstream of the dam (USACE, 2017b). Jacobson et al. (2009) characterize the upstream reach between Omaha and Nebraska City as stable-to-aggrading based on changes in low discharge water surface profiles.

2.2.2. Dikes and revetments

The Bank Stabilization and Navigation Project (BSNP) begins at RKM 1212 in Sioux City, Iowa, and runs to the confluence with the Mississippi River at St. Louis, Missouri (RKM 0). The BSNP is a federally authorized and maintained navigation project that includes a system of perpendicular and parallel river training structures known as dikes and revetments. The BSNP includes approximately 5000 active structures along the lower 800 km of the Missouri River. Most of these structures were constructed between 1930 and 1965 (Jacobson et al., 2009) and construction was declared officially complete in 1980. These structures narrow and deepen the channel, reduce bank erosion, and by stabilizing the channel location, prevent meander migration into previous floodplain deposits (see Figs. 2 and 3).

2.2.3. Channel mining

Commercial sand and gravel miners dredge segments of the lower Missouri River. From 1994 to 2014, channel miners removed more than 110 million tons (71.9 M m^3) of bed material from the lower 800 km of the Missouri River, an average removal of 5.5 million tons per year of bed material. For comparison, USACE (2015) computes that in the absence of channel mining, the aggradation rate of the riverbed would have been 2.2 million tons/year over the same time period. Sand mining was concentrated along urban corridors in the river, with most of the sediment extracted near cities (see Section 5.3 for more discussion on the effects of the magnitude and location of channel mining).

3. Methods

The study team computed bed change from historic surveys to estimate the relative contributions of flood-rebound processes and inter-flood erosion to Missouri River incision.

3.1. Cross section data

For nearly a century, the U.S. Army Corps of Engineers (USACE) has collected bathymetric cross sections on the lower 800 km of the Missouri River to monitor navigation depths. In 2007, concerns about bed incision prompted the USACE to establish consistent transects to monitor bed change systematically. The 2007 survey included measured cross sections every 76 m from RKM 0 to 802 with denser cross section spacing at a few specific bends. The USACE surveyed the same transect locations several times since 2007, though not always with the same density or longitudinal extent.

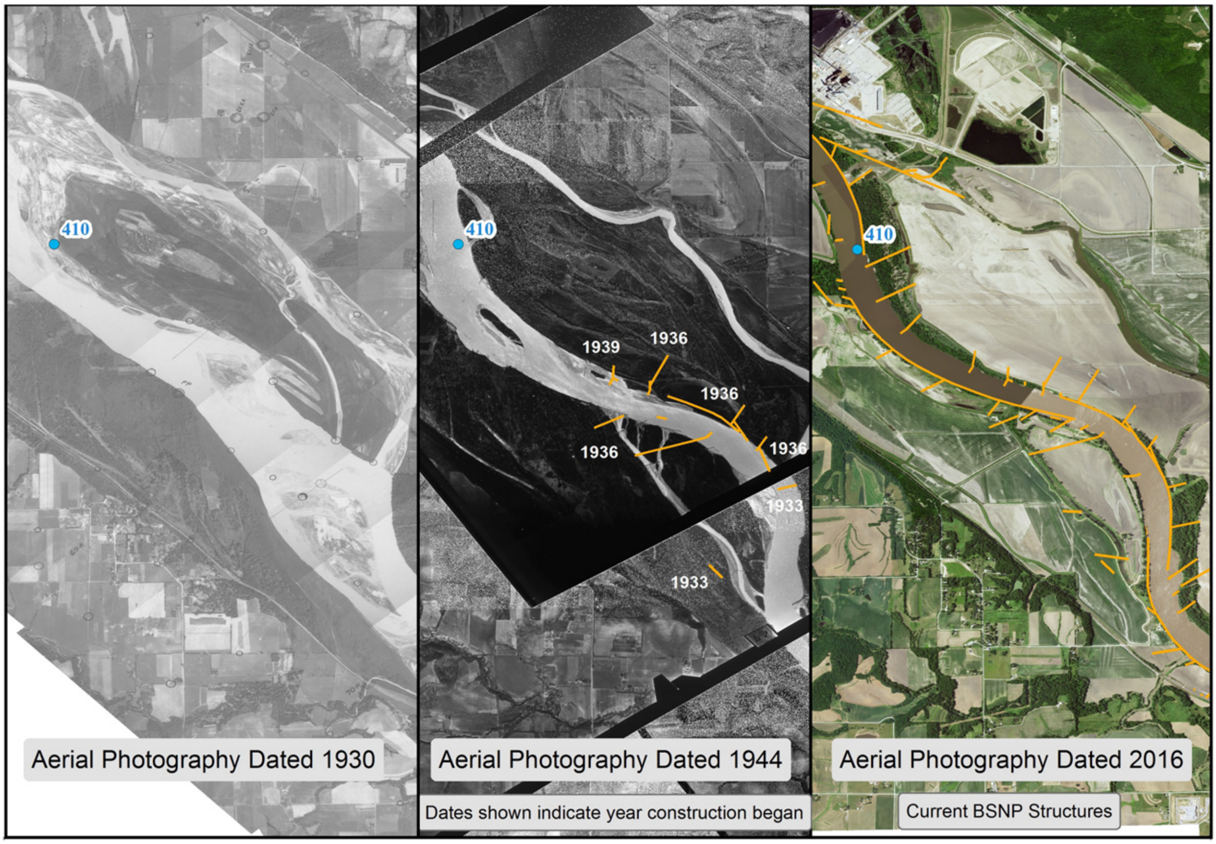

Fig. 2. Effect of Bank Stabilization and Navigation Project structures on the Missouri River near River Mile 410 (Brown, 2019).

Surveys collected in 2007 and later were digital. Therefore, all cross sections were automatically included in the analysis. The study team also digitized select cross sections from older surveys (1987 and 1994). These historic surveys each included over 5000 cross sections in the 800 km study reach, with an average cross section spacing of about 160 m. The study team did not have resources to digitize these complete surveys, so they selected a consistent cross section spacing, then digitized the closest cross sections from the 1987 and 1994 data to the 2007 transect location on that spacing. Table 1 lists the number of cross sections and average spacing for each of these surveys. This study time window (1987 to 2014) includes the historic floods of 1993 and 2011.

The data include two temporal and spatial scales: lower frequency-complete reach surveys and higher frequency, sub-reach surveys. Eight surveys collected cross sections along the lower 800 km of the Missouri and four sub-reach surveys collected data at higher temporal resolution (four surveys in five months) over limited spatial extents (254.3 km), tracking bed evolution during the 2011 event. These data provide the opportunity to quantify the scour and rebound of a large sand-bed river during a major flood (2011) against the background of an incising system.

3.2. Data analysis

Shelley and Bailey (2017) developed the Cross Section Viewer, a tool to analyze the 50,723 cross sections in this dataset. This tool standardizes and stores cross section data, facilitates data retrieval, and automates several computations to generate geomorphic metrics that summarize and track bed change. This study used the Cross Section Viewer to analyze historic Missouri River bed change.

3.2.1. Longitudinal volume change analysis

The Cross Section Viewer computes "longitudinal cumulative volume change" (LCVC) curves from sets of cross sections repeated over time. LCVC curves are an information-dense approach to visualizing bed change and spatial rates of change (Thomas, personal communication; Gibson et al., 2017; Dahl et al., 2019; Sclafani et al., 2018; Wang and Xu, 2018). The LCVC plot offers two specific advantages for visualizing large, repeated, cross section datasets with different spatial resolutions. First, LCVC curves spatially integrate cross-sectional area changes, which dampens the noise of individual cross sections to emphasize overall geomorphic trends. Second, by integrating bed change spatially, the LCVC can also compare bed change between surveys with different cross section resolutions.

On the Missouri River, water level on the day of survey determines boat accessibility to areas on the channel margins, causing the lateral extent of the survey to differ from year to year. A consistent lateral extent is required to avoid attributing bed change to differences in survey extent. The Cross Section Viewer identifies cross sections at the same locations in two surveys and trims them to their common lateral extent. The tool then computes the area difference between cross section pairs and computes volume change by multiplying the average area change by the distance between cross sections. The Cross Section Viewer computes a LCVC by summing the volume change between each shared cross section from upstream to downstream.

3.2.2. Lateral bed change analysis

In addition to analyzing the reach-scale volume of bed change, the study team also used the cross section database to assess the effect of flood disturbance on channel shape (i.e., laterally-variable bed change or deposition and erosion across the cross section). This study hypothesized that the thalweg and sand-bar portions of these cross sections

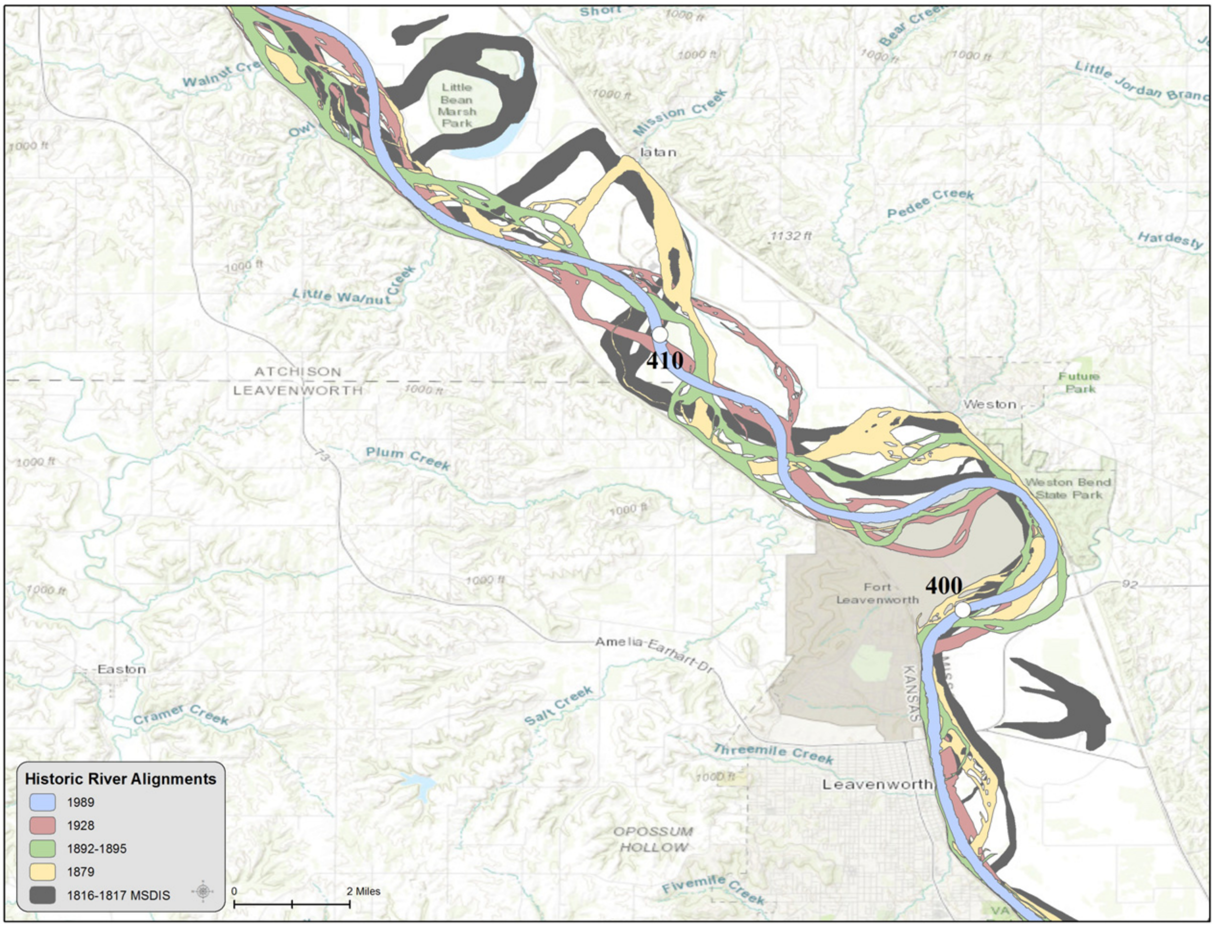

Fig. 3. Historic alignments of the Missouri River (Brown, 2019). The 1969 alignment persists to present (2019) due to the Bank Stabilization and Navigation Project structures.

could adjust disproportionately or even in opposite directions. Specifically, this study tested the hypothesis that the channel scoured the thalweg and deposited in shallower channel bars during the 2011 flood, and then reversed the process, depositing in the channel and eroding the bars after the flood.

The study team used a categorical approach to test this hypothesis, visually examining 136 cross section pairs to independently evaluate bed change in the thalweg and shallower side-channel bars. This analysis assigned bed change in the thalweg and channel bar to one of four categories: erosion, equilibrium, deposition, or indeterminate. The final analyses excluded between one (rising limb) and fourteen (falling limb) indeterminate cross sections (e.g., cross sections that eroded and deposited in roughly equal measures in the thalweg or bar or that did not have a clear distinction between thalweg and bar). The cross sections with clear, visual elevation changes in the thalweg and bar were assigned to one of nine possible thalweg-bar change categories (e.g., thalweg erosion-bar erosion, thalweg erosion-bar deposition, thalweg deposition-bar equilibrium, etc.). These analyses were repeated on two time frames: between the 2009 (pre-2011-flood) survey and August 2011 (just after flood peak but before the falling limb), and between the August 2011 and 2012 (one year after flood) surveys, to

Table 1
Missouri River cross section surveys (bold entries are full river surveys).

Survey date	Min RK	Max RK	# XS	Ave spacing (m)
1987	**1.2**	**801.6**	**776**	**1031**
1994	**8.2**	**802**	**1812**	**438**
2007	**0**	**802.1**	**11782**[a]	**76**
2009	**0**	**803.2**	**10,550**	**76**
2011 (Jun 13–24)	471.7	726	406	626
2011 (Aug)	471.7	726	185	1374
2011 (Jun 13–24)	471.7	726	406	626
2011 (Nov 7–15)	471.7	726	367	693
2012	**0**	**801.6**	**1302**	**616**
2013	**0**	**803.2**	**10,548**	**76**
2014	**0**	**801.7**	**5263**	**152**

[a] The 2007 survey includes additional cross sections in chutes.

Table 2
Summary of research questions and results.

Research question	Results
1. What is the disturbance-recovery response on the lower 800 km of the Missouri river?	Reach Scale: The river scoured during the flood (including the falling limb) and then rebounded (70% of total volume) after 2011. XS Scale: Over 50% of cross sections scoured the thalweg and deposited bars during the flood with the process reversing during rebound.
2. What are the relative contributions of floods and non-flood flows to long-term incision on the Missouri River?	The 1993 event scoured more sediment than the subsequent flood and inter-flood incision combined. The 2011 event (including rebound) accounts for less than a quarter of the erosion since 1994.
3. What sediment sinks could contribute to incision during floods and between events?	The sediment volume removed by channel mining exceeds the total incision between the 1993 and 2011 floods. The estimated floodplain deposits during the 2011 flood exceed the flood scour during that event.

investigate the laterally-varying morphological response to the flood and rebound. This analysis tested the hypothesis that sediment transfer between the bed and the bar is part of the river's disturbance-rebound process.

4. Results

Results address the three main research questions of this study in turn and are summarized in Table 2.

4.1. Flood disturbance and recovery: bed change during and Immediately following the 2011 flood

The four 2011 subreach (labeled in Fig. 1) surveys (Table 1) were combined with comparable cross sections over the same subreach, from the full-river surveys in 2009, 2012, and 2014 to investigate the first research question: the flood-disturbance and recovery response of the lower 800 km of the Missouri River.

4.1.1. Reach-scale flood scour and rebound

Fig. 4 plots the LCVCs computed between these sub-reach surveys for different phases of the 2011 flood. These surveys bound the rising limb of the 2011 flood hydrograph (Fig. 4a), a period that roughly corresponds to the extended peak (Fig. 4b), and the falling limb of the hydrograph (Fig. 4c).

The Missouri River scoured during all three flood phases (rising limb, peak, and falling limb -Fig. 4a–c). The river scoured the most sediment (16.2 million m^3) between 2009 to June 2011 (Fig. 4a), which includes the rising limb of the flood (as well as 1.9 million m^3 channel mining). From June to August 2011, roughly the peak of the flood (the 2011 flood was characterized by an extended peak), this reach incised and aggraded locally with a net erosion of 4.8 million m^3. Then, during the falling limb (August and November 2011- Fig. 4c) the river continued to incise, eroding an additional 12.4 million m^3.

The river aggraded during the three measurement periods following the flood. Fig. 5 includes three annual post-flood rebound curves are with the Kansas City hydrograph. These rebound curves were computed by comparing the post-2011-flood, sub-reach survey (November 2011) to the corresponding cross sections from the full-reach surveys collected in 2012, 2013, and 2014.

The deposition rate fell during each successive post-flood period. Recovery began downstream and moved upstream. Between November 2011 and 2012 (just after the flood) the river deposited almost all of the 17.2 million m^3 recovery downstream of RKM 650. From 2012 to 2013, the river deposited an additional 6.5 million m^3, mostly upstream of RKM 600. The rebound between 2013 and 2014 (3.6 million m^3) deposited more or less uniformly along the subreach. The 2011 flood did not follow the classic flood disturbance-recovery model, with scour on the rising limb and deposition on the falling limb. The 255 km subreach eroded 37% of the total eroded mass on the falling limb and did not start to rebound until after the flood.

4.1.2. Cross section response to flood disturbance and rebound

Longitudinal bed change analysis does not distinguish different modes of cross section evolution. The categorical analysis of cross section shape assessed thalweg and bar change independently to investigate lateral cross section response to disturbance-recovery processes. The thalweg was identified visually as the region of the cross section with the lowest elevation, excluding scour holes that form off the tip of dikes. The bar was identified as the region of the cross section from the thalweg to the far bank.

Figs. 6 and 7 summarize the results, reporting the percentage of subreach cross sections associated with each of the cross section change categories. More than half the cross sections eroded the thalweg and deposited in the bars during the rising limb and peak of the flood (2009–Aug 2011). The falling limb and rebound period (Aug 2011–2012) inverted this trend. Forty-six percent of the falling limb-rebound cross sections deposited in the thalweg and eroded the bar (Figs. 6 and 7).

The net cross section shape change over the full flood-rebound period is similar to the period between floods (see Supplemental materials). However, while the Missouri River incises on the reach scale during floods, and is net erosional on the cross section scale, it tends

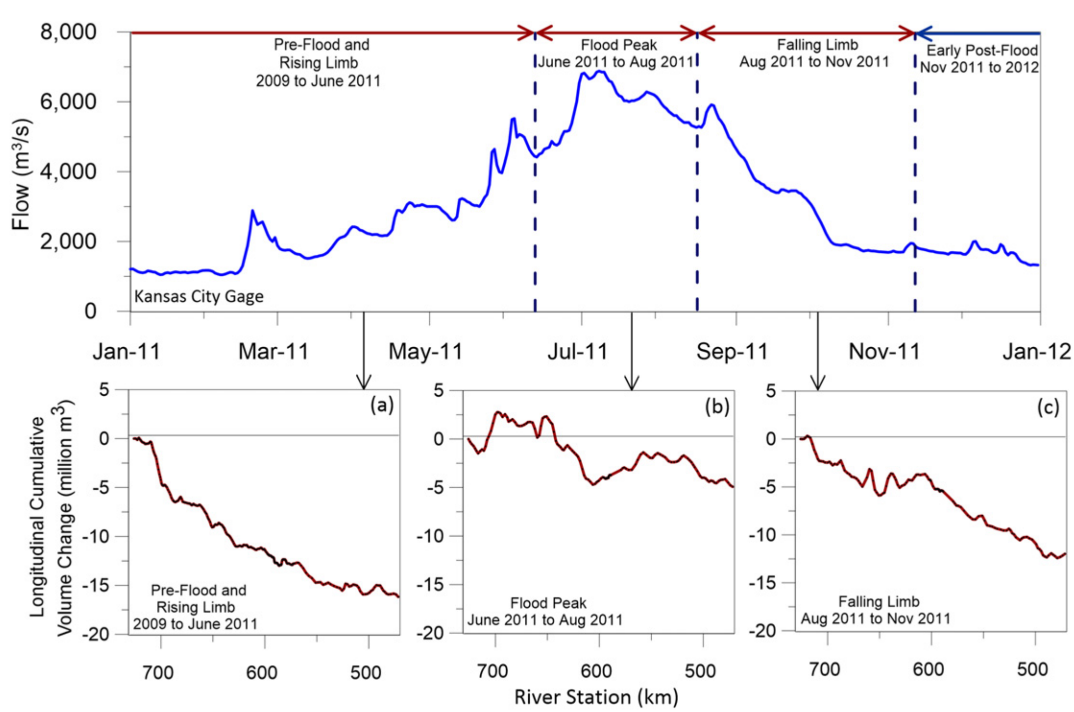

Fig. 4. Longitudinal cumulative volume change, during the 2011 flood, from St. Joseph, Missouri, to Waverly (rm 450 to 293), Missouri (RKM 472 to 726). The top pane plots the hydrograph and the lower panes showing incision through several phases of 2011 flood at the Kansas City gage (a-rising limb, b-extended peak, c-falling limb).

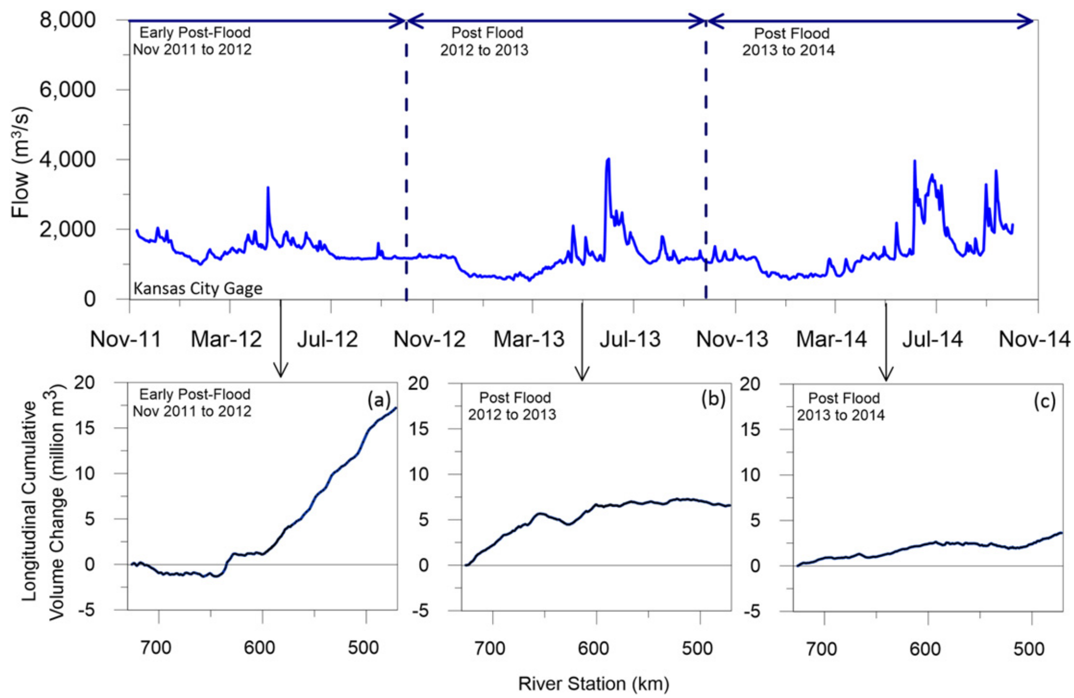

Fig. 5. Longitudinal cumulative volume change from St. Joseph, Missouri, to Waverly (rm 450 to 293), Missouri (RKM 472 to 726), showing three years of recovery (a–c) following the 2011 flood at the Kansas City gage (directly after the previous plot).

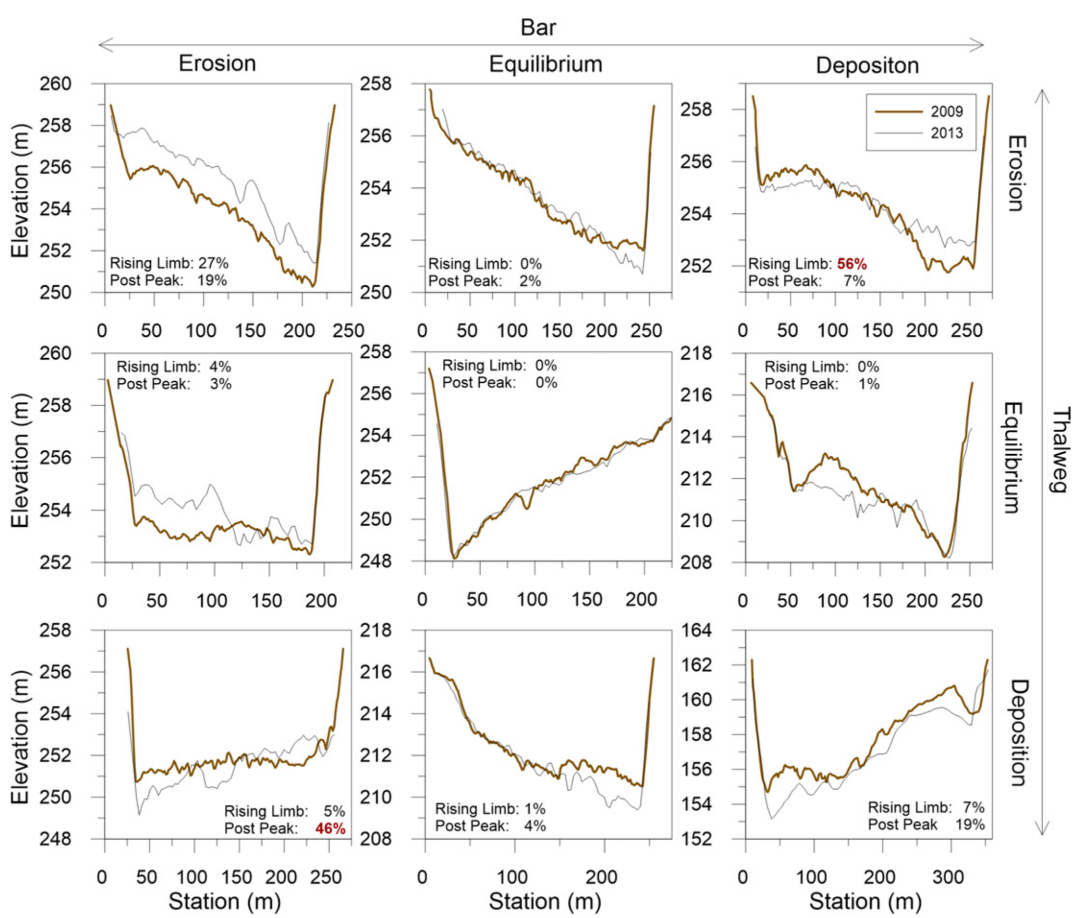

Fig. 6. Categorical taxonomy of cross section change. Cross sections were classified based on thalweg and bar change (deposition, erosion, or equilibrium) and then assigned to one of these nine categories. "Rising Limb" includes 2009–Aug 2011 bed change (rising limb and peak) and "Post Peak" includes Aug 2011–2013 (falling limb and rebound). Thalweg erosion and bar deposition was the most common rising limb category and the inverse (thalweg deposition and post peak erosion) was the most common post-peak category.

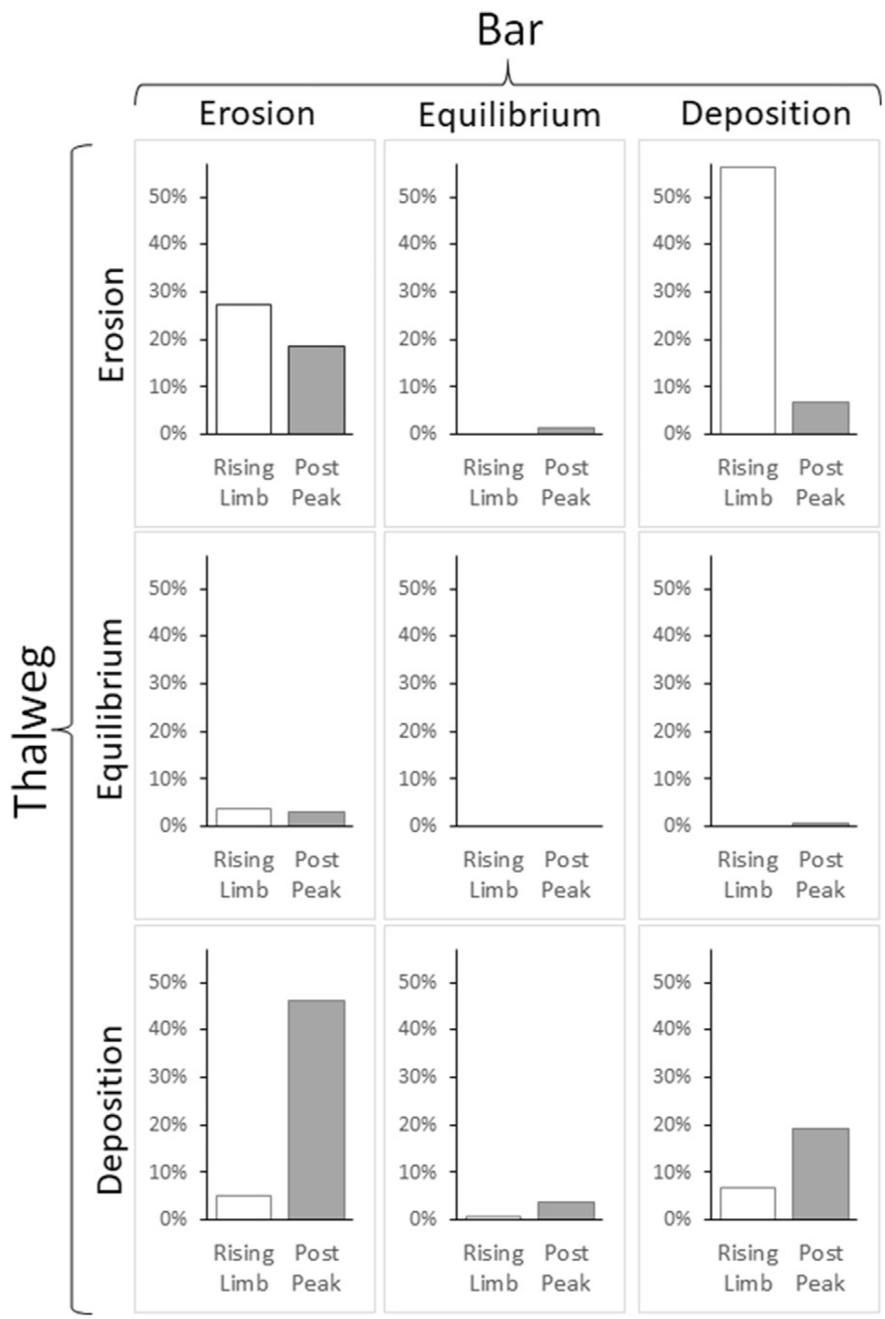

Fig. 7. Categorical cross section shape change associated with the rising limb and falling limb-rebound periods (and cumulative response) of the 2011 event for a 255 km subreach. The river tends to scour the thalweg and deposit on the bars during the flood and reverse that process as it rebounds. “Rising limb” includes peak (2009–Aug 2011) and “Post Flood” includes falling limb and rebound after the flood (Aug 2011–2013).

to shift sediment from the channel to higher elevation (lower depth) channel bars during the flood and then shifts sediment back from the bars to the channel during the falling limb and/or recovery period.

4.2. Relative contributions of flood and inter-flood incision (decadal scale-full reach response)

Fig. 8 plots the LCVC curves between each successive whole-reach survey of the lower 800 km of the Missouri River with the hydrograph at Kansas City, Missouri (RKM 589.3). Fig. 9 aggregates these data into a time series of total reach volume change. This plot summarizes the total reach response during the period between 1987 and 2014.

The first period included the most bed change (Fig. 8a). The river eroded 143.6 million m^3 between 1987 and 1994, a period including the 1993 flood (15,300 m^3/s at Kansas City). Stage trends (USACE, 2017a) indicate that most of this bed change occurred during the flood. The flood eroded the riverbed at a relatively consistent erosion-per-km rate throughout the reach (i.e., Fig. 4a has a relatively constant slope indicating consistent erosion through the entire reach). This is consistent with spot measurements and narrative accounts during the event. USACE (1994) reported 2.4 to 3 m of scour from St. Joseph, Missouri (RKM 726), to Hermann, Missouri (157.6 km) (Fig. 1). The U.S. Geological Survey (USGS) measured 4.5 m of scour during the flood event (July 12 to 28) and then 2.6 m of rebound immediately after it (July 28 to August 12) for a net scour of 1.9 m (USACE, 1994).

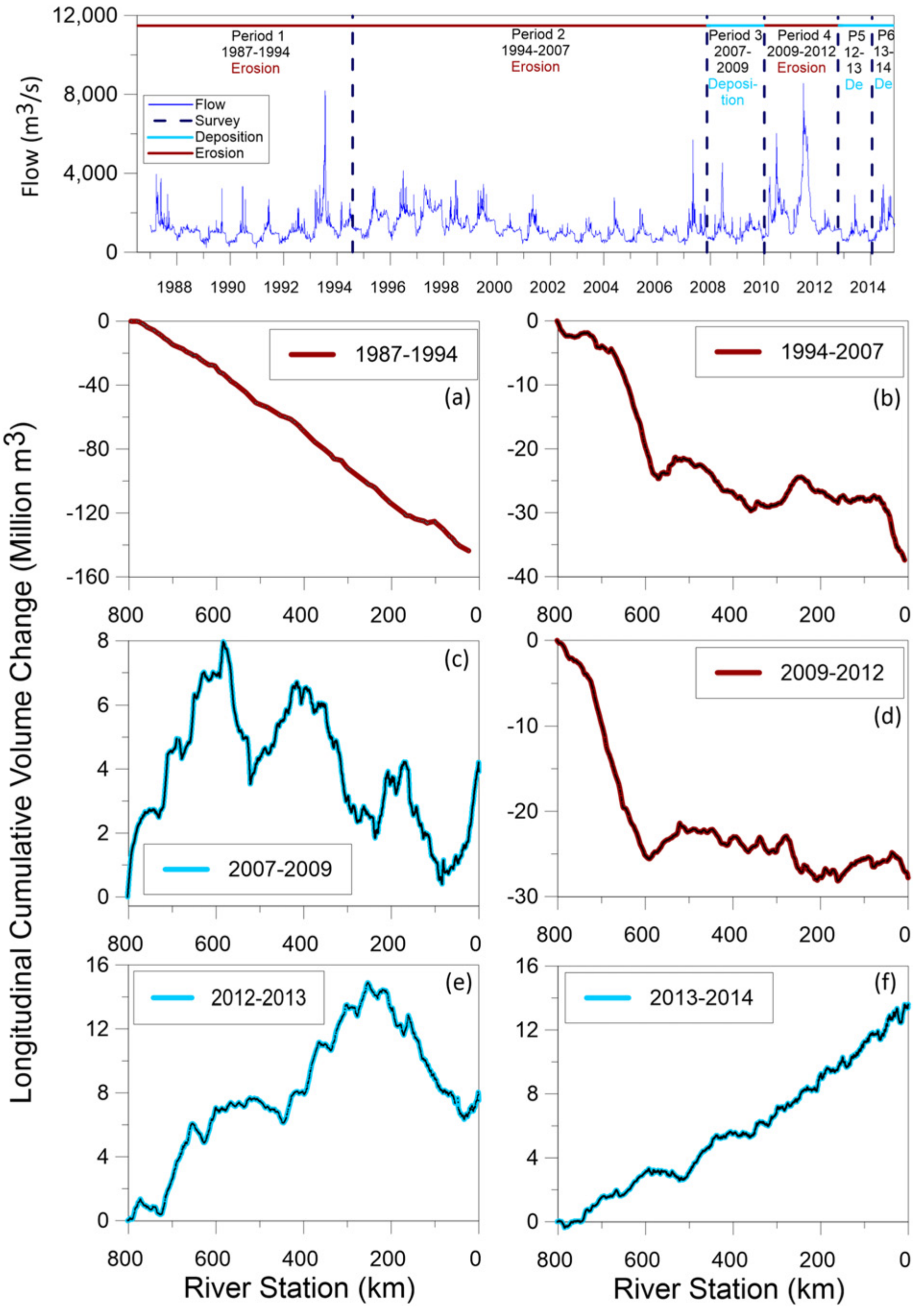

Fig. 8. Longitudinal cumulative volume change between successive river-wide surveys (blue = net depositional periods and red = net erosional periods).

The river continued to incise from 1994 to 2007 (Fig. 8b), scouring an additional 37.4 million m^3 in the 13 yr following the 1993 flood. The cumulative channel mining volumes are included in Fig. 9 for scale. The 53.1 million m^3 of channel mining during this period exceeded the incision by an average of 1.2 million m^3/yr. This period ends with a moderately high flow event, just before the 2007 survey.

The two year window between 2007 and 2009 (Fig. 8c) includes localized erosion and aggradation with overall aggradation of 3.9 million m^3. Deposition is concentrated in the region of maximum scour in the previous period, which might suggest minor rebound from the 2007 flow.

From 2009 to 2012 (Fig. 8d), the river eroded 27.8 million m^3, principally as a result of the 2011 flood. Following the flood (2012 to 2013 - Fig. 8e), the river recovered from RKM 800 to 254 but continued to erode from RKM 254 to 0, with a net recovery of 7.5 million m^3. From 2013 to 2014 (Fig. 8f) the river responded more uniformly, depositing 13.6 million m^3, at a relatively constant longitudinal rate. The river deposited more than two-thirds of the sediment scoured during the 2011 event in the two years after the event (the combined 2012–13 and 2013–14 bed change).

4.3. Major sediment sinks during and between floods

Two substantial sediment sinks - measured during the floods and between the flood periods - exceed total erosion during those periods. First, the total volume of aggregate mined from the channel exceeds the incision volume between the flood events. Second, the estimated volume of overbank deposition exceeds the volume scoured during the 2011 flood.

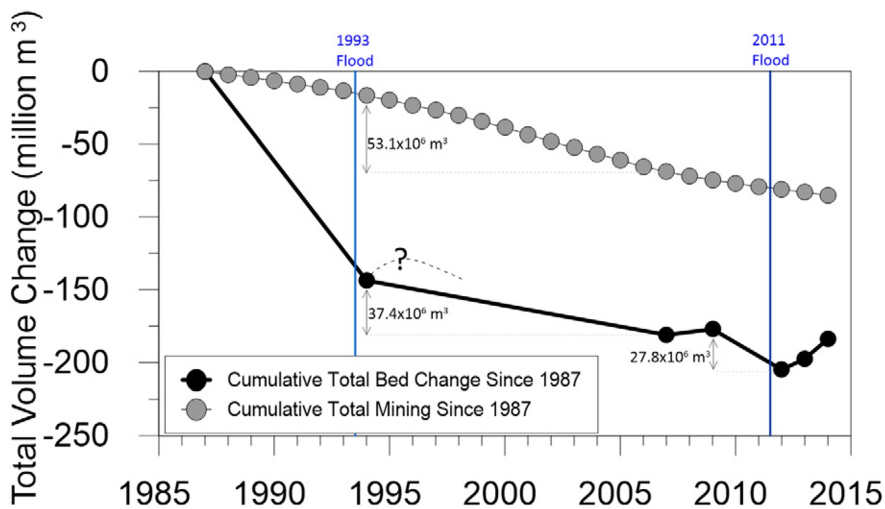

Fig. 9. Cumulative bed change volume and channel mining over the lower 800 km of the Missouri River. Dotted lines reflect speculation about how narrative accounts of river rebound after 1993 might plot on this curve.

4.3.1. Scour between floods and channel mining volumes

Fig. 10 plots the LCVC in the thirteen year, low-to-moderate flow period, between the 1993 and 2011 floods (1994–2007 - from Fig. 8b). A LCVC of channel mining during the same period is also included in Fig. 10 for comparison. The channel mining was compared to the 1994–2007 bed change because this was the longest period without a major flood. Comparing the channel mining to inter-flood incision isolates the analysis from flood effects. Channel mining data were developed from historic records, which include date, location, and tonnage information.

Two important observations emerge. First, channel mining removed nearly twice (183%) the volume (63.3 million m^3) of observed bed incision (34.6 million m^3) during the period between the floods. Second, the riverbed lowered most around the reach with maximum aggregate extraction. The channel mining data indicate that channel mining concentrated around the urban center, and mining extracted about 44% of the total aggregate from the Kansas City metro area (RKM 571 to 610). Third, about half (51%) of the incision in this period was also measured in the 100 km through and just upstream of Kansas City (RKM 571 to 671).

4.3.2. Intra-flood scour and overbank deposition volumes

Fig. 11 plots the LCVC associated with the 2011 flood (2009–2012 - Fig. 8d) with the LCVC of channel mining (dredging) during that period. Scour between 2009 and 2012 (which, likely, includes substantial rebound) is almost double the mining volume. Fig. 11 also plots the low bound of the Alexander et al. (2013) estimate for overbank deposition during the 2011 flood. Alexander et al. (2013) used satellite images to map (Jacobson, 2016) the areal extent of overbank sand deposits greater than 0.6 m thick after the 2011 flood (Jacobson, 2016). The study team computed the area of these deposits and multiplied them by the 0.6 m minimum thickness to convert the area to a minimum volume of overbank deposits. Fig. 11 aggregates these overbank deposit volumes longitudinally into the LCVC of overbank deposits. This analysis provides a "low bound" estimate for overbank sand deposition by ignoring sand deposits less than 0.6 m thick and by ignoring sand volume exceeding the 0.6 m threshold thickness in the mapped areas.

Three observations emerge from comparing the bed change and floodplain deposition curves. First, the total overbank sand deposition roughly corresponds to the total bed change (though both represent low estimates because of rebound in the bed change and measurement

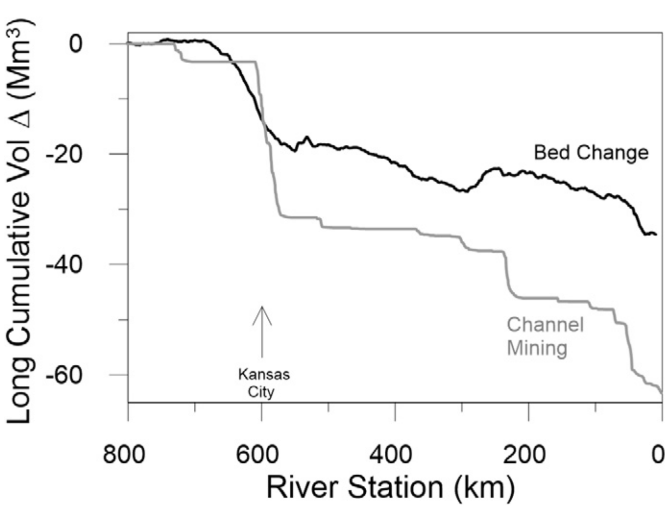

Fig. 10. Longitudinal cumulative volume curves (accumulated volume change downstream) depicting bed change and channel mining volumes mined from the channel between the 1994 and 2007 surveys, an interflood period between the 1993 and 2011 floods.

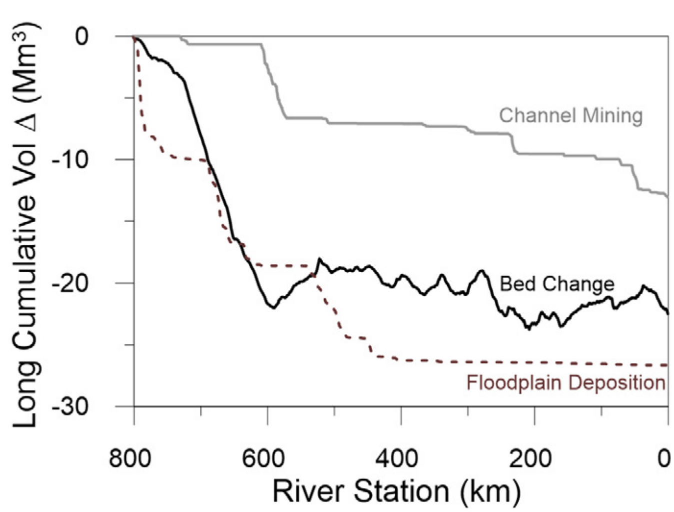

Fig. 11. Longitudinal cumulative volume curve (volume change accumulated from upstream to downstream) between 2009 and 2012, including the 2011 flood, plotted with LCVCs of channel mining and floodplain deposition.

limitations in the overbank estimate). Second, the river scoured along the same subreach that Alexander et al. (2013) report most of the floodplain deposition. Both channel scour and overbank deposition are concentrated in the upper 300 km of the study reach (where the flows were large relative to the channel capacity, see discussion in Section 5.4). Third, the total volume of sand deposited in the floodplain (26.7 million m^3) and eroded from the channel (22.6 million m^3) are on the order of the USGS estimate of the total, combined suspended sand flux (29 million m^3) at Kansas City for the three water years 2009, 2010 and 2011 and the total suspended sediment flux (29–64 million tons) tAlexander et al. (2013) computed for several sediment gages during the 2011 event.

Geospatial floodplain deposition data are not available for the 1993 event, but three 1993 floodplain deposit estimates have been reported. The Soil Conservation Service (SCS, 1993) reported 417 million m^3 of overbank deposition during the 1993 flood (though they also suggested much of this sediment was scoured from floodplain rather than from the channel). SCS (1993) offered no evidence for this estimate and the authors were not able to find the analyses. USACE (2017a) estimated 91 million m^3 of 1993 floodplain deposits came from the channel with a simplified sediment budget approach; the floodplain deposition is computed as the difference between the incoming and outgoing sediment fluxes minus the bed change. Finally, IFMRC (1994) estimated that the 1993 event deposited sediment on 455,000 acres (184,132 ha) along the Missouri River Valley including 60,000 acres (24,281 ha) with deposits at least 0.6 m thick, translating into a lower bound of about 150 million m^3. The river scoured 143.6 million m^3 during this period (including the flood). These floodplain deposition volumes are reasonable for a large sand-bed river in this context; Jacobson and Oberg (1997) estimated that 22–36% of the Mississippi flood sediment deposited on the floodplains during the same event.

Based on these data, the floodplain deposits during the 1993 and 2011 floods had a similar magnitude to bed scour.

5. Discussion

5.1. Filters and amplification on the Missouri River

Wolman and Gerson (1978) framed early disturbance-recovery theory in terms of the magnitude of the disturbance and the time require to recover. Phillips and Dyke (2016) developed a more detailed taxonomy, recognizing that the disturbance-recovery process can generate different end states, including, but not limited to, the pre-flood condition (i.e., complete rebound). They highlighted the importance of "filter" and "amplification" processes (negative and positive disturbance feedbacks) to determine if, and, on what time scale the system will return to its pre-flood conditions. Filter processes mitigate disturbance, either resisting flood effects or encouraging post-disturbance rebound. Amplifying processes increase disturbance effects.

These data demonstrate that the Missouri River currently includes operational filter mechanisms. It partially rebounds after floods and compensates for channel mining, only eroding about half the mined volume removed in low-to-moderate flow periods. The river retains processes that mitigate disturbance. However, amplification processes exceed filter mechanisms, leading to long-term incision, including asymmetrical disturbance-recovery flood responses and inter-flood incision. While the asymmetrical disturbance response (at least in 2011) does not fit Phillips and Dyke (2016) catastrophic change model (S(n)-S(Ø)), which pushes the system to a totally novel, alternate state, it also does not fit the "transitional" disturbance-rebound model (S(t + 1) = S(t-i)). The lag or "relaxation time" on this reach is important to consider, because time t + 1 is not the end of the event, but months-to-years later. These large Missouri River floods (particularly 1993) fit their "state space expansion" category better (where S(t + 1) does not return to So, S(t-i), or S(t)). More descriptively, bed change on the Missouri (Fig. 9) evokes a version of Schumm's (1976) model of 'dynamic metastable equilibrium' (on an engineering time scale), where gradual long-term incision is punctuated by episodes of accelerated erosion (and rebound).

5.2. Disturbance thresholds

In Schumm's (1976) 'dynamic metastable equilibrium' model, episodes of disturbance accelerate change against a background of directional bed evolution when the system exceeds some morphologic threshold (Schumm, 1973; Magilligan, 1992; Church, 2002). A geomorphic threshold is an incremental step in a gradually changing external variable that causes an abrupt morphologic impact, sudden failure, or disproportional process response. Fluvial geomorphology often associates disturbance thresholds with particle competence (Howard, 1980; Church, 2002; Konrad et al., 2002) or bank processes (Lewin, 1989). However, these threshold hypotheses were generally developed in smaller, coarser systems. Neither of these thresholds apply on the Missouri. Moderate flows on the Missouri are competent to transport its sand bed and stabilized banks largely remove mass wasting thresholds from the equation. Large sand-bed rivers require an alternate flood disturbance threshold.

Significant floodplain deposition that creates a sediment sink on the order of the total bed-material load during the event could represent a disturbance threshold for this system. On the Missouri, flood stages sufficient to breach agricultural levees divert more sediment than the total bed-material load flux during the flood. This local sink increases supply limitation and induces scour.

5.3. Post-flood rebound

The Missouri does not conform to the rising limb-scour/falling limb-rebound model on the sub-reach scale. The river continued to scour on the falling limb of the hydrograph and did not begin its asymmetrical, asymptotic rebound until substantially after the flood. The falling limb of the hydrograph actually eroded more than the peak (Fig. 4).

The 2011 flow-load relationships flattened at higher flows (Fig. 12) and included clockwise hysteresis, with lower loads for the same flow on the falling limb. Load gradations also coarsened on the falling limb of the 2011 event (Galloway et al., 2013). The 1993 data do not capture these effects at Kansas City, but Holmes (1996) clearly demonstrates similar effects at the Hermann, Missouri gage (downstream) during the 1993 flood. Most of the flow from the 2011 event came from upper basin snowpack - upstream of the dams - rather than local tributaries. The flood was also unusually long. In this case, the extended, regulated, flood flows exhausted the sediment supply and coarsened the bed (Shelley and Gibson, 2015). These processes made the falling limb of the hydrograph more supply limited than the rising limb, delaying rebound until after the flood. This is consistent with Magilligan et al.'s (1998) assertion that sediment supply can affect flood response on large sand-bed rivers and that the geomorphic response to disturbance is a function of the flood magnitude, frequency, *and* duration.

Heimann (2016) and Holmes (1996) hypothesize that sediment stored in tributaries, sediment-rich flows draining the floodplain, and knickpoints that worked upstream through floodplain deposits supplied some of the sediment that caused the rebound after the falling limb (Jacobson, personal communication).

5.4. Difference between 1993 and 2011 flood response

The 1993 flood eroded more than the 2011 flood, even though the 2011 flood lasted much longer. The Missouri River scoured more than five times more sediment from 1987 to 1994 (including the 1993 flood) than it scoured from 2009 to 2012 (including the 2011 event). The floods had comparable peaks at the upstream end of the study reach and the 2011 event exceeded the 10% annual exceedance

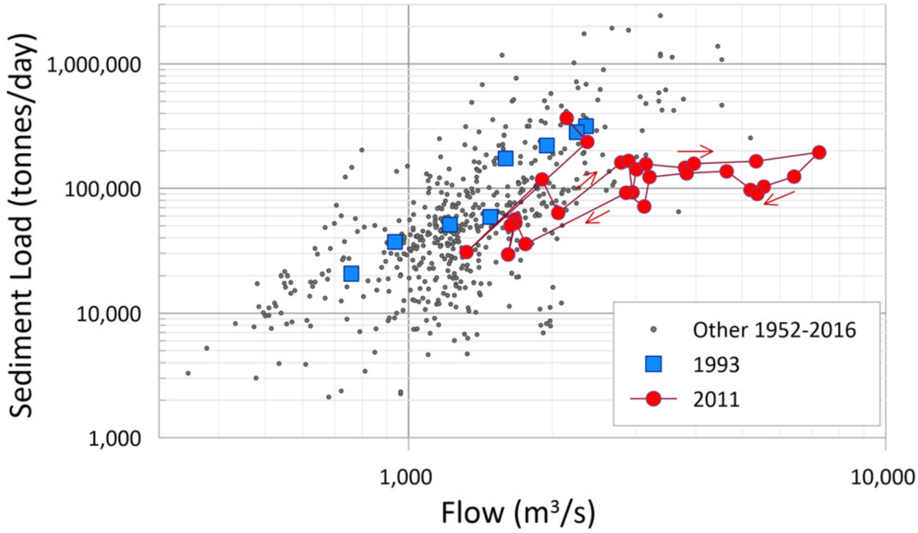

Fig. 12. Flow-load data from 1993 and 2011 flood years at the Kansas City gage plotted with other load measurements from 1952 to 2016. The 2011 data are connected sequentially to illustrate hysteresis. The "bent" 2011 curve illustrates the supply limitation of this event, exacerbated by the hysteresis. Data source: USGS Gage #06893000.

probability (AEP) flow at Rulo for 71 d, compared to 16 d in 1993. Two hypotheses may explain this difference.

First, more overbank deposition during 1993 could have caused more erosion. While overbank deposition volumes are uncertain, all estimates of 1993 floodplain deposition exceed 2011 estimates, which could exacerbate the supply limitation and induce more scour.

Second, coincident high flows from tributaries in Kansas and Missouri increased the 1993 flood discharge as it moved downstream, which maintained high flows relative to channel capacity for the entire lower Missouri River. In contrast, upstream reservoir releases drove the 2011 flood with the lower tributaries contributing very little. As a result, the flood attenuated as it moved downstream because channel capacity increased more quickly than discharge. The result was that the 1993 event was out of bank along the entire river length, while the 2011 event was out of bank only in upstream reaches.

Fig. 13 plots hydrographs for the two floods at upstream (Rulo) and downstream (Hermann) gages with the LCVC curves that include the two events. The floods had comparable peaks at the upstream end, both exceeding the 1% AEP (100-yr return interval).

However, whereas the 1993 flood exceeded the 1% AEP throughout the reach, the 2011 attenuation dropped the flood peak well below the 10% AEP at Herman.

The two floods scoured at approximately the same rate along the upper 200 km, where the peak flows were comparable, and the flows were out of bank. However, scour essentially stopped downstream of Kansas City in 2011, while it continued at a similar rate throughout the reach in 1993.

It is worth noting, however, that the sediment scoured from the upstream reach in 2011 did not deposit in the moderate flow reach downstream. Flows along the downstream 500 km of the river were sufficient to translate scoured sediment to the Mississippi.

5.5. Channel incision and sediment sinks

Differentiating the impacts of multiple natural and anthropogenic drivers in a cumulative reach analysis can be difficult (Downs et al., 2013). Warnings about "single impact" analyses (Reid, 1993; Downs et al., 2013) that simplify cumulative morphological change signatures into single-driver stories are valuable and apt. Establishing causal linkages between channel incision and the mining and floodplain sediment sinks requires mechanistic modeling studies.

However, the relative *magnitude* and coincident *location* of the incision and sediment sinks invite inference, that both the flood (floodplain deposition) and the inter-flood (channel mining) sediment sinks affect channel incision. Channel mining emerges as the most likely driver of recent scour between floods and asymmetrical recovery for three reasons: relative magnitude, synchronous location, and coincident timing. This is consistent with other studies that established connections between channel mining and channel incision (Erskine, 1990; Collins and Dunne, 1990; Kondolf, 1994; Rinaldi et al., 2005; Padmalal et al., 2008) including systems with multiple anthropogenic factors (Zilani and Surian, 2012; Calle et al., 2017). Morphodynamic modeling of this system supports this inference. A mobile bed model of this system (USACE, 2017b) was calibrated to the actual historic incision. When

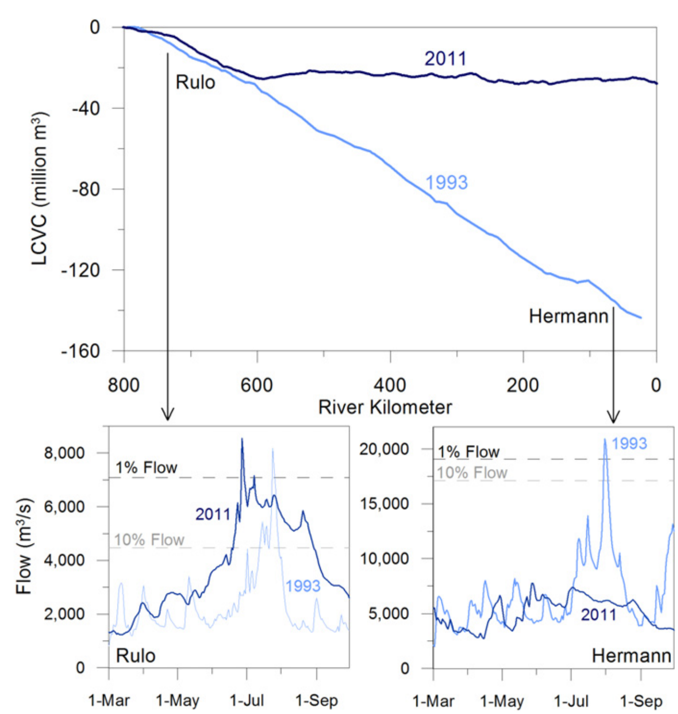

Fig. 13. Longitudinal cumulative volume change curves associated with the 1993 and 2011 events with hydrographs from those events near the upstream and downstream ends of the reach. The 2011 event had a comparable peak and was almost three times longer than the 1993 flood but attenuated downstream, while the 1993 event maintained flood peaks greater than the 1% exceedance probability throughout the reach.

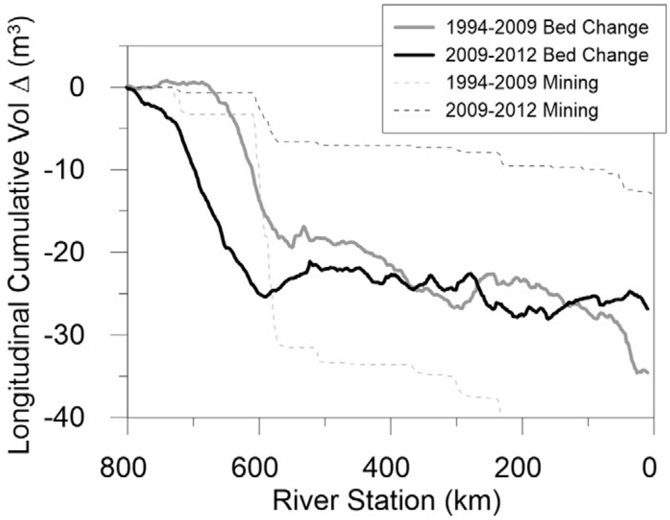

Fig. 14. Longitudinal cumulative volume curves for inter-flood incision curve (1994–2007) and flood curve (2009–2012) indicating the zone of concentrated erosion moved upstream.

the model simulated the inter-flood period from 1994 to 2009 without channel mining, the river recovered, depositing between floods instead of eroding.

5.6. Progressive headcut in response to channel mining

Kondolf (1994) argues that channel mining not only affects the river in the immediate vicinity of aggregate extraction, but can also cause incision downstream and upstream. Most mining-induced headcuts have been observed on smaller coarser systems (Rinaldi et al., 2005). However, the bed change results on the Missouri illustrate this process on a large sand-bed river, as the river seems to push a headcut upstream of the most intense mining location. The maximum bed scour from 1994 to 2007 corresponded with the location of maximum mining with a diffuse upstream tail (Fig. 14). The maximum incision extended over 50 km upstream of the maximum channel mining zone. From 2009 to June 2011, the greatest incision occurred directly upstream of previous incision zone (1994 to 2007), which is consistent with a headcut moving about 80 km upstream (Fig. 14).

6. Conclusions

Volume change analysis from eleven surveys over thirty years of the lower 800 km of the Missouri River document relative contributions of flood disturbance and recovery and inter-flood scour on long-term incision. The Missouri River follows an asymmetrical erosion-deposition model of flood disturbance and recovery. Intra-flood surveys of the 2011 flood measured scour during the rising limb, peak, and falling limb of the hydrograph. After the flood, the river deposited a volume equal to 70% of the sediment scoured during the event. Post-flood deposition progressed upstream and decreased over time. The river also moved sediment from the channel thalweg to shallower in-channel bars during the rising limb and peak of the 2011 flood, then reversed this process, transferring sediment from the bars back to the thalweg during the falling limb and rebound. The volume of the floodplain deposits during both the 1993 and 2011 floods scaled to the total bed scour. This suggests that flood stages sufficient to overtop agricultural levees - inducing overbank deposition – may represent a flood-disturbance threshold on the Missouri.

The Missouri River also scours between floods. The total bed incision from 1994 to 2007 was less than the 1993 flood incision but more than the net 2011 incision (after recovery). Channel mining removed almost twice the quantity of sediment eroded during this period. Inter-flood incision was also concentrated just upstream of the maximum channel mining locations, suggesting the mining may have induced a headcut. While the Missouri River still has active filter mechanisms driving asymmetrical recovery after flood disturbance and mitigating channel response to long-term sediment sinks, mining may reduce these filtering mechanisms, driving incision between floods and, potentially, reducing post-flood rebound.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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