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Air-photo based change in channel width in the Minnesota River basin: Modes of adjustment and implications for sediment budget

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ABSTRACT

The Minnesota River and major tributaries have experienced large increases in discharge over the past century. Aerial photograph-based measurements of channel width were made for the 1938–2015 period at 16 multibend subreaches by digitizing the area between vegetation lines and dividing by centerline length. Results show considerable increases in width for the main stem ($0.62 \pm 0.10\%/y$) and major tributaries ($0.31 \pm 0.08\%/y$) but are inconclusive for smaller channels (width < 25 m). Width change for a 146.5-km reach of the lower Minnesota River between 1938 and 2008 is similar to that from the subreach-scale analysis. Widening was associated with lateral centerline movement and temporal change in at-a-station hydraulic geometry for water surface width, indicating that widening is associated with cross-sectional change and not simply upward movement of the vegetation line. Digital elevation model analysis and regional hydraulic geometry show that the main stem and larger tributaries account for the vast majority (~85%) of bankfull channel volume. High-order channels are thus disproportionately responsible for sediment production through cross section enlargement, although floodplains or off-channel water bodies adjacent to these channels likely represent important sediment sinks. Because channel enlargement can play an important role in sediment production, it should be considered in sediment reduction strategies in the Minnesota River basin and carefully evaluated in other watersheds undergoing long-term increases in discharge.

1. Introduction

The geometry of alluvial river channels depends strongly on water discharge and sediment loads delivered from upstream (ASCE Task Committee, 1998a, 1998b; Savenije, 2003; Eaton et al., 2004; Parker et al., 2007; Kleinhans, 2010; Li et al., 2015; Call et al., 2017). Changes in channel width can thus be indicative of changes in discharge (Schumm and Lichty, 1963; Schumm, 1968), sediment supply (Trimble, 2009) or possibly changes in vegetation dynamics and/or bank cohesion (Tal and Paola, 2010; Dean and Schmidt, 2011; Eke et al., 2014). While extreme events sometimes cause reach-wide changes in channel geometry that may persist for years (Harvey, 2007; Konrad et al., 2011), the widespread acceptance of downstream hydraulic geometry relationships (e.g., Leopold and Maddock, 1953; Wilkerson and Parker, 2011; Knighton and Wharton, 2014, and references therein) implies that despite short-term variability, cross-sectional geometry depends on long-term conditions in regionally consistent ways. This raises obvious questions regarding the implications of potential future land use and climate change on the geometry of alluvial rivers such as: How well might existing hydraulic geometry relationships characterize geometry under new discharge regimes? Will the adjustment play out quickly, continuously, and uniformly? Will there be lags between perturbation and response?

In meandering rivers, changes in channel width occur because of complex interactions between vegetation, discharge, bed elevation, bank erosion, and sediment deposition. Vegetation strongly influences floodplain development and channel width by redirecting flow, trapping fine sediment, and strengthening sedimentary deposits (Hickin, 1984; Millar and Quick, 1993; Millar, 2000; Gran and Paola, 2001; Braudrick et al., 2009; Tal and Paola, 2010; Gurnell et al., 2012; Corenblit et al., 2014; Kleinhans et al., 2015; Gurnell et al., 2016). Rivers subjected to reductions in sediment supply or increases in sediment transport capacity often respond by incising, widening, and eventually creating an inset floodplain (Schumm et al., 1984; Simon, 1989). Conversely, channels subjected to overloading by bed material sediment can respond through bed aggradation and bar formation. These responses can increase bank erosion rates and/or flood flow rates on the floodplain, thereby stripping out vegetation and floodplain material (Burroughs et al.,

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2009; Madej et al., 2009; Zheng et al., 2014; East et al., 2015; Call et al., 2017). In either case, the finer fractions of eroded material are exported downstream, a process that makes channel widening a potentially large contributor to a river's sediment budget and an important water quality management consideration (Simon, 1989; Belmont et al., 2011; Schottler et al., 2014). By extension, systematic narrowing or aggradation of channels or storage of sediment in floodplains throughout a river basin may represent a significant sediment sink.

1.1. Identifying and measuring bankfull width

When changing environmental conditions force change in channel geometry, the bankfull discharge (Leopold et al., 1964) also presumably changes (Wilkerson and Parker, 2011). Detecting such a change, however, is challenging because most definitions of bankfull discharge require field identification of banks or other indicators of recent channel occupation (Knighton and Wharton, 2014). Furthermore, the definition of a streambank can be ambiguous (Navratil et al., 2006) and even using a single definition, the top-of-bank elevation can be subject to significant spatial variability (Lauer and Parker, 2008). In many cases, particularly where a river is adjusting to new conditions, certain channel boundaries (e.g., the top of cutbanks along an eroding terrace) may depend more upon historic conditions rather than on contemporary river processes. Consequently, making a retrospective assessment of *bankfull* discharge is difficult, even in well-gaged rivers with historically surveyed cross sections.

In many instances, the characteristic width of a river channel is more readily apparent from above than from the ground. Aerial photographs of rivers that are not flowing *full* generally contain easily recognizable areas of bare sediment. The discharge that just begins to submerge all of the unvegetated sediment in the active channel is similar conceptually to the traditionally defined *bankfull* discharge. In other words, the lowest discharge that fills the entire width of the channel, which we refer to here as the *width-filling* discharge (as opposed to the more traditional definition, which requires that the flow to vertically fill the channel up to a predetermined bankfull elevation) is a characteristic discharge that, once exceeded, can mobilize much or most of the sediment along a channel's boundary. Focusing on channel width has the advantages of i) straightforward measurements (i.e., viewing a reach from above and determining the width of the unvegetated zone is relatively simple) and ii) removing ambiguity introduced through field identification of *banks*. Drawbacks include the subjective definition of what constitutes *bare* sediment, as opposed to a surface colonized by perennial vegetation, and regional variation in the ability of vegetation (particularly fast-growing annual species) to colonize fresh sediment. In any case, temporal changes in driving variables such as discharge or climate are likely to shift the balance between processes of erosion, sediment deposition, and vegetation colonization that shape the boundary between channel and floodplain. Such changes should manifest themselves as measurable changes in the average width of a channel's unvegetated zone.

1.2. Mechanisms of channel width change

For systems undergoing net channel widening, the rate at which widening supplies sediment to the downstream system depends on the overall banktop widening rate, the depth of the channel, and whether adjustment occurs over the entire cross section. Fig. 1 illustrates several possible geometric responses to a long-term increase in water discharge along a simple, single-thread river (see also ASCE Task Committee, 1998a, 1998b). The simplest geometric response occurs when the channel boundary remains fixed while vegetation shifts vertically because of changes in flood frequency and duration that make near-channel areas more (or less) suitable for the hardiest species. Such a response, which we refer to here as *mechanism a*, could occur in relatively stable channels with boundaries consisting of immobile bedrock or lag deposits or in low gradient systems with relatively low coarse sediment supply and highly cohesive bed and banks. In the case of a long-term increase in discharge (Fig. 1A), upward movement of the lower limit of vegetation would lead to an increase in the width of the unvegetated zone. In this case, the magnitude of width change would depend on the shape of the fixed channel boundary. While upward movement of the vegetation line itself does not change sediment flux, it does leave the sediment that is no longer protected by vegetation more susceptible to mobilization.

A second potential response to increased discharge would be for erosion to occur on both banks because of increased shear stress (Fig. 1B). This mechanism (*mechanism b*) is most plausible along straight reaches with relatively stable centerline positions or curved reaches in which the outside bank is particularly resistant to erosion such as along valley walls or bluffs. As with mechanism a, this would lead to an increase in width of the unvegetated zone; however, in this case, the increase would be associated with a net transfer of bank sediment into the channel zone. A third mechanism (*mechanism c*) applies to actively migrating rivers that undergo significant centerline change while width adjustment occurs. In mechanism c (Fig. 1C), cutbank erosion and deposition on the opposite bank occur in tandem, and the long-term difference between these leads to widening. As with mechanism b, width change by mechanism c is associated with net transfer of sediment to the channel. The size distribution of any sediment exported downstream would depend on the size distributions of sediment eroded from cutbanks as well as that deposited in point bars. In real river systems, channel width probably adjusts through all three mechanisms, but we maintain that mechanism c best represents the dominant driving force in the widening of meandering rivers. Mechanism a may act as an important feedback process that contributes to the channel widening process in mechanism c.

In this paper, we estimate bankfull width change for extended reaches of the Minnesota River, Minnesota, USA, and several of its major tributaries using aerial photographs spanning 1938 to 2013. Even cursory review of aerial photography shows that channel width has increased significantly in the lower Minnesota River valley in response to large increases in discharge that have occurred over the past century. For example, aerial photographs from 1940 and 2008 along the lower Minnesota River ~57 river km upstream from the confluence with the Mississippi River (Fig. 2) illustrate that the channel has shifted laterally and widened in tandem, consistent with mechanism c. However, some reaches of the Minnesota River have experienced erosion on both banks (as in Fig. 1B), and increases in discharge may have affected the elevation at which vegetation is able to colonize point bars (Lenhart et al., 2013). Consequently, the extent to which width change influences the sediment budget for the lower Minnesota River has not yet been determined. The objectives of this study include (i) estimating bankfull width change throughout the Minnesota River basin, (ii) identifying which of the processes presented in Fig. 1 best represents this change, and (iii) quantifying and discussing the implications of width change for the sediment budget of the Minnesota River.

2. Regional setting

The Minnesota River drains a 45,000-km^2 watershed that includes parts of Minnesota, Iowa, and South Dakota (Fig. 3). It meanders across a 3–4 km wide valley that was carved during the Pleistocene by Glacial River Warren, an outlet of Glacial Lake Agassiz (Clayton and Moran, 1982; Thorleifson, 1996). Because the valley bottom is topographically much lower than the surrounding landscape, the lower portions of tributaries have incised through the substrate of consolidated glacial sediments, forming steep knickzones that mark the extent of incision since glacial times (Belmont, 2011; Gran et al., 2011). Bluffs along the lower reaches of major tributaries continue to provide a significant amount of sediment to the channel system (Thoma et al., 2005; Belmont et al., 2011; Day et al., 2013; Lenhart et al., 2013).

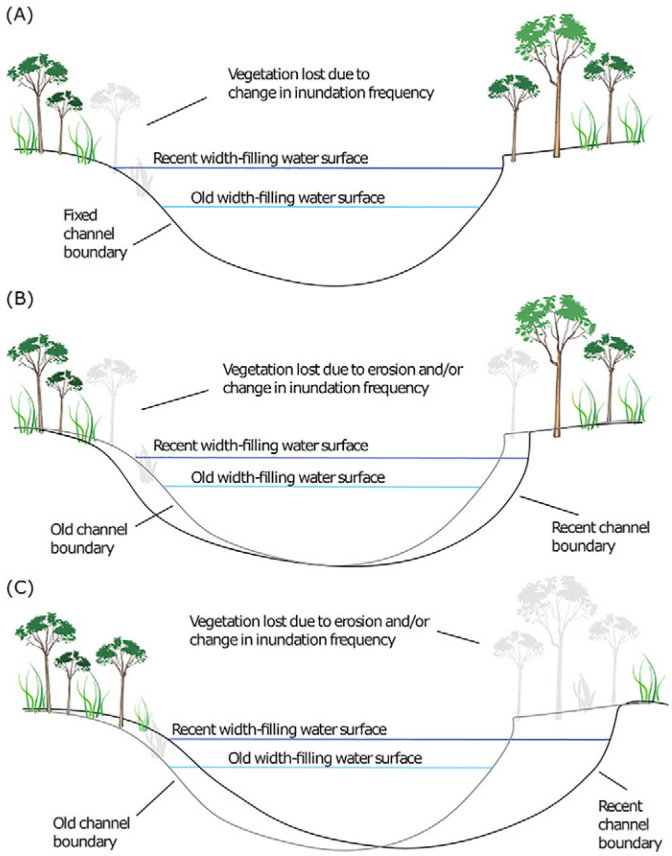

Fig. 1. Conceptual representation of several modes of width change. Mechanisms include (A) change in channel bankfull geometry depends only on increased water level and change in vegetation line, (B) change in bankfull geometry depends on erosion of both banks, (C) change in bankfull geometry occurs because of a change in overall cross-sectional geometry consistent with a migrating river.

The Minnesota River has undergone large increases in water discharge over the past century and thus represents an interesting site to study the implications of long-term hydrologic change on channel geometry. It is also listed as impaired by high turbidity under section 303d of the U.S. Clean Water Act, meaning that the sediment budget implications of the geomorphic adjustment have important management implications (MPCA, 2009; Wilcock, 2009; Gran et al., 2011; Lenhart et al., 2013; Belmont and Foufoula-Georgiou, 2017). Belmont et al. (2011) conducted geochemical fingerprinting analyses on sediment cores from Lake Pepin, a naturally dammed lake on the Mississippi River downstream of the confluence with the Minnesota River. Results indicated dominance of near-channel sediment sources (banks and bluffs) ca. 500 YBP, when this landscape was mostly covered by tall-grass prairie and wetland. In addition, fingerprinting analyses documented a pulse of agricultural erosion in the mid-twentieth century followed by a more recent shift back toward near-channel sources in the past few decades. The same study compiled a sediment budget for the Le Sueur River, a major tributary of the Minnesota River, which corroborated the dominance of near-channel sediment sources during 2000–2010.

Prior to agricultural development, much of the Minnesota River watershed was grassland and contained large areas of poorly drained prairie (MCBS, 2007; Musser et al., 2009). Today, the vast majority of the watershed is intensively cultivated and includes extensive surface and subsurface drainage systems (Musser et al., 2009). Ditches now connect most of the closed basins to the river network, and subsurface tile drains allow for relatively rapid removal of moisture from the upper meter of the soil column. Average annual precipitation has increased slightly over the past few decades, but Schottler et al. (2014) and Kelly et al. (2017) showed that monthly precipitation amounts have not changed significantly in the May to June time period. This suggests that artificial drainage practices are driving the observed increases in flow during the sensitive time of year when soil pore pressures are high and bank cohesion is relatively low.

Regardless of mechanism, discharge in the Minnesota River basin has clearly increased significantly over the historical period (Novotny and Stefan, 2007; Lenhart et al., 2011, 2013; Schottler et al., 2014). For example, the USGS has maintained a stream gage on the Minnesota River at Mankato that represents one of the longest gage records available in the United States. While data were not typically recorded in winter prior to 1930, daily discharge is available for April through November beginning in 1903. At this site, mean April–November discharge for the second half of the 1903–2015 time period is just over twice the mean April–November discharge for the first half. Similarly, mean annual discharge after 1975 is essentially twice the mean annual discharge from 1930 to 1974.

Increases in flow are significant across the entire flow duration distribution, including high discharges responsible for doing geomorphic work and during spring and early summer, when vegetation typically colonizes point bars (Lenhart et al. (2013)). Fig. 4A shows the time series for the 1% exceedance probability discharge, as interpolated from all daily data in a given calendar year (starting 1930) or from April through November daily discharges (starting 1904). Exponential curves fit to the 1% exceedance data show similar trends for either data set, indicating year-on-year increases of $1.25 \pm 0.48\%$/y for the April–November data or $1.63 \pm 0.65\%$/y for the annual data, with error representing 95% confidence limits. Fig. 4B shows a flow duration curve based on daily discharge for the 1930 through 1974 period and the 1975 through 2015 period. At essentially any exceedance probably, the ratio between these two distributions (Fig. 4C) shows an increase of a factor of ~2 to 3, even in the geomorphically important top 15–20% of the distribution. Lenhart et al. (2013) and Foufoula-Georgiou et al. (2015) provided additional discussion of hydrologic changes affecting this site.

3. Methods

3.1. Measurements of channel width

Historical river channel width can be measured using either ground-based data or by aerial photograph analysis. When historic cross-sections have been surveyed, the ground-based approach allows for the reconstruction of detailed sediment budgets (Trimble, 1997, 2009) and has the advantage of characterizing geometric change across the entire cross-section, not just near the top of bank. However, ground-based methods are only feasible in cases where carefully surveyed historic cross-sections are available and would not provide representative coverage without an extremely large number of sites.

Where ground-based surveys are not available, aerial photograph analysis has been used to document geomorphic changes in channel bankfull width and associated sediment fluxes. Buckingham and Whitney (2007) developed a sediment budget for a reach of the Las Vegas Wash, Nevada, using historic photographs to estimate channel volumes for three historic periods. Galster et al. (2008) used aerial photographs to analyze changes in width for two streams in the Lehigh Valley, Pennsylvania. Based on two photographic periods, 1946/1947 and 1999, they concluded that width change is discernable for streams ranging from 6 to 15 m wide given a sufficiently large sample size. Many other studies have used sequential aerial imagery to document channel change or estimate alluvial sediment loads on larger rivers (e.g., Martin and Ham, 2005; Lauer and Parker, 2008; Aalto et al., 2008; Belmont et al., 2011; Cadol et al., 2011; Konrad et al., 2011).

For the present study, channel width changes were assessed using aerial photographs spanning 1937 and 2015. Some of the aerial photograph-derived estimates of width change presented here were

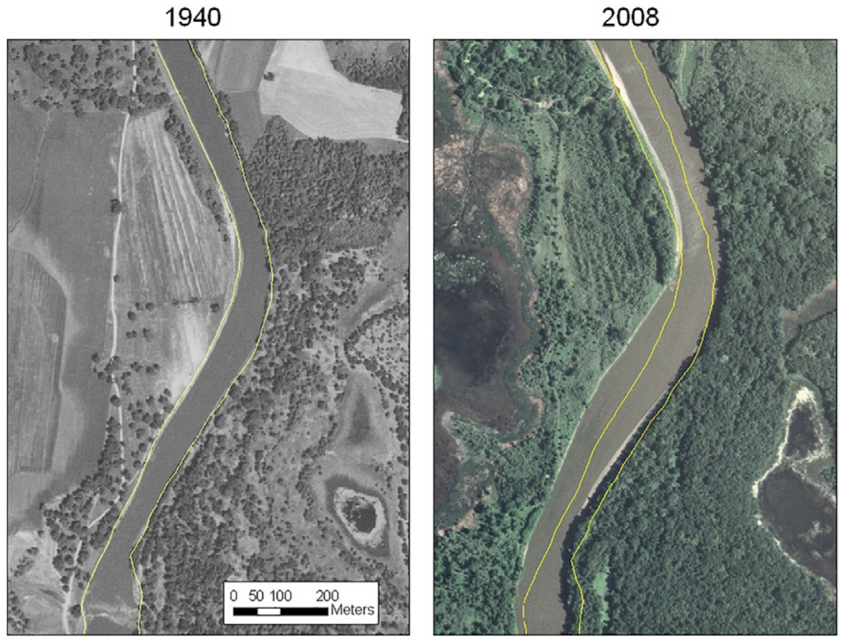

Fig. 2. Historic and recent channel width for a low amplitude meander bend on the lower Minnesota River. Apex of bend is located at 44°43′58″N, 93°37′42″W. Also note the afforestation and apparent increase in overbank inundation in the 2008 image.

originally presented in Schottler et al. (2014). However, we have expanded the area under analysis and extended the length of the record to include 2015 measurements. In addition, we extend and improve upon the Schottler et al. (2014) results by using width change estimates, bathymetric data, and grain size measurement to develop first-order estimates of the widening-induced supply of sediment to the channel of the lower Minnesota River, while accounting for channel migration that occurs along this reach. We also extend beyond previous work by using regional hydraulic geometry relationships to determine which parts of the channel network (i.e., small tributaries vs. large main-stem channels) likely play the largest role in supplying sediment through the widening process.

Historic photographs were obtained from the Minnesota Department of Natural Resources and the John R. Borchert map library at the University of Minnesota. In most cases, the scale information for the original image had been stripped from the digital images. However, in general,

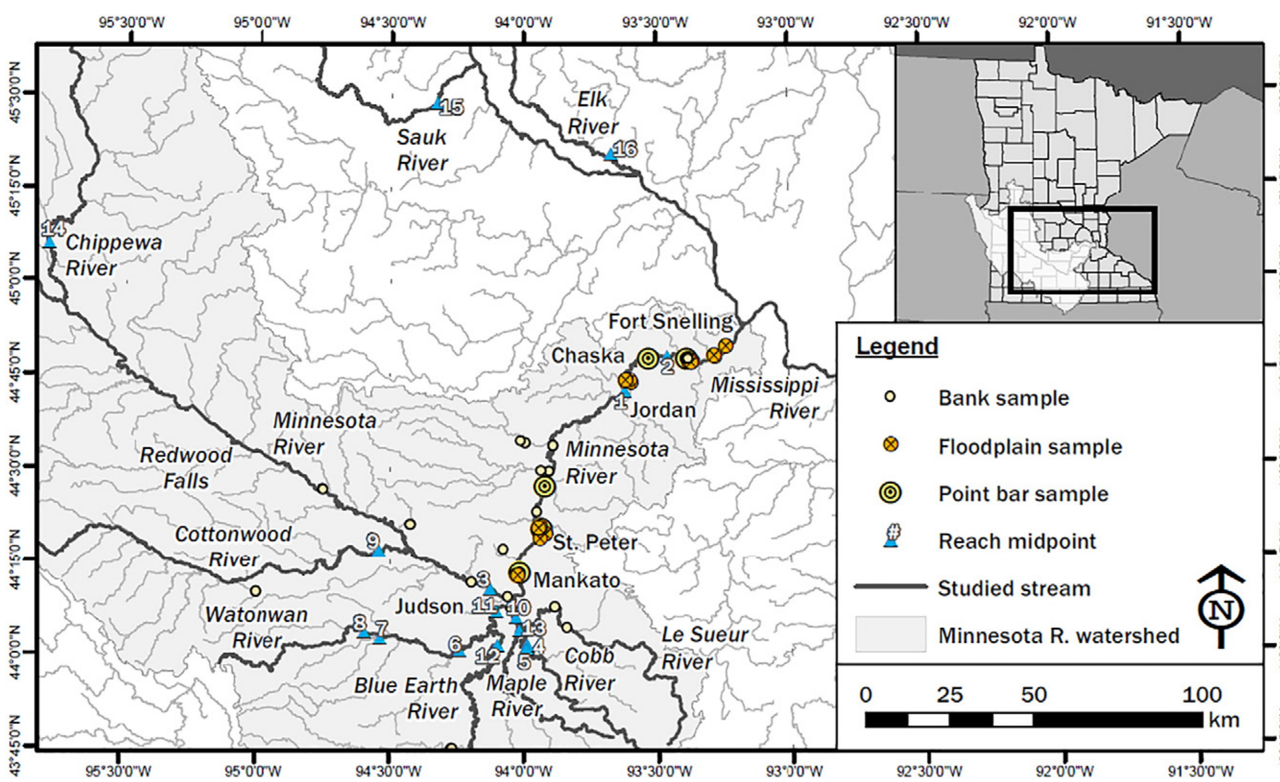

Fig. 3. Minnesota River watershed and locations of width measurement subreaches.

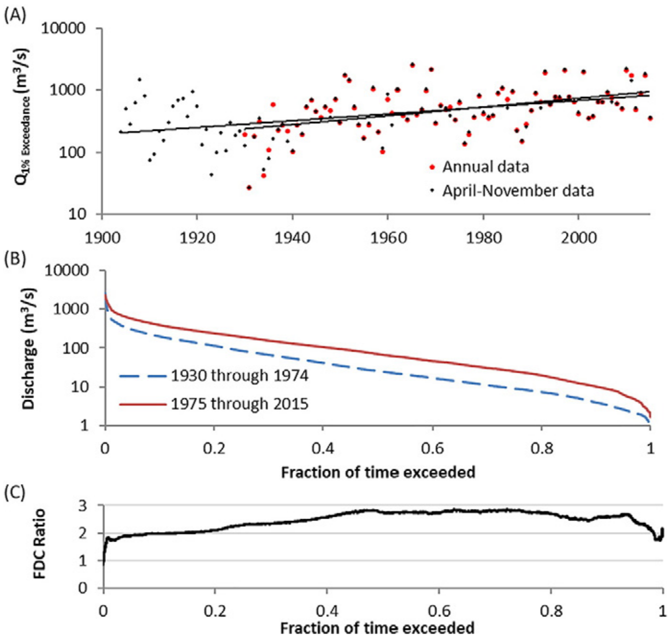

Fig. 4. Changes in discharge at USGS 05325000 (Minnesota River at Mankato) over the period of record. (A) Time series of 1% exceedance probability daily discharge for entire calendar year or April–November period (April–November data extend further back in time), with best-fit exponential trend lines for each. (B) Flow duration distributions based on all daily discharge observed for 1930–1974 or 1975–2012. (C) Ratio of discharge at a given exceedance probability for the 1975–2012 period relative to the 1930–1974 period.

these aerial surveys produced standard 9-inch by 9-inch (22.9-cm by 22.9-cm) panels with ground resolutions on the order of 1:20,000. Pixel resolutions are on the order of 2 m for the lowest resolution images and better than 1 m for most images, including most of those from the 1930s. While we recognize that scale-related effects may reduce precision in measurements based on the earlier images, we have no reason to believe such effects would bias measurements.

Photographs were georeferenced to the year 2009 National Agricultural Imagery Program (NAIP) aerial photographs using a minimum of 10 ground control points and a second-order polynomial transformation (see Hughes et al., 2006). Note that any alignment error between historic and modern images would be unlikely to influence scale-related measurements such as width or channel planform area.

While automated procedures are available for the delineation of water/sediment boundaries (e.g., Merwade, 2007), light and dark regions associated with shadows and variable amounts of glare on both water and bare sediment prevented the bank delineation from being automated (Güneralp et al., 2013, 2014). Consequently, banks were manually delineated along each study reach. In general, the bank position was relatively obvious on the outside of meander bends, particularly where lighting conditions were good. However, some judgment was required when delineating banks located on freshly deposited point bars or where shadows or overhanging trees obscured cut banks. Where shadows or overhanging vegetation were an issue, the operator attempted to find points where vegetation clearly abutted water or unvegetated bar sediment. The bank line was then interpolated across the intervening visual obstructions. Operators attempted to place vertices in the bank lines at intervals of ~50% of the bankfull channel width. Operators were encouraged to regularly zoom in and out on the photograph in order to identify the best position for each point, but in general, points were digitized with no more than a single meander bend visible on the screen. To minimize systematic errors caused by subjectivity in bank delineation, we used the same GIS technician for as many points on a given study reach as possible.

Banks were defined through this process on 16 separate river reaches, each of which was ~10 meander bends in length. Sites were selected based on good visibility of the channel boundaries and representativeness of distinct process domains, such as above and within knickzones on major tributaries. We found the 10 meander bend length scale to be sufficiently long to average out subreach variability, yet sufficiently short to minimize systematic increases in width in the downstream direction. Average width for each reach was computed by dividing total bank-to-bank planform area by the reach's centerline length. Dates for which analysis was performed are provided in Table 1, which includes several reaches not analyzed by Schottler et al. (2014). For all but one reach, the oldest photograph was taken during the late 1930s. Because the relative importance of error in identifying bank position increases as overall channel width decreases, we focused primarily on the largest tributaries of the Minnesota River and did not consider channels narrower than about 10 m. Field observations suggest that many of these smaller channels have widened less, possibly because of strong root cohesion associated with mature woody vegetation exposed in both banks and because of relatively low energy gradients (average slope ca. 0.0005 m/m) above the knickzones on tributaries.

Average rates of increase in width were derived for each of the 16 study reaches by computing the slope of a simple linear regression line placed through the raw width vs. time data for each reach. Comparison between reaches was facilitated by also computing width change rates relative to the average width during the 2000–2009 period. Spatial variability outside of the 16 sampled subreaches was characterized by measuring channel width at evenly spaced intervals of 40 m (approximately ½ channel width) along the majority of the lower Minnesota River below Mankato for 1938 and for 2008 (the uppermost 20 river km, based on the 2008 channel centerline, were not available at the time of analysis). Work was performed using the Planform Statistics Toolbox (Lauer and Parker, 2008, available at www.NCED.umn.edu), which develops centerline points at evenly spaced intervals between the manually digitized bank lines. Width was estimated at each centerline point by measuring the distance to the nearest part of each bank polyline. Width change between the 1938 and 2008 photo sets was assessed at each point by tracing a trajectory from the 1938 centerline to the 2008 centerline and then subtracting the 1938 width from the 2008 width at corresponding points. While the approach does not account for the total change in channel bankfull area because of channel sinuosity change between the two dates associated with several engineered bend cutoffs and increased rates of natural cutoffs (Lenhart et al., 2013), it provides a simple mechanism for characterizing spatial variability in width change and for relating this to overall lateral channel activity.

We quantified the area reworked via channel migration as the summation of lateral offsets between the 2008 and 1938 centerlines multiplied by centerline point spacing (40 m). However, some of the centerline offset occurred near 11 bend cutoffs that formed between 1938 and 2008 and thus does not actually represent area reworked by channel change. To develop a better estimate of the area reworked due to lateral change, we recomputed the offset while excluding the bends affected by cutoff.

Because it is theoretically possible for bankfull width to change even without real geomorphic change (e.g., mechanism a in Fig. 1), we tested whether change occurred at stages below bankfull by using the historic aerial photographs to estimate average water surface width for all dates when a daily stream discharge was available from a nearby stream gage. The analysis was performed at three locations on the main stem Minnesota River: Judson (upstream from Mankato), Jordan, and Chaska. In some cases, the photographs covering the respective reaches were taken several days or weeks apart. In these cases, a representative discharge was computed by weighting the daily discharges on the dates of each photograph by the relative length of the reach included in the photograph. Discharge data from the Jordan gage (USGS 05330000) were used for the Jordan and Chaska study reaches. Discharge at the

Judson study reach, which is located several kilometers upstream from the confluence of the Blue Earth and Minnesota Rivers, was estimated by subtracting the sum of the gaged discharge on the Blue Earth River near Rapidan (USGS 05320000) and the Le Sueur River near Rapidan (USGS 05320500) from the daily discharge on the Minnesota River at Mankato (USGS 05325000). Discharge was not available for the Blue Earth or Le Sueur Rivers in 1938, so the discharge associated with the 1938 photograph of the Judson study reach was estimated by regression between discharge of the Minnesota River at Mankato and the estimated discharge of the Minnesota River at Judson for all dates after gaging began on the Blue Earth and Le Sueur rivers.

In each set of historic aerial photographs for which a discharge could be estimated, the average water surface width in the study reaches was determined by visually delineating the edge of water in the photograph, which was usually easily identifiable, particularly at low flow stage, and then dividing the wetted planform area by the overall reach length.

3.2. Hydraulic geometry/channel cross-sectional area

We validated our in-channel water surface width estimates by developing a power-function relationship between water surface width on the date of a given photograph and discharge. We compared historical measurements of this relationship (prior to 1975) to recent measurements (2000–2009) to see whether change occurred on average at below the bankfull level.

We also used flow measurements at the Jordan gage and width measurements at the Jordan and Chaska study reaches to develop estimates of the bankfull cross-sectional area representative of the 2000–2009 period. While 2010–2015 data were available, high flow events in 2010 and 2011 widened the channel considerably. The process involved i) using flow measurements at the gage to derive a power-function relationship between discharge and cross-sectional area for all discharges between 75 and 750 m^3/s and ii) independently relating the aerial photograph-based water surface width in our study reaches to discharge for all 2003–2009 photographs and then evaluating at the average 2003–2009 total bankfull width. The resulting *width-filling* discharge can be interpreted as the discharge that just submerged the un-vegetated zone during the 2003–2009 period. We then evaluated the relationship developed between discharge and cross-sectional area developed in i) with the width-filling discharge estimate made in ii), thereby providing the cross-sectional area at the Jordan gage for flow conditions similar to those that just fill banks in our study reaches.

We compared the photo-/gage-based cross-sectional area estimates to field-measured areas derived from a combination of LiDAR and multibeam River Ray Acoustic Doppler Current Profiler (Teledyne RD Instruments, Poway, CA) bathymetric measurements. The depth-below-bankfull surface was constructed at a point density of ~3 points/100 m^2 along 33 km of the main stem near the confluence with the Blue Earth River, ~16 km upstream and ~17 km downstream from the confluence. Bankfull cross-sectional area was computed by dividing the volume below the bankfull datum by the centerline length of the reach.

We extrapolated bankfull cross-sectional areas to the entire watershed-wide channel network by combining our mainstem Minnesota River cross-sectional area estimates with several other existing data sets to generate a functional relationship between channel cross-sectional area and drainage area. Regional hydraulic geometry data surveyed throughout Central Minnesota by Magner and Brooks (2007) were supplemented by the reach-average cross-sectional areas described above along with 54 cross-sections that were measured in the field over a total of 160 km on the Maple and Le Sueur rivers in summer 2008 using an Impulse laser rangefinder and stadia rod (Belmont, 2011). Bank position was identified based on breaks in slope at the geomorphic transition between channel and floodplain. Data from Magner and Brooks (2007) are also based on field-surveyed cross-sections in riffles near USGS gage sites, with bankfull defined using field indicators.

Flow lines from the National Hydrographic Dataset (NHD) were rasterized and burned into a Shuttle Radar Topography Mission (SRTM)-based DEM (CGIAR-CSI, 2008) of the watershed with cell size of 80 m. Flow direction and flow accumulation were computed in ArcGIS and were used to estimate the drainage area at the upstream end of each link in the NHD flow line network. The associated cross-sectional area for each link was then computed using a regional hydraulic geometry equation derived from the channel cross-sectional area data sources described above.

3.3. Sediment size

Particle size information was collected as part of several separate studies. Data describing banks along the Minnesota River were obtained from samples collected at six separate sites evenly distributed downstream from Redwood Falls. Four samples were collected at each site, three spaced evenly along the face of the bank and one from the top of the bank (Hansen et al., 2010). Floodplain particle size samples were collected beyond the streambanks within the interior of the floodplain from the surface down to a depth of 2 m (Lenhart et al., 2013). Point bar samples were collected at five separate sites on the main stem Minnesota River downstream from Mankato. At each site, a

Table 1
Reaches considered in width change analysis.

Reach name	Midpoint coordinate	Length (km)	Width (2000–2009 average) (m)	Photograph years
Blue Earth R. upstream	94°05′52″W, 44°01′59″N	5.84	49.0	1939, 1949, 1973, 1991, 2003, 2004, 2005, 2006, 2008, 2009
Blue Earth R. downstream	94°06′08″W, 44°07′17″N	14.0	58.2	1939, 1949, 1973, 1980, 1991, 2003, 2005, 2006, 2008, 2009, 2015
Chippewa R.	95°47′43″W, 45°05′57″N	5.75	34.2	1938, 1956, 1991, 2003, 2006, 2008, 2009, 2010, 2015
Cottonwood R.	94°32′33″W, 44°17′11″N	7.05	38.0	1938, 1955, 1991, 2003, 2004, 2005, 2006, 2015
Elk R.	93°40′20″W, 45°20′56″N	14.0	41.4	1939, 1953, 1991, 2009
Le Sueur R.	94°01′51″W, 44°06′26″N	9.42	47.5	1939, 1949, 1950, 1958, 1964, 1971, 1991, 2003, 2004, 2005, 2006, 2008, 2015
Little Cobb R. upstream	93°59′24″W, 44°01′22″N	2.62	17.7	1939, 1949, 1991, 2003, 2005, 2006, 2008, 2009, 2015
Little Cobb R. downstream	93°59′17″W, 44°01′57″N	1.69	20.3	1939, 1949, 1991, 2003, 2004, 2005, 2006, 2008, 2009, 2015
Maple R.	94°01′04″W, 44°04′21″N	4.62	24.8	1938, 1949, 1964, 1971, 2003, 2004, 2005, 2006, 2008, 2009, 2015
Minnesota R. at Chaska	93°27′46″W, 44°48′23″N	11.4	90.8	1937, 1940, 1951, 1960, 1962, 1967, 1971, 1991, 2003, 2004, 2005, 2006, 2008, 2009, 2010, 2013, 2015
Minnesota R. at Jordan	93°37′29″W, 44°42′49″N	7.02	107.3	1937, 1940, 1951, 1963, 1964, 1991, 2003, 2004, 2005, 2006, 2008, 2009, 2010, 2013, 2015
Minnesota R. at Judson	94°7′34″W, 44°10′56″N	8.31	88.5	1938, 1949, 1950, 1958, 1964, 1971, 1991, 2003, 2004, 2005, 2006, 2008, 2009, 2010, 2013, 2015
Sauk R.	94°19′38″ W, 45°29′08″ N	13.7	33.4	1938, 1958, 1978, 2004
Watonwan R. downstream	94°14′23″W, 44°01′03″N	1.89	36.7	1938, 1949, 1964, 1991, 2003, 2004, 2005, 2006, 2008, 2009, 2015
Watonwan R. middle	94°32′05″W, 44°03′04″N	1.54	15.2	1939, 1991, 2003, 2006, 2009, 2015
Watonwan R. upstream	94°35′34″W, 44°04′02″N	1.38	11.5	1939, 1991, 2003, 2009, 2015

Data prior to 2010 on the Minnesota, Cottonwood, Le Sueur, Blue Earth upstream, Chippewa, Sauk, and Elk River reaches were analyzed by Schottler et al. (2014).

soil auger was used to collect soil samples at depths of 0–25 and 25–50 cm. Sample pits were spaced evenly across the point bar in a transect perpendicular to the river from the water line to the mature tree line. The number of samples collected at each site ranged from 7 to 9 depending on the width of the bar, resulting in a total of 41 sample pits. Particularly near the tree line, some of the point bar sites were in the process of being colonized by woody vegetation such as sandbar willow (*Salix interior*) and may thus include higher fractions of silt and clay than are characteristic of fresh point bar deposits. Grain size distributions were obtained by sieving and hydrometer analysis, respectively, for point bar and floodplain samples. Sediment sample sites are shown in Fig. 3.

4. Results

4.1. Width change measurements

Average linear trends in channel width (m/y) for each of the 16 study reaches are presented in Table 2. These temporal trends, which in many cases are not statistically significant at the 95% confidence level, are nevertheless all positive except for reaches with average 2000–2009 widths below 25 m. Data were collapsed by normalizing the width measured from each photograph in a given reach by the average of all widths for that reach measured between years 2000 and 2009. These normalized data are shown in Fig. 5 for (i) all reaches on the main stem Minnesota River, (ii) all tributaries with 2000–2009 width > 25 m, and (iii) all tributaries with 2000–2009 width < 25 m. Linear and exponential curves were fit to the relative change data and provide results that are sufficiently similar that only the linear fits are shown in Fig. 5. Results for both regressions (i.e., annual rates of change relative to the average 2003–2009 width from the linear fit, or annual rates of change computed over the entire study period from the exponential fit) are provided in Table 2. Width increase is apparently greater for the main stem Minnesota River and larger tributaries than for the smaller tributaries. At least for the reaches located on the main stem Minnesota River below Mankato, there do not appear to be any periods when width increased at a rate that was noticeably higher than the long-term average.

Sources of error in width estimation include photographic misinterpretation caused by shadows and poor lighting conditions as well as natural seasonal and year-to-year variability in the vegetation that was used as the indicator of bankfull position. We assessed error in our estimates by computing the RMSE between the average width for a given reach estimated during the 2003–2009 period. We excluded post-2009 data because 2010 was a particularly wet year, with the second-largest mean annual discharge in the Mankato flow record. While the RMSE for 2003–2009 width also includes what may be real width changes, it provides a reasonable upper limit on the precision of our methods. For the 12 reaches where at least four width estimates were available between 2003 and 2009, the RMSE with respect to the mean 2003–2009 width for the respective reach is 2.3 m ($n = 66$). Particularly for the larger channels in the data set, the magnitude of change between the late 1930s and 2008 is well above this error estimate.

Widening and overall centerline position change for the downstream-most 146.5 km of the main stem Minnesota River between 1938 and 2008 are shown in Fig. 6. In general, width change is highly variable, although very little of the reach (<1% of total channel length) experienced a net decrease in width between the two dates. The most significant decrease occurred 105 river km upstream from the Mississippi River in an area that was shortened significantly by a natural bend cutoff that occurred between 1998 and 2003. The overall average width for the entire reach increased from 69.9 to 101.1 m between 1938 and 2008. This represents an average annual rate of 0.44% of the recent (2008) width per year (0.53%/y if compounded annually), which is similar to the rate obtained from the subreach-based analysis along all main stem Minnesota River study reaches (0.52% of mean 2003–2009 width/y or 0.62%/y if compounded annually). Furthermore, for this 146.5 km reach, the overall amount of widening, as illustrated in Fig. 6B, closely follows the overall rate of lateral offset (excluding cutoffs), implying that widening and lateral change from meander migration occur in tandem, consistent with mechanism c in Fig. 1.

Temporal change evident in Figs. 5 and 6 and Table 2 illustrates that widening has occurred consistently throughout the watershed and not just in isolated reaches. Despite some bend-to-bend variability, Fig. 6 shows that the increase is distributed relatively uniformly along the entire lower Minnesota River. The results in Fig. 6 show that at least for the lower Minnesota River, widening appears to occur most rapidly upstream from Jordan, where the total along-channel change in centerline position is greater than the total along-channel change in width. In other words, above Jordan, widening appears to be associated with a process more similar to that illustrated in Fig. 1C—where the primary mode of channel change is meander migration, and widening occurs simply because of a disparity in erosion and deposition rates. The widening process is less clear downstream of Jordan, where, with the exception of a few bends within 5 km of the confluence with the Mississippi River that were cut off artificially in the 1960s for the purpose of improving commercial barge navigation, the overall areal change since 1938 due to widening has been roughly equal to the overall along-channel accumulated change in centerline position. Here, lateral centerline change is not sufficiently high for widening to have occurred exclusively along actively migrating meander bends. In other words, mechanisms a or b of Fig. 1, neither of which results in net centerline position change, could be partly responsible for the widening.

4.2. Change in hydraulic geometry

Estimating the net export of sediment associated with widening requires some assumptions regarding the mode of change illustrated in Fig. 1. If the observed increases in width of the unvegetated zone are primarily caused by changes in the vertical position of vegetation resulting from increased flood frequency or changes in flood timing (e.g., mechanism a), width increase may not result in much sediment export. However, if the geometry of the entire section changes (mechanisms b and/or c), then width change should be associated with an overall increase in bank-to-bank volume and thus should influence the sediment budget for the reach. Because repeat cross-section or bathymetric surveys are generally unavailable except for recent periods or at gage locations and because the three USGS gages along the lower Minnesota River are built near relatively stable cross-sections, the at-a-station hydraulic geometry for water surface width is one of the few available approaches for evaluating whether change occurred below the bankfull level during this period.

Results for at-a-station analysis are shown in Fig. 7 for the pre-1975 and post-1975 periods, along with power-function regressions representing relationships between average water surface width and discharge for each reach. Note that with the exception of a single data point from 1991, as labeled in the figure, all post-1975 data are for photographs taken after the year 2003 and are thus representative of relatively recent conditions. In all cases, the power-function representing width vs. discharge for the later period plots well above the power function for the pre-1975 period, indicating that the water surface width was typically much greater for a given discharge during the more recent period. Determining whether either of these results are statistically significant is complicated by the lack of available data for the pre-1975 period, the larger discharges during the post-1975 period, and because change in the cross-section probably occurred continuously throughout each period. However, the figure supports the idea that water surface widths have increased through time even at relatively low discharges, implying that cross-sectional enlargement similar to that shown in Fig. 1B has occurred throughout the lower Minnesota River valley. Because the width change is greatest at Jordan and Judson, in reaches

Table 2
Summary of width analysis results.

Reach name	Rate of increase (m/y)	Annual rate of increase relative to average 2003–2009 width	Annual rate of increase based on exponential curve
Blue Earth R. downstream	0.05	0.09%	–
Blue Earth R. upstream	0.23	0.48%	–
Chippewa R.	0.06	0.20%	–
Cottonwood R.	0.05	0.17%	–
Elk R.	0.03	0.07%	–
Le Sueur R.	0.18	0.44%	–
Little Cobb R. upstream	0.02	0.23%	–
Little Cobb R. downstream	−0.07	−0.24%	–
Maple R.	0.05	0.35%	–
Minnesota R. at Chaska	0.34	0.37%	–
Minnesota R. at Jordan	0.47	0.42%	–
Minnesota R. at Judson	0.71	0.80%	–
Sauk R.	0.02	0.06%	–
Watonwan R. downstream	0.15	0.44%	–
Watonwan R. middle	−0.03	−0.18%	–
Watonwan R. upstream	0.00	−0.01%	–
Minnesota R. only	–	0.52 ± 0.08%	0.62 ± 0.10%
All reaches excluding Minnesota R.	–	0.22 ± 0.10%	0.24 ± 0.09%
Reaches > 25 m wide only	–	0.38 ± 0.06%	0.44 ± 0.07%
Tributaries > 25 m wide only	–	0.28 ± 0.08%	0.31 ± 0.08%
Tributaries < 25 m wide only	–	0.08 ± 0.22%	0.08 ± 0.19%
All data	–	0.32 ± 0.08%	0.36 ± 0.08%

where the channel migrates regularly, as shown in Fig. 6, an imbalance between cut bank erosion and point bar deposition appears to be the most likely mechanism for the enlargement.

4.3. Cross-sectional area estimates

Estimates of width-filling discharge calculated for each of the three main-stem Minnesota River study reaches as well as the corresponding cross-sectional areas for the Jordan and Chaska reaches are presented in Table 3. Bathymetric survey-based estimates of bankfull cross-sectional area are also presented for 16 km of the main-stem Minnesota River immediately upstream from the confluence with the Blue Earth River (i.e., roughly the Judson study reach), and 17 km immediately downstream from the Blue Earth confluence, near Mankato (labeled Mankato in the table). We note that each of the cross-sectional area estimates derived from the width-filling discharge depend on the discharge-area function at the Jordan gage site, which is located in a relatively stable location that could result in smaller cross-sectional areas than are typical for the reach. In any case, either approach (width-filling discharge-based estimates or reach-scale bathymetric surveying) results in cross-sectional areas that are somewhat larger than cross-section based estimates of average cross-sectional area used by Lenhart et al. (2013).

4.4. Size distribution data

Grain size fractions for material sampled from eroding cutbanks and point bars are presented in Table 4. The lowest sand fractions were observed in floodplain samples collected along the main Minnesota River valley downstream from Mankato. Samples collected from cut banks in this part of the valley contained similar sand fractions but were somewhat less clay-rich than the floodplain surface deposits. In both cases (cutbanks and floodplains), average sand fractions were between 40 and 50%. Cutbanks on tributaries were sandier, with average sand fractions exceeding 60%. Point bars on the lower river were the sandiest of all observed deposits, with average sand fractions exceeding 80%.

4.5. Bankfull volume estimates

Our regional compilation of cross-sectional area and drainage area is presented in Fig. 8. While there is a lot of scatter, perhaps because of differences in climate through the watershed or differences in geomorphic processes occurring above and within knickzones in tributaries, a single power function,

$$A_{xs} = 0.164 A_D^{0.82} \tag{1}$$

where A_{xs} represents bankfull cross-sectional area (m^2) and A_D represents drainage area (km^2), appears to hold reasonably well across a wide range of scales, from drainage areas as small as 1 km^2 up to the entire basin area. However, note that primarily because of the inclusion of the Maple River data set (Belmont, 2011), which is characterized by particularly large cross-sectional areas, the regression results in an apparent positive bias for the largest drainage areas.

Fig. 9 maps the results of the cross-sectional area analysis across the stream network, using three separate classes of drainage area: below 640 km^2, between 640 and 10,000 km^2, and above 10,000 km^2. The lower threshold was selected because our width estimates in the Le Sueur River basin show that 640 km^2 is about the threshold at which the width of the active channel falls below 25 m. As shown in Fig. 5, at these widths, our data do not show any measurable widening, although we are unsure whether the lack of a significant trend for these small channels is from lack of resolution in our methods. The threshold of 10,000 km^2 conveniently delineates most of the main stem Minnesota River. Channels with drainage areas between the thresholds typically are large, named tributaries.

The potential for widening-related sediment supply presumably correlates with the parts of the channel network that contain the most bankfull volume. We estimate bankfull volume by multiplying the streamwise length of each link by the cross-sectional area estimated using Eq. (2). Cumulative bankfull volume for all links with drainage areas less than a given value is presented in Fig. 10. Well over half of the total of 0.7 km^3 bankfull volume in the basin is represented by the main stem Minnesota River below the Pomme de Terre River. Another roughly 23% is represented by the main trunks of major tributaries (green in Fig. 9). Small channels narrower than 25 m account for only around 15% of the overall channel volume in the basin. Note that this result is similar even if we exclude Maple and Le Sueur River data from the regression shown in Fig. 8, which would eliminate the apparent positive bias in estimated cross-sectional area for the largest drainage areas. This more conservative estimate reduces the overall volume for the basin by roughly a factor of two, but the main stem still represents the majority of the bankfull volume. For this reason, Fig. 10 should

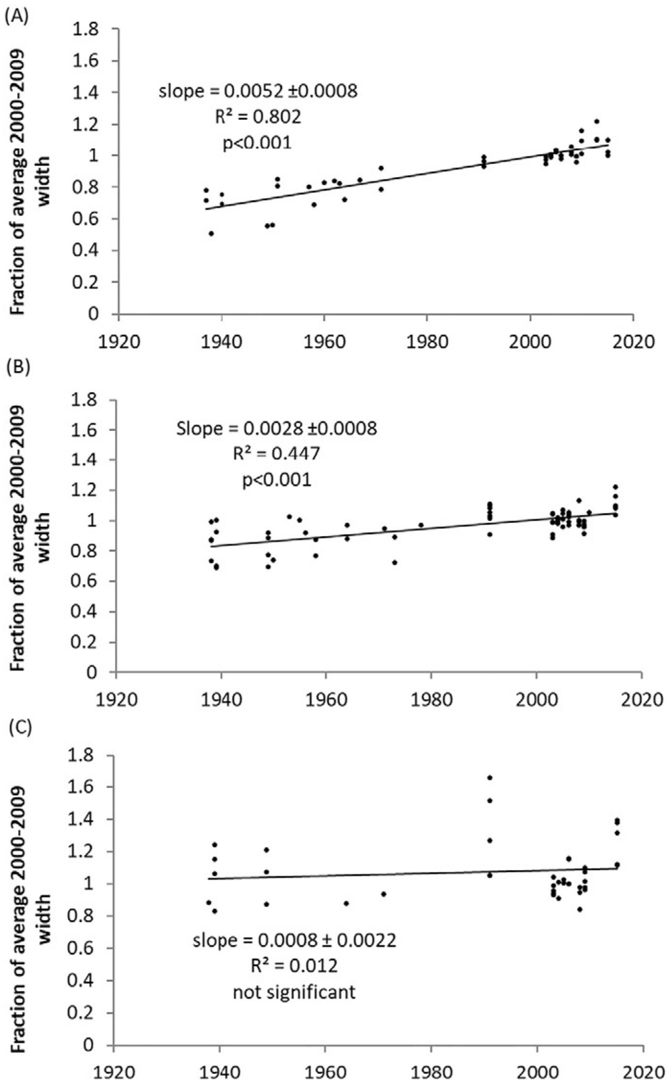

Fig. 5. Trends in normalized width over time. Data are plotted separately for (A) main stem Minnesota River reaches; (B) tributary reaches with mean 2000–2009 width > 25 m; and (C) reaches with mean 2000–2009 width < 25 m.

be interpreted as providing a general description of relative position of channel volume within the watershed, but it should not be used as a definitive estimate of the watershed-wide total. Additional bathymetric surveys along the main stem Minnesota River upstream from Mankato would be necessary to increase confidence in the overall volume estimate.

5. Discussion

5.1. Temporal change in hydraulic geometry

The well-documented, large, and relatively continuous change in discharge in the Minnesota River basin over the twentieth and early twenty-first centuries makes this system a useful test case for river response to environmental change. If there are no significant lags between adjustment in driving variable (discharge Q) and response variable (width W), the standard power-function form for hydraulic geometry for width,

$$W = aQ^b \tag{2}$$

implies that the ratio of bankfull widths measured at two separate times, W_2/W_1, can be found from the ratios of driving discharges at the corresponding times:

$$(W_2/W_1) = (Q_2/Q_1)^b \tag{3}$$

Eq. (3) makes the simplest possible assumption, that coefficient a and exponent b remain constant throughout the adjustment process. Church (1995) showed that Eq. (3) can represent geomorphic change over decadal timescales, particularly on systems that experience changes in formative discharge large enough to mobilize bed material during the adjustment period. The changes on the Minnesota River documented here represent one of the longest timescale tests we are aware of for evaluating the fluvial response to a long-term increase in discharge.

As discussed above, perhaps the simplest way to characterize long-term change in formative discharge along the lower Minnesota River is to use the simple exponential curves shown in Fig. 3A. While this clearly neglects the important physics behind watershed-scale change, it provides a growth rate that can be used to place our width change estimates in an appropriate context. In the case of the Minnesota River at Mankato, the annual growth rate in the 1% exceedance daily discharge for the 1930–2015 period gives $Q_2/Q_1 = 1.0163 \pm 0.0065$. Similar annual growth rates result when using other potential representations of formative discharge, such as mean annual discharge or discharge at other exceedance probabilities.

Using standard error propagation (95% confidence limits) and the frequently cited value of 0.5 for the hydraulic geometry exponent b (Knighton and Wharton, 2014), the error in the annual increase in width should be half the error in the annual increase in discharge. This implies that width should have increased over this period at an annual rate of $W_2/W_1 = (1.0163 \pm 0.0065)^{0.5} = 1.0081 \pm 0.0033$. This derived annual rate of increase in width, 0.81 ± 0.33%/y, is within the error of the observed annual change in width for our main stem Minnesota River study reaches, which is computed to be 0.62 ± 0.10%/y based on a semi-log regression of the normalized data in Fig. 5A. The similarity between the rates predicted by hydraulic geometry and measured from historical images suggests that the lower main stem of the Minnesota River has remained near an equilibrium between width and discharge during much of the past century. Thus, continued widening over the past decades may be primarily due to recent increases in discharge and not to long-term lags in geomorphic response. However, the lower Minnesota River is not presently capable of transporting all sediment supplied to it from upstream (MPCA, 2009), implying that it may be undergoing long-term depth adjustment. Some of the adjustment depends at least partly on storage of sediment on the floodplain, as described by Wilcock (2009) and Lenhart et al. (2013) and elaborated upon below. This raises the possibility that geometric adjustment of channel depth could lag well behind adjustment of width, particularly in aggrading systems.

5.2. Basin wide implications

Near-bank sediment sources have become an increasingly important component of the sediment load of the Minnesota River in recent decades (Belmont et al., 2011). Some of this sediment originates in bluffs that are present along tributaries, particularly in the Blue Earth and Le Sueur basins (Sekely et al., 2002; Thoma et al., 2005; Day et al., 2013; Belmont et al., 2014; Schaffrath et al., 2015). Our results indicate that in addition to these localized sources, channel widening is probably occurring consistently at many locations in the basin. Furthermore, the at-a-station hydraulic geometry analysis supports the idea that widening is associated with net geomorphic change. An obvious question, then, is whether basin wide changes in channel geometry could be responsible for significant amounts of sediment production, and if so, where in the basin the effect would be strongest.

Our observed increases in channel width are greatest for the widest channels. Furthermore, our hydraulic geometry analysis shows that

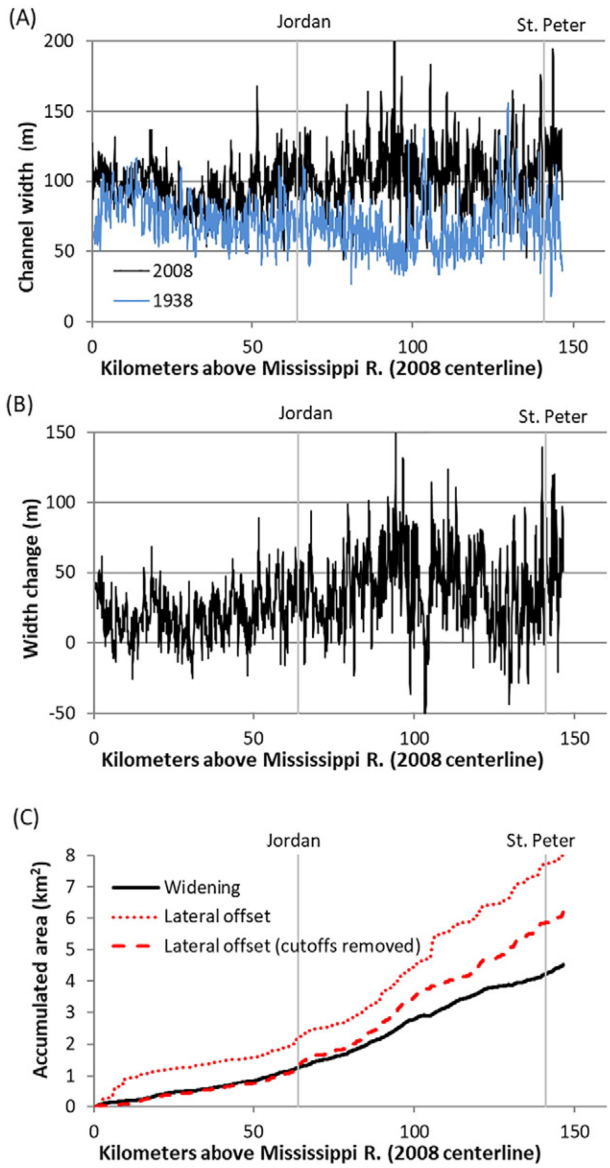

Fig. 6. Spatial variability in width and width change on lower Minnesota River between 1938 and 2008. The figure shows (A) width at a given 2008 channel coordinate, (B) local change in channel width at corresponding points on the 1938 and 2008 centerlines, and (C) cumulative area of change computed by summing local change rates multiplied by centerline point spacing, starting at the confluence with the Mississippi River and extending upstream to ~20 river km downstream of Mankato. Also shown in (C) is the cumulative area represented by centerline offset, computed on a point-by-point basis. Steep sections in the curve are generally associated with bend cutoffs (engineered and natural), which move the channel centerline a great deal over a short distance. A curve that does not include reaches affected by bend cutoff in the summation is also included.

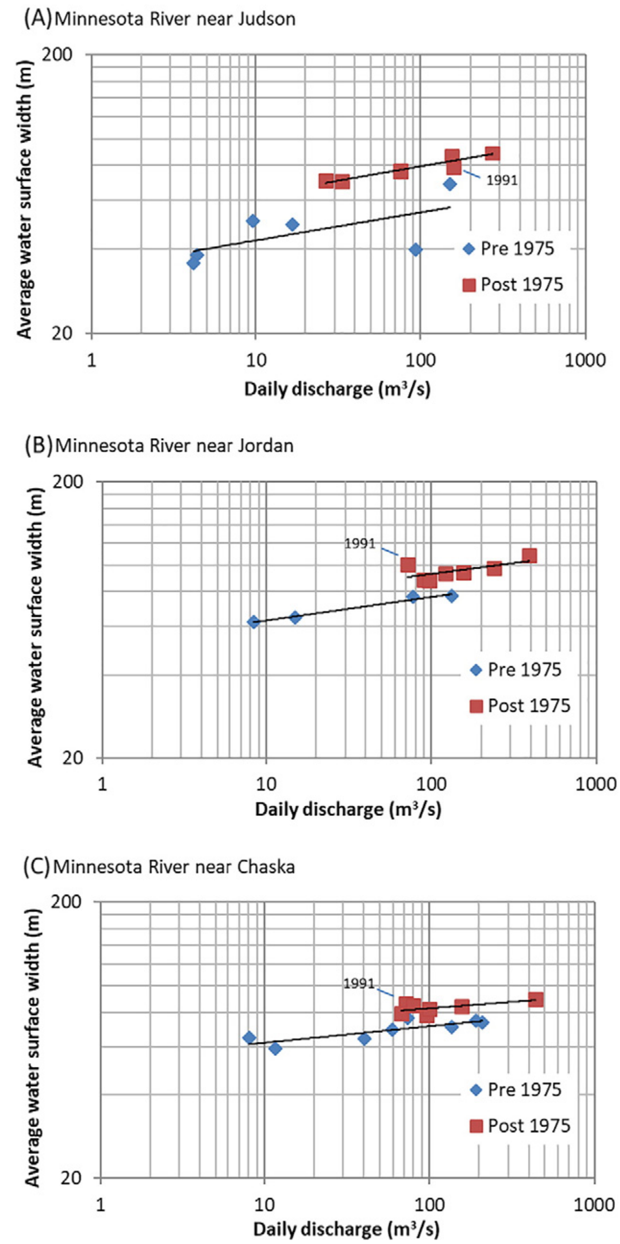

Fig. 7. At-a-station hydraulic geometry and best-fit power function regressions for reach-average water surface width versus daily discharge. Data are as observed in the pre- and post-1975 air photo records along the Minnesota River for (A) Judson, (B) Jordan, and (C) Chaska. In all cases, the water surface width for a given discharge appears to be larger for the more recent period, implying widening has occurred throughout the cross section.

overall cross-sectional area and thus overall bankfull channel volume are strongly weighted toward the highest order channels. Consequently, any sediment production caused by widening would appear to be most important on the main stem Minnesota River and its main tributaries. This is likely the case even if the resolution limitations of our analysis caused us to miss widening along channels below 25 m in width. Small, low-order channels simply do not account for enough cross-sectional area for widening there to outweigh sediment production on larger, higher-order channels. However, this should not be taken to mean the overall sediment contribution from low order streams is universally small. On the contrary, particularly in systems undergoing rapid hydrologic change, net incision and/or net erosion into terraces along even small channels may represent very large components of sediment budgets (Simon, 1989; Trimble, 2009; Stout et al., 2014). Our analysis does not consider these other potential, nonwidening related sediment inputs, although previous studies have shown that channel erosion high in the network is probably not a major sediment source (Gran et al., 2011; Belmont et al., 2014).

Despite the relative paucity of bankfull volume along the lowest-order segments of the stream network, Fig. 10 indicates the channel network may contain as much as 0.5 km^3 of channel volume upstream from Mankato. Most of this volume occurs in larger tributaries and the main stem Minnesota River itself. Accepting this volume as plausible, and assuming it is enlarging at the average widening rate for all our subreaches, 0.36%/y, then the overall annual volume of sediment supplied to the channel network would be on the order of 0.5 km^3 * 0.0036 = 1.8×10^6 m^3/y. This calculation assumes that widening is occurring because of enlargement of the cross-section rather than vertical change in the vegetation line (i.e., mechanisms b or c in Fig. 1), and it also makes the relatively conservative assumption that depth has not increased along these channels through bed incision. Presumably, a large influx of sand from widening would lead to bed aggradation, not degradation, although we are not aware of any analysis in this part of the basin that has quantified long-term bed elevation change. If incision is occurring instead, our volume estimate would necessarily be larger. In any case, at a bulk density of 1.35 Mg/m^3, our estimated volume represents around 2.4×10^6 Mg/y of sediment produced simply from widening. While this number admittedly depends on the regional hydraulic geometry presented in Fig. 8 and could be improved significantly with additional cross-section surveys on the main stem Minnesota River upstream from Mankato, its magnitude is clearly large relative to observed loads. Ellison et al. (2014) estimated an annual silt/clay load at Mankato of 1.16×10^6 Mg/y based on suspended sediment concentration measurements. Even if only 40% of our widening-related sediment supply is finer than sand and thus travels as washload (a reasonable estimate according to Table 4), widening probably represents a significant near-channel source of sediment. Furthermore, taken together with other well-documented sediment sources such as bluffs, surface erosion, ravines, etc., the results imply that there is probably a relatively large sediment sink distributed throughout the system (c.f. Beach, 1994), even upstream of Mankato. This sink is probably strongest for sand-size and larger sediment, but even silt/clay loads could be influenced by net storage along channels and in floodplains.

5.3. Significance of widening-related sediment for lower Minnesota River

The consistently large increase in width along the main stem Minnesota River, together with its relatively important contribution to overall bankfull volume in the basin, indicates that widening here has probably represented an important transfer of sediment to the channel during much of the twentieth century. Here we consider the nature of the sediment transfer and the implications it may have on the sediment budget for the reach.

Lenhart et al. (2013) estimated a gross widening-based sediment supply for the lower Minnesota River of 280,000 ± 56,000 Mg/y. This estimate is based on the overall change in channel planform area between 1938 and 2009 and a bank height of 3.2 m that was derived from surveyed bank profiles at seven cross sections. However, this gross sediment production estimate may be somewhat low because the cross-sectional areas we estimate here are larger than those available to Lenhart et al. (2013) and because our widening rates, which are based on a more extensive dataset, are also somewhat larger. Assuming for the time being that average channel depth remains constant, consistent with Lenhart et al. (2013), using the average of the three cross-sectional area estimates presented in Table 3, 522 m^2, and using the average widening rate for the main stem Minnesota River presented in Fig. 5, 0.52%/y (relative to average 2003–2009 width), the overall volumetric sediment supply from the 166.4-km lower Minnesota River downstream of Mankato is approximately 450,000 m^3/y. At the average bulk density from the cut bank samples in Table 4 of 1.35 g/cm^3, this is equivalent to 610,000 Mg/y, or roughly twice the estimate of Lenhart et al. (2013). Placing error bars on this estimate is challenging because we do not have sufficient data to place confidence limits on our average cross-sectional area estimate, but using the confidence limits on the slope of the widening rates implies that 95% confidence limits are at least ±90,000 Mg/y.

A more precise accounting for sediment eroded by channel widening would consider the possibility of storage within the reach. Because bed material is mostly sand but banks contain a significant fraction of silt/clay size sediment, this requires a size-specific calculation. Based on the data in Table 4, sand probably represents between 40 and 50% of the material eroded from banks or deposited on floodplains along the main stem Minnesota River and perhaps 60% of the material eroded from the banks of tributaries. If widening typically occurs into cutbanks (Fig. 1C) that have a sand fraction of 46%, widening could be responsible for a gross supply of sand to the channel of the main stem Minnesota River downstream from Mankato of roughly 610,000 ± 90,000 Mg/y * 0.46 = 280,000 ± 41,000 Mg/y. Incidentally, this is over 50% of the suspended sand load at Mankato reported by Ellison et al. (2014).

Sand also enters and leaves the channel through regular meander migration, even if the channel is not widening. A long-term estimate of this flux can be developed using the overall area of lateral offset (without cutoffs) presented in Fig. 6, which we refer to here as A_o. If widening occurs exclusively through erosion of a single bank (mechanism c in Fig. 1), the resulting centerline offset would be half of the overall widening. Assuming that this is the primary process responsible for widening, and neglecting major changes in sinuosity, migration should have reworked an area roughly equal to A_o minus half of the cumulative widening:

$$A_m = A_o - 0.5A_w \tag{4}$$

where A_m is the total area reworked by migration, and A_w is the total increase in channel planform area for the reach.

For the 146.5 km considered in Fig. 6, the cumulative lateral offset from 1938 to 2008 (neglecting cutoffs) represents an area of 6.17 km^2, while the cumulative widening represents 4.53 km^2. This implies an area reworked by lateral migration between 1938 and 2008 of 6.17–4.53/2 = 3.91 km^2, or, if divided across the 146.5-km length for which the figure applies, a lateral migration rate of 0.38 m/y simply due to progressive bend migration. Lateral migration at such a rate would presumably have occurred even in the absence of any widening. If migration erodes sediment over a bank thickness of 5 m (roughly the average bankfull depth at Jordan, as presented in Table 3), a migration rate of 0.38 m/y would produce a volumetric flux of roughly 166.4 km * 0.38 m/y * 5 m = 316,000 m^3/y for the lower Minnesota River downstream from Mankato. We note that cumulative lateral offset in Fig. 6 is weighted toward the upstream end of the reach, so most of this erosion probably occurs upstream from Jordan. If banks and bars had identical elevations and consisted entirely of sand, migration would simply be associated with the exchange of sand from one bank to another, with little net impact on the reach-scale budget. However, because our data show that cutbanks contain less sand than do point bars (46 vs. 81% sand, respectively, as shown in Table 4), migration probably represents a net sink for sand. Furthermore, bulk density for sandy point

Table 3
Width-filling discharge (Q_{wf}) and associated cross-sectional area estimates.

Study reach	Regression between discharge Q (cms) and water surface width B (m), using 2000–2009 data	Average 2003–2009 width from aerial photographs (m)	Q_{wf} at 2003–2009 width (m^3/s)	Cross-sectional flow area at nearest gage (Jordan) at Q_{wf} (m^2)	Reach-average surveyed bankfull cross-sectional area from bathymetry (m^2)
Minnesota R. at Judson	$Q = 47.9B^{0.112}$	88.5	244	N/A	450
Minnesota R. at Jordan	$Q = 48.7B^{0.131}$	107.3	420	412	N/A
Minnesota R. at Chaska	$Q = 62.4B^{0.059}$	90.8	601	502	N/A
Minnesota R. at Mankato	N/A	N/A	N/A	N/A	651

Aerial photograph analysis not performed in the Mankato study reach.

Table 4
Particle size data on streambanks and point bars along the Minnesota River.

Site locations	Sample size	% gravel/sand/silt/clay	Soil texture (USDA classification)
Streambanks on mainstem of Minnesota River (from Judson to St. Paul)	29	0/46/51/3	Sandy loam
Floodplain samples (valley of main-stem of Minnesota River between Mankato and St. Paul)	24	0/40/36/24	Loam
Tributaries	34	0/61/36/4	Sandy loam
Point Bars on mainstem of Minnesota River (from Judson to St. Paul)	82	2/81/–/– (silt + clay = 17%)	Sand

bar deposits may be higher than the value of 1.35 Mg/m^3 we estimate from our relatively silt-rich cutbank samples. For natural quartz sand deposits with typical porosities of around 40% (Fraser, 1935; Román-Sierra et al., 2014), bulk density should be about 1.59 Mg/m^3. Multiplying the 316,000 m^3/y exchange flux by the appropriate sand fractions and bulk densities results in sand supply at cut banks of 316,000 m^3/y $*$ 0.46 $*$ 1.35 Mg/m^3 = 196,000 Mg/y and deposition in point bars of 316,000 m^3/y $*$ 0.81 $*$ 1.59 Mg/m^3 = 407,000 Mg/y, for a net difference (i.e., net migration-related sand storage) of 211,000 Mg/y. It is thus plausible, at least to within the error of our flux estimates, that most of the sand produced by widening (280,000 ± 41,000 Mg/y) is sequestered in nearby point bars. Dividing the remaining sand across the channel area of the lower Minnesota River would result in an aggradation rate of under 3 mm/y, so small changes in average bed elevation or natural deposition in oxbow lakes could easily be sequestering the rest.

Another implication of our findings relates to the supply of fine (silt/clay–size) sediment associated with eroding banks. Unless most widening occurs on point-bar banks, which is not consistent with Fig. 2 or Fig. 6, or into cutbanks that are significantly sandier than we observed, roughly 50 to 60% of material supplied to the channel through widening and channel migration consists of silt and clay. Using our overall estimate of volumetric widening from the 166.4-km lower Minnesota River of ~450,000 m^3/y and a silt + clay fraction of 54% (streambanks below Mankato, Table 1), this implies a flux of 450,000 m^3/y $*$ 0.54 $*$ 1.35 Mg/m^3 = 330,000 Mg/y of silt/clay transferred to the channel exclusively from widening. Net erosion of cut banks by regular meander migration presumably transfers another 330,000 m^3/y $*$ 0.54 $*$ 1.35 Mg/m^3 = 239,000 Mg/y of silt/clay to the channel. Assuming that none of this silt/clay is deposited in point bars, the total production of silt/clay from meander migration and widening together comes to ~569,000 Mg/y. Unlike sand, silt/clay size material is unlikely to be stored in a channel deposit, so it probably does increase the net down-channel load unless it is deposited on the floodplain.

While fully characterizing the silt/clay budget for the lower Minnesota River valley is beyond the scope of our study, our results indicate that the trap efficiency of floodplains and channel cutoffs in this reach could be much higher than previously recognized. Wilcock (2009) used total suspended solids (TSS) loads gaged at several points along the lower Minnesota River to estimate a net TSS sink (presumably mostly silt/clay) of 350,000 Mg/y. Even without considering the supply of silt/clay associated with widening of the mainstem Minnesota River, Wilcock (2009) estimated that 25–50% of washload is stored downstream from Mankato. If the 569,000 Mg/y silt/clay we estimate as being transferred to the channel by widening and channel migration is assumed stored within the reach, which is necessary for the Wilcock (2009) budget to close, the overall sequestration of fine sediment within the reach becomes considerably larger. This is generally consistent with Groten et al. (2016), whose SSC load estimates for the 2011–2014 period show a large increase in suspended sediment load between Mankato and Jordan and a large decrease, to levels somewhat below those at Mankato, between Jordan and Fort Snelling. The increase occurs within the reach where we show the greatest long-term widening and the most active channel migration (Fig. 6), and the decrease occurs in a reach with much lower overall migration rates and extensive off-channel water bodies. In fact, adding ~569,000 Mg/y silt/clay to the Wilcock (2009) storage estimate implies that sediment storage within the reach could have a magnitude similar to upstream sediment supply at Mankato, which has been estimated at 797,000 Mg/y (2000–2008 TSS load, MPCA, 2009) or 1.6 × 10^6 Mg/y with 28% coarser than 62.5 μm (2007–2011 SSC-based estimate; Ellison et al., 2014).

5.4. Other geomorphic adjustments

An increase in formative discharge should eventually lead to increases in depth as well as in width. In principle, depth adjustment can occur through changes to either average bed or bank-top elevation. Because widening provides bed material stored in the floodplain to the channel, sufficiently large rates of widening could theoretically mobilize so much sediment that it could overwhelm the down-channel transport capacity of the system, causing bed aggradation and thus decreasing

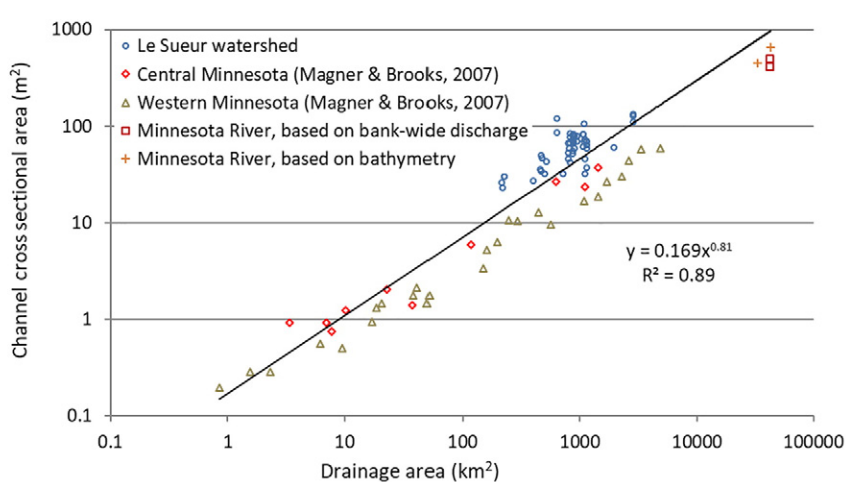

Fig. 8. Regional relationship between channel cross-sectional area at bankfull stage and drainage area. Data are for the Minnesota River and nearby watersheds. Data from Magner and Brooks (2007) were digitized from the reference and included sites outside the Minnesota River basin. Cross-sectional areas for the Minnesota River are based on aerial photograph-based width-filling discharge estimates at the Jordan and Chaska study reaches or field-surveyed bathymetry at Mankato and Judson.

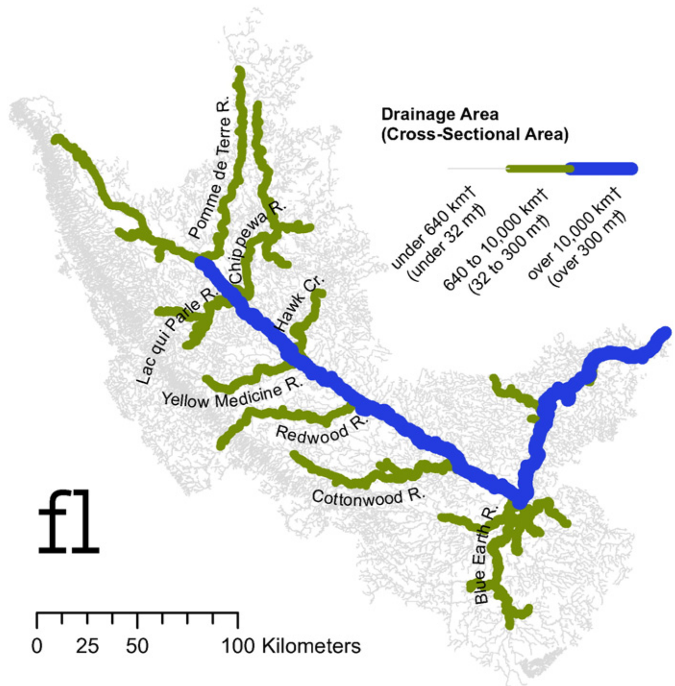

Fig. 9. Channel network of the Minnesota River, split into three categories based on contributing drainage area. The majority of the main stem of the Minnesota River has a drainage area > 10,000 km^2.

depth. However, in the present study, we calculate relatively high storage of sand in bars and thus minimal to modest net storage of sand on the bed. Furthermore, cross-section surveys within our lower-most study reach at Chaska show minimal overall bed elevation change between 1948 and 2000 (Lenhart et al., 2013). In-channel dredging, which has been used to maintain navigability along the downstream-most 23 km of the Minnesota River since the 1960s (Lenhart et al., 2013), may also locally play some role in preventing bed aggradation. However, the effect is probably limited because dredging occurs well downstream from Chaska.

Whether or not bed elevation has remained relatively stable, increased discharge has presumably led to an increase in flood duration and frequency, providing ample opportunities for sediment accumulation at the top of bank. This is consistent with the apparent storage of large quantities of fine sediment within the valley of the lower Minnesota River (Wilcock, 2009; Lenhart et al., 2013; Groten et al., 2016). However, dividing the sum of the Wilcock (2009) storage estimate and our 569,000 Mg/y of widening-related silt/clay production across a ~ 130-km-long, ~1-km-wide lower Minnesota River floodplain produces average deposition rates on the order of just 5 mm/y. So, to the extent that the Minnesota River cannot incise to gain depth, many years of overbank sediment accumulation would be required to build banks to a level sufficiently high to regain equilibrium. This is particularly true if net sand storage is causing moderate amounts of bed aggradation.

Finally, meander bend cutoffs along the lower Minnesota River may serve as yet another important sediment sink. Although cutoffs did not occur within our two lower Minnesota River study reaches, bend cutoffs (natural and engineered) and local straightening at bridges reduced the overall sinuosity of the uppermost 82 km of the lower Minnesota River by about 18% between 1938 and 2009 (Lenhart et al., 2013). The largest cutoff occurred in 2001, causing the abandonment of ~4 km of channel ~105 river km upstream from the confluence with the Mississippi River. Oxbow lakes associated with these cutoffs were usually partially filled with sediment several years after formation. Even where lakes have persisted, they are generally connected to the channel during floods and continue to experience sedimentation. The cutoffs may also have had important implications for widening. Channel adjustment near bend cutoffs can occur through upstream incision and/or bed coarsening, downstream aggradation, and the growth of new bends that increase sinuosity and thus eventually allow slope to relax back toward the pre-cutoff value. However, because meander regrowth can occur slowly relative to bed adjustment (Talbot and Lapointe, 2002), the slope increase associated with cutoff can persist for some time. To the extent that channel width is set by a formative bankfull Shield's stress (e.g., Parker et al., 2007; Wilkerson and Parker, 2011), the increased slope would lead to an increase in width even if formative discharge remained unchanged. Fig. 6 clearly shows a larger increase in width on the lower Minnesota River upstream from Jordan than farther downstream where fewer cutoffs occurred. It thus appears plausible that width increase may have been exacerbated by slope changes near

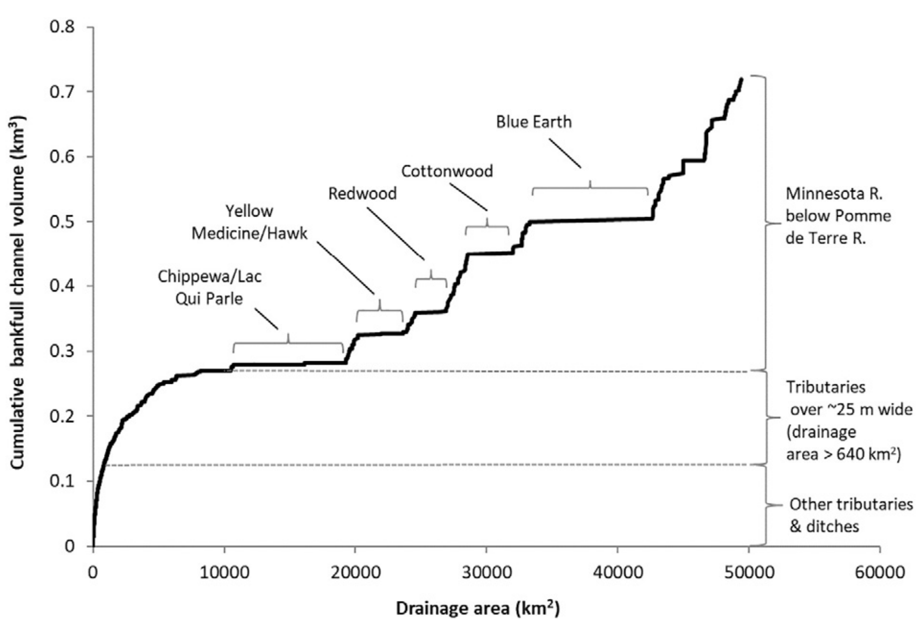

Fig. 10. Cumulative bankfull channel volume for all channel segments with contributing drainage areas up to a given threshold. The computation starts at the drainage divide and extends downstream to the confluence with the Mississippi River. Horizontal brackets identify major confluences. Vertical brackets represent total bankfull volumes associated with the three drainage area classes mapped in Fig. 9.

cutoffs. However, the increase in width even for the lower section of the lower Minnesota River, downstream from the cutoffs, as well as the observation that width has continued to increase relatively consistently in all main-stem study reaches, indicate that the observed increase in discharge is the primary driver.

5.5. Management implications

These findings have important implications for sediment management. Specifically, sediment reduction strategies should consider the large and dynamic sources and sinks for sediment that exist within a relatively narrow near-channel corridor that comprises the channel and its geomorphically active floodplain. This corridor represents a small fraction of the total landscape but plays a disproportionately important role in the sediment budget of large, transport-limited alluvial rivers like the Minnesota River. Furthermore, because this corridor tends to become exponentially larger and more dynamic in the downstream direction, stream stabilization on relatively small first- and second-order channels may not provide the overall sediment supply reduction benefits that are sometimes assumed. Additional analysis focused on the role of these low-order channels is probably warranted, but such studies should recognize that the majority of bankfull volume—and thus the majority of the potential for volumetric adjustment to influence the sediment budget—is located farther downstream. On the other hand, while relatively dynamic high-order channels do apparently provide an important sediment reduction target, the highly distributed nature of the widening and the fact that widening often occurs in tandem with natural meander migration means that simply stabilizing the most rapidly eroding banks along the Minnesota River mainstem would probably not be effective at reducing overall widening-related sediment supply. Furthermore, interrupting natural bend growth and cutoff processes through bank stabilization could influence the sand budget on the main stem Minnesota River and may have important ecological consequences. Addressing the increases in discharge that have been caused by increased precipitation and agricultural drainage may represent a more effective management strategy.

6. Conclusions

Air photograph analysis of the unvegetated zone of the Minnesota River and major tributary channels shows that long-term widening has occurred at a relatively consistent rate since at least 1937, a period characterized by a large increase in overall water discharge. The overall widening rate computed using all of our data is on the order of 0.36%/y, with rates as large as 0.62%/y for the largest channels in the watershed. Error on these estimates is on the order of $\pm$0.1%/y. On the main stem Minnesota River below Mankato, widening occurred on most meander bends and was somewhat higher in areas that experienced large amounts of centerline change. Furthermore, changes in the width of the water surface during low discharge periods along three reaches of the Minnesota River indicate that widening has occurred throughout the cross-section and is not exclusively associated with changes in the elevation and horizontal position of top-of-bank vegetation. A regional relationship between channel cross-sectional area and drainage area was used to develop estimates of overall bankfull volume in the basin. Most of the bankfull volume occurs within the Minnesota River itself, and major tributaries (width > 25 m) account for the majority of the remainder. Extrapolation of our 1937–2015 widening rates to all of these channels indicates that widening could conceivably produce more sediment than has been observed at gages monitored for TSS and SSC on the lower Minnesota River over the past several decades.

While we did not observe measureable width change in the smallest channels we studied (those with widths between roughly 10 and 25 m), this may have resulted from an inability to clearly delineate banks from aerial imagery on relatively small channels that often have dense riparian vegetation. Furthermore, we did not attempt to measure width change in channels narrower than 10 m. Larger relative changes in width along small channels would increase the importance of widening as a sediment source. Our results also imply that significant floodplain-related sinks for sand and easily suspended silt/clay-size sediment are present along the main stem Minnesota River and its major tributaries. The widening-related source and the floodplain sink represent very important and underappreciated parts of the overall sediment budget for the watershed. Managing widening-related sediment production is complicated by the fact that the source is highly distributed. Because widening appears to be driven primarily by increases in flow caused by increases in precipitation and agricultural drainage, management strategies that focus on reducing high flows may be the most prudent and sustainable mechanism to reduce the associated sediment loads.

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