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ADJUSTMENT OF PRAIRIE POTHOLE STREAMS TO LAND-USE, DRAINAGE AND CLIMATE CHANGES AND CONSEQUENCES FOR TURBIDITY IMPAIRMENT

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ABSTRACT

Changes in land use and drainage have contributed to channel adjustment in small-order to medium-order streams in the prairie pothole region of south-west Minnesota. Although conversion from prairie to agriculture occurred a century ago, recent decades have seen increased subsurface tile drainage, annual row crop coverage and channel modifications, particularly at road crossings such that channel adjustment is ongoing. Channel evolution in Elm and Center Creeks, two fourth-order streams in the Blue Earth River basin, was studied to understand relationships between changes in channel morphology and suspended sediment concentrations. The construction of drainage ditches and expanded subsurface tiling has connected isolated basins to stream channels, effectively increasing drainage areas of Elm and Center Creeks by 15–20%. Sinuosity has been reduced by grading and drainage of first-order sloughs, channel straightening at road crossings and natural cut-offs and agricultural ditching that have shortened Elm Creek by 15% between 1938 and 2003. Stream cross-sectional area was enlarged in response to the land-use and drainage changes. In the headwaters, public ditches are wider than historic channels and entrenched by berms. Unchannelized headwater and upper mainstem portions of Elm Creek are also highly entrenched (up to 1.07 meters below the pre-channelization bed elevation with a bank height ratio > 1.5) but have not widened substantially. In contrast, the lower main channel has widened by an average of 68%. These channel adjustments contribute to the suspended sediment load and violations of Minnesota's turbidity and Index of Biotic Integrity standards. The watershed has a low sediment delivery ratio because it is a flat, poorly connected landscape and likely delivers less sediment to the Minnesota River than steeper rivers downstream, such as the Blue Earth River. Entrenchment and increased sediment transport capacity in the lower reaches of the river have lead to increased sediment delivery to the downstream Blue Earth and Minnesota rivers. Understanding geomorphic changes will be important for addressing water-quality impairments in the region.

KEY WORDS: channel evolution; suspended sediment; channelization; prairie pothole region; turbidity; total maximum daily load; Minnesota River basin

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INTRODUCTION

The Minnesota River basin (MRB) is the largest source of sediment to the Mississippi River at St. Paul, Minnesota (Engstrom *et al*., 2009). Determining the contributions of stream channel adjustment to suspended sediment in the Minnesota River is necessary to address high levels of sediment that add to the turbidity impairment. Sediment from tributaries such as Elm and Center Creeks increases turbidity downstream in the Blue Earth and Minnesota rivers. All of these streams exceed the criteria for turbidity (25 NTU for Minnesota Class 2B waters) and have been placed on the 303(d) list as specified by the Clean Water Act (BERBI, 2003; MPCA, 2006). They are also impaired for biotic health as measured by the Index of Biotic Integrity. Such streams require that a total maximum daily load be developed which specifies the sources of pollution, allocates loads and indicates necessary reductions in order to meet the state water-quality standard. Excessive levels of channel erosion exist throughout the upper Midwest, including in much of the Blue Earth River (BER), a major contributor to downstream turbidity, sedimentation and water-quality problems (Odgaard, 1987; Simon and Rinaldi, 2000). In many Midwestern watersheds, channel erosion now exceeds field erosion as the primary source of suspended sediment in rivers (Trimble, 1983; Fitzpatrick *et al*., 1999; Thoma *et al*., 2005). However, channel adjustment dynamics and the contributions of channel erosion to impaired water quality remain poorly understood in this region.

Channel adjustments to changes in land use and hydrology have been reported for the upper Midwest following European settlement and agricultural conversion in the mid-to-late 1800s in western Wisconsin and south-eastern Minnesota (a region with steeper terrain because it was less recently glaciated). Channel evolution resulted

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from increased run-off and surface soil erosion in upland areas, gully erosion of headwater streams and subsequent deposition of sediment on floodplains and aggradation of lower reaches of streams (Knox, 1977; Trimble, 1983; Fitzpatrick *et al*., 1999). Although less pronounced than in the higher relief part of western Wisconsin, many flat recently glaciated regions of the Midwest experienced similar post-European settlement increases in upland erosion and valley sedimentation (Yan *et al*., 2010). For instance, Engstrom *et al*. (2009) found that fine sediment loading from the MRB to the Mississippi River increased about 10-fold following European settlement. From the early 1900s to about 1930, particularly in the prairie pothole region, hydrologic storage was lost via wetland drainage, ditching and surface drainage that corresponds to an increase in sediment delivery from the headwaters to downstream stream valleys. Following focused soil conservation efforts beginning in the 1930s driven by the Dust Bowl era disaster, there was a reduction in upland sediment load allowing streams to cut through accumulated sediment leaving high banks (Knox, 1977; Wilson *et al*., 2008). However in the MRB, rates of channel erosion have been exacerbated in recent decades by extensive subsurface drainage and land cover changes that have contributed to increased streamflow in many southern Minnesota streams (Zucker and Brown, 1998; Nowak, 2009; Lenhart *et al*., 2011).

High rates of channel erosion are a major contributor to high suspended sediment levels in many Minnesota streams (Waters, 1995; Nieber *et al*., 2010). Widening has occurred on the main channel of the Minnesota River and many tributaries. Although channels naturally migrate laterally over time (Knighton, 1998), anthropogenic and/or climatic changes that increase run-off and direct channel modification can accelerate rates of lateral bank erosion (Potter *et al*. 2004). For example, Knox (1977) and Fitzpatrick *et al*. (1999) found that channel enlargement occurred following European settlement in Wisconsin. Whereas bluff erosion has been found to contribute large quantities of fine sediment in bigger rivers such as the BER (Sekely, 2001), smaller streams such as Elm and Center Creeks have few bluffs and so the majority of channel-derived sediment is believed to come from streambanks.

In contrast with natural channels, surface ditches often act as depositional areas because of increased width-to-depth ratios and decreasing sediment transport capacity (Landwehr and Rhoads, 2003; Hansen *et al*., 2006). Because the headwater streams in Elm and Center Creeks are largely ditched or channelized, these areas may act as net sediment sinks. Because the upper reaches of these watersheds are actively maintained ditches, they are not allowed to return to an equilibrium state as they are dredged every 5 to 10 years keeping them in an over-widened, sediment trapping condition. Unchannelized natural streams that became entrenched due to flow increases are more efficient sediment transporters.

Little is known about the role of channel erosion in the total suspended solids (TSS) load and turbidity level in Elm Creek. However, Gran *et al*. (2009) document rates of bluff and bank erosion in the LeSueur River located in the far south-eastern part of the prairie pothole region, finding that bluff erosion was the largest sediment source. It is known that many streams in the region are in an unstable, disequilibrium state as a result of the following: (i) land-use change; (ii) direct channel modifications; and (iii) increased streamflow (Magner and Steffen, 2000; Simon and Rinaldi, 2000; Schilling and Libra, 2003).

Land-use change has continued in the region, although original conversion from prairie to agriculture occurred in the 1850s to early 1900s. In the latter half of the 20th century, there have been large increases in corn and soybean coverage, with the two crops increasing from 8% to 25% of the total land area of Minnesota since 1941. In Martin County (where most of Elm Creek lies), perennial crops, which yield less run-off, have declined from 6% to 0.8% coverage in the last 50 years (USDA, 2009). Ennaanay (2006) found that increased streamflow was related to changes in land use and drainage density in the Cottonwood watershed located in western Minnesota. Increased mean flows strongly influence both suspended sediment and turbidity levels by increasing the frequency of sediment mobilization and the duration of turbidity. Increased mean flow also increases the duration of streambank saturation and mass-wasting frequency contributing to higher turbidity and suspended sediment levels.

Research questions and hypotheses

We had two major research questions:

(1) How have tributary channels of the BER adjusted to changes in land use, drainage and streamflow since European settlement? We hypothesize that channels have enlarged which is now primarily through the process of channel widening.
(2) What were the consequences of channel changes for sediment transport and suspended sediment levels? We hypothesize that the net result of these changes was to increase the sediment transport efficiency of tributaries to the BER. We also investigated how channel evolution condition varied by watershed position.

Study sites

Elm and Center Creek watersheds are adjacent basins located in south central Minnesota within the flat to slightly rolling Des Moines Lobe glacial till plain of the Laurentide Ice Mass (Hobbs and Goebel, 1982; Ojakangas and Matsch,

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2004). Both streams drain from west to east into the BER near Winnebago, Minnesota (Figure 1). Elm Creek has one of the highest concentrations of suspended sediment (flow-weighted mean of 193 mg L^{-1} in 2005) of any tributary of the BER, which is the largest contributor of sediment in the MRB (Quade, 2000). Elm and Center Creek watersheds are located in the Western Cornbelt prairie ecoregion (Omerik, 1987) south-west of the prairie/forest boundary. Prior to European settlement, much of the area consisted of isolated prairie pothole basins that were historically non-contributing portions of the watershed (Leach and Magner, 1992; Tester and Keirstead, 1995; Kuehner 2004). Sediment delivery was inherently low in flat glacial landscapes (Beach 1994) with isolated basins (prairie potholes) retaining much of the sediment eroded from fields. Wetlands covered more than half of the Elm and Center Creek watersheds prior to European settlement and the conversion from prairie to agriculture that began in the late 1850s. Loss of wetlands and shallow lakes contributed to increased peak flows in streams of the MRB (Miller, 1999).

First-order tributaries evident on the early General Land Office (GLO) survey maps were highly sinuous and much wider than current headwater streams of comparable drainage area. These tributaries, referred to as ‘sloughs’ on the early GLO maps, were similar to wetlands in terms of vegetation, soils and landscape position. They occurred on hydric soils and were likely covered with wet prairie and emergent vegetation, greatly reducing velocity and sediment transport of flowing waters while filtering out sediment. This slow, gradual flow is quite different than what occurs on the landscape today.

Today, 86% of the Elm Creek watershed is comprised of corn–soybean agriculture, 2% wetlands, 1.7% lakes and 10.3% a mixture of grassland, pasture, roads and small urban areas (Quade, 2000). Center Creek has 77% row crops, 2% wetland, 4% lakes and 17% grassland, pasture, roads and small urban areas. Grasslands and pasture are more common in the western portion of the watershed, with forests found primarily along major stream corridors. Fine to medium textured loamy soils predominate (USDA, 1989).

Streamflow has increased significantly in recent decades in southern Minnesota, with low to moderately high flows having the greatest percentage increases (Figure 2) (Lenhart *et al.*, 2011). Large floods, with more than a 50-year recurrence interval, were not found to increase significantly ($\alpha > 0.10$) in comparing the past 30 years with the 1950–1980 time period for the study watersheds (Nieber *et al.*, 2010). Mean monthly streamflow has increased by two and three times during the 1980–2009 time period compared to 1930–1979 in many large southern Minnesota streams with

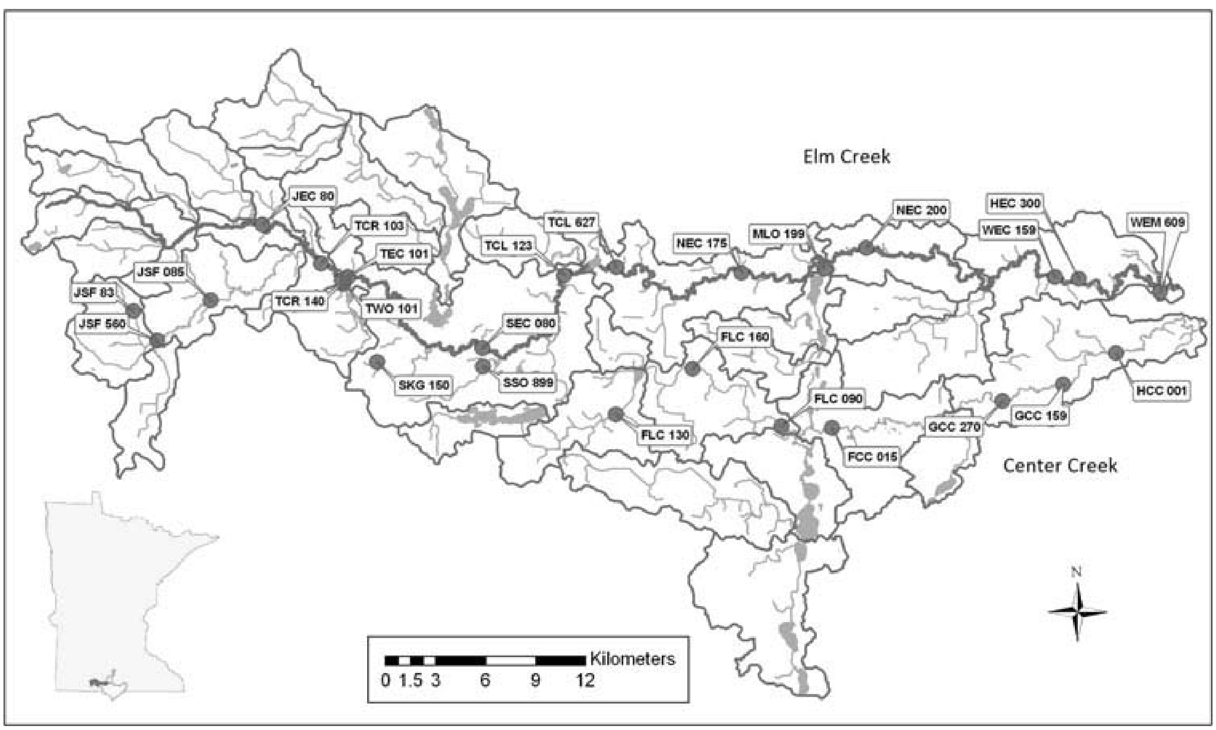

Figure 1. Elm and Center Creek watersheds. Location within Minnesota shown in lower left. Elm Creek lies to the north of Center Creek in the image. Detailed geomorphic surveys were done at the 25 sites, shown in the figure. A summary of data collected at these sites is shown in Table 1. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

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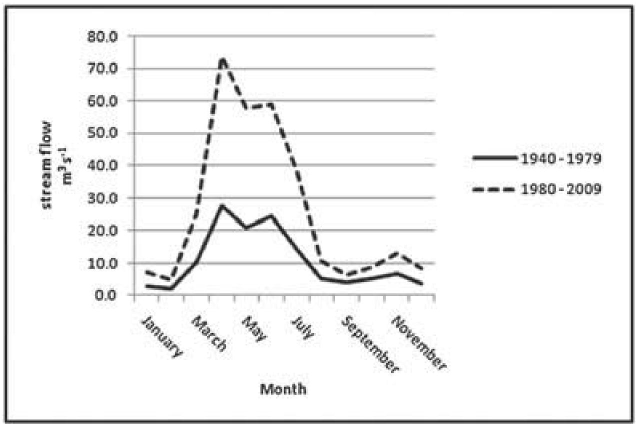

Figure 2. Median monthly streamflow by water year for the Blue Earth River comparing the last 30 years to the 1940–1979 time period. Median monthly flow is shown for the historic period of record 1940–1979 in $m^3 s^{-1}$. The median streamflow has increased significantly in 10 of 12 months over the last 30 years (1980–2009) (Lenhart *et al*., 2011). There was not a significant increase in the magnitude of floods of the 2-year or greater flows, but there was a significant increase in mean flows and high flows such as the 75% and 90% flows.

long-term USGS streamflow records (Lenhart *et al*., 2011). For example, mean monthly flow in the BER at Rapidan (38 km north-east of Elm Creek) increased two to three times (Figure 2), with 10 of 12 months having significant increases ($\alpha = 0.05$) in mean flow during the 1980–2009 time period. No long-term streamflow records were available for Elm and Center Creeks, but it is assumed that similar increases in flow have occurred there because all of the surrounding streams with USGS gauges have shown increases in streamflow.

METHODS

Geomorphic surveys were conducted at 25 stream sites along Elm and Center Creeks to characterize existing channel conditions for comparison to historic channel dimensions. Field survey data consisted of cross-section and longitudinal profiles, measurements of entrenchment, bed materials, sediment deposition and channel stability using techniques described in Harrelson *et al*. (1994). In addition, changes to channel sinuosity and width were estimated over the past 150 years, using aerial photos, GIS and early land-survey notes.

Channel cross-section and longitudinal profile were surveyed with a laser level at 25 sites. Profiles were surveyed over a distance of at least 20 times the channel width. Channel cross-sectional area was calculated at the bankfull elevation, defined as the elevation of the channel-forming discharge, the flow with a recurrence interval most frequently between 1.4 and 1.6 years (Dunne and Leopold, 1978). Bankfull elevation was determined by field indicators, primarily the presence of a flat depositional surface as evidence of the active floodplain. We also calculated the discharge needed to overflow the banks using the Darcy–Weisbach equation with data obtained from the field surveys. Finally, calculations of flood frequency using data obtained from a stream gauge located near the mouth of Elm Creek with an 8-year record were compared to the discharge estimates from individual site locations to further corroborate the field estimates.

During the surveys, entrenchment was measured using two metrics, the entrenchment ratio and the bank height ratio (*BHR*) (Rosgen, 1996). Entrenchment ratio (defined as the flood-prone width divided by the bankfull width) is a coarse-scale measurement of channel incision. The flood-prone width equivalent to the 50-year floodplain was calculated at the elevation two times the maximum depth. Streams that are not deeply entrenched within the valley have entrenchment values >2.2, whereas deeply entrenched streams have entrenchment values <1.4. The *BHR* is calculated as the current bank height divided by the active channel (bankfull) height.

Bed materials were assessed using the Wolman Pebble Count to define the median (D_{50}) and 84th percentile particle size (D_{84}) (Wolman, 1954). Sediment deposition on the streambed was measured at 15 locations at each site, using a modified Lisle method with a 60-mm-wide steel probe (Lisle and Hilton, 1992). Depth of fine sediment (<0.25 mm) was measured at the point of resistance, when the probe could not be pushed any further. This was used to characterize the processes of aggradation versus degradation occurring in the channel as well as the channel evolution stage. *T*-tests were used to assess the significance of differences in fine sediment depth between channel types.

Channel stability was measured using the Bank Erosion Hazard Index (BEHI) and Pfankuch stability indices. The BEHI requires data on depth and density of plant roots within streambanks, percentage of plant coverage, stream bank angle, bank height and bank materials (Rosgen, 1996, 2006). These data are being used in combination with other information in ongoing research to get better estimates of the total channel erosion load. The Pfankuch stability index is a semi-quantitative worksheet that has been used for over three decades with reproducible results (Pfankuch, 1975). Pfankuch stability index data are not presented in the results because the great variability in the scores made it difficult to identify any meaningful trends.

Channel stability and evolutionary stage were characterized at each site according to Simon's channel evolution model (Simon, 1989). Simon describes six stages of channel evolution in response to a disturbance such as channelization or increased flow: stage I is pre-disturbance (equilibrium),

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stage II is constructed, stage III is downcutting, stage IV is widening, stage V is aggradation and revegetation and stage VI is return to quasi-equilibrium. The determination of these stages was based on extensive research on past channel dimensions and soil borings in channel cut-offs since European settlement (1855) to determine changes to channel form over time.

Historic dimensions of channel cut-offs since 1855 were compared to current dimensions by surveying six relict channels in the Elm Creek watershed to determine changes to cross-sectional dimensions and bed elevation. Abandoned channels were surveyed at sites HEC 300, NEC 200, NEC 175, JEC 080, JSF 085 and JSF 560 where they had been intentionally straightened for road or public ditch projects since 1855. A soil auger was used to bore down to the original streambed, which had aggraded with sediment since being cut-off. Streambeds typically have coarser bottoms than adjacent floodplain soils because of fluvial sorting. In this case, the boundary was marked by a change in texture from silt and fine sand to gravel or coarse sand. At all sites, the banks of the old channel were still visible so that the former channel width was directly measurable. Current and past bed elevations were compared to determine if entrenchment or aggradation had occurred.

Aerial photos from 1938 and early land survey maps were examined to determine landscape and channel changes over the past 100–150 years. Changes to channel width were measured by comparing current widths to the 1850s' GLO land survey measurements which were measured from top of bank to top of bank at the township section lines only. Width data were obtained in the field at additional sites beyond the geomorphic assessment sites shown in Figure 1 at township section lines corresponding with the location of the 1850s' GLO stream width measurements. Past and current widths were compared using paired *t*-tests to determine the significance of differences at the $\alpha = 0.05$ level.

Plan-view measurements of river length and sinuosity were made using 2007 aerial photos and 1938 aerial photos. Comparisons between current and previous river length, width and sinuosity were made to assess channel evolutionary changes and their consequences for sediment transport. GLO survey notes were also examined to document alterations to the planview configuration, including elimination of headwater streams. The GLO notes in this area had unusually detailed survey maps of the surface-water drainage system which actually delineated first-order 'sloughs', typically not shown on GLO maps (Figure 3).

The influence of channel morphology on turbidity and suspended sediment was assessed through a water-quality and hydrology-sampling programme carried out across the Elm Creek basin at 10 sites that coincided with geomorphic survey sites (Lenhart *et al*., 2010). The influence of channel incision on sediment transport was modelled using the Ackers–White sediment transport equation in the RIVERMORPH software (RIVERMorph, LLC, Louisville, KY, USA) to determine how entrenchment has affected sediment

Figure 3. General Land Office survey map of 1855 showing small tributaries to Elm and Center Creeks, Minnesota. Many first-order and second-order streams that were wide (100–400 m) and highly sinuous (referred to as 'sloughs' in survey notes) have been graded into farmland, channelized and/or drained by subsurface pipes. Some surface ditches were constructed in areas where streams did not previously exist. Overall there was a net loss in headwater stream length of approximately 20%. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

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transport capacity (Ackers and White, 1973). Bankfull elevations were determined in the field for active channels and compared with stream gauge data for verification. The discharge at different flow stages was calculated using Manning's equation based on field-measured bed roughness and calibrated using a stream gauge located on Elm Creek. We modelled sediment transport rates for different flow stages at all research sites listed in Table 1 to examine total load transported and stream competence. At one site on the South Fork of Elm Creek (JSF 560), with a typical entrenchment level, we modelled past and present channel transport conditions using field-measured dimensions for the current and historic channel cut-off in the 1950s.

RESULTS

Plan view changes to stream dimensions

Elm and Center Creeks have undergone three major types of planview changes: (i) drainage area expansion via public drainage ditches and subsurface drainage pipes; (ii) loss of river sinuosity and length by channelization at road crossings; and (iii) elimination of headwater channels or sloughs through draining, ploughing and burial via deposition from field erosion.

The contributing watershed area of Elm Creek increased by about 15% to 700 km^2 (270 miles^2), whereas Center Creek increased by about 25% to 390 km^2 (150 miles^2) between 1850 and 2007 (primarily through addition of the Lily Creek watershed). Headwater drainages had a greater percentage increase than larger drainage basins as non-contributing watershed areas were added to streams with small watershed area via ditching projects. For example, the Elm Creek South Fork drainage area increased by 66% from about 30 to 50 km^2.

Elm Creek lost 17.5 km (11 miles) or 14% of its length between 1938 and 2006 from private ditching projects, straightening at roads and oxbow cut-offs at high flows. The loss in length reduced river sinuosity, resulting in increased slope which is directly correlated with more sediment transport efficiency. Center Creek also lost considerable stream length compared since 1938. However, the connection of Lily Creek to non-contributing basins through ditching added about 5 km, counterbalancing length lost via channelization.

Although many of the second-order to third-order tributaries (with drainage areas of 25–250 km^2) were channelized, many first-order headwater streams and linear wetlands were eliminated by a combination of grading, ploughing and subsurface drainage (Figure 3) (Beach, 1994).

Table I. Data from stream surveys on Elm and Center Creeks

	Drainage area	Bank height ratio	Mean depth	CEM stage	Bankfull area	Slope	Bankfull Q	Bed particle D_{50}
Site code	km^2	m m^{-1}	m	Type	m^2	%	m^3 s^{-1}	mm
FCC 015	181	1.6	0.65	IV	6.37	0.08	19.9	0.27
FLC 090	88	1.4	0.44	IV	6.57	0.07	24.6	0.12
FLC 130	16	1.8	0.28	IV–V	2.12	0.14	6.1	0.08
FLC 160	54	2.2	0.66	II	4.65	0.00	14.0	0.19
GCC 159	290	1.4	1.23	IV	17.01	0.08	73.4	0.70
GCC 270	259	1.5	0.90	IV	12.18	0.20	64.3	0.89
HCC 001	324	1.6	1.03	IV	15.71	0.10	73.3	0.43
HEC 300	681	2.1	1.34	IV	27.61	0.07	85.8	1.10
JEC 085	73	1.8	0.55	VI	4.31	0.13	12.3	4.11
JSF 083	10	1.0	0.25	II	0.80	0.10	2.8	0.04
JSF 085	62	2.9	0.47	IV	4.87	0.08	12.8	0.32
JSF 560	41	1.5	0.55	IV	3.67	0.11	15.1	0.16
NEC 175	544	1.6	1.09	IV	18.78	0.08	77.4	0.79
NEC 200	619	1.2	1.02	IV	16.27	0.14	78.4	0.48
SEC 080	285	1.3	1.06	IV	0.00	0.04	46.5	3.00
SKG 150	3	2.4	0.56	III	1.02	1.20	12.1	0.07
SSO 899	16	2.7	0.38	V	3.11	0.11	11.2	0.19
TCL 123	319	1.0	0.78	V	32.90	0.01	48.3	0.31
TCL 627	495	1.2	0.80	IV	19.43	0.05	53.4	0.70
TCR 103	207	1.4	0.87	IV–V	9.76	0.10	37.8	4.49
TCR 140	241	1.9	0.89	IV–V	8.50	0.09	39.1	0.21
TEC 101	215	1.4	1.16	VI	12.18	0.03	38.5	1.00
TWO 101	26	2.6	0.64	III	2.49	0.12	8.6	1.10
WEC 159	673	2.0	0.91	V	22.39	0.08	77.4	6.20
WEM 607	699	2.1	1.14	V–VI	25.19	0.10	92.0	7.10

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Cross-sectional changes to streams

Changes to channel cross-sectional dimensions in the last 150 years varied by watershed position in Elm and Center Creeks. Headwater streams were disproportionately impacted in terms of the percentage change to cross-sectional area, width, depth and entrenchment. Relict channel data show that Elm Creek has enlarged over the last century; the greatest channel capacity increases (250%) occurred in headwater ditches that were historically small meandering streams such as the South Fork of Elm Creek. Most of the channel capacity enlargement occurred by a combination of overbank floodplain deposition and channel incision through those materials (Table 2). Channel incision was also indicated by the high *BHR* (>1.5) in the headwaters. *BHR* often exceeded 2.0, which indicates a high risk of bank collapse. Field evidence of bank collapse in the form of widespread fresh bank slumps confirmed the index values, particularly in the lower half of Elm Creek where bank height exceeded 2 m.

Channel entrenchment has occurred across the Elm and Center Creek watersheds in the past century, increasing streambank height and reducing connectivity between streamflow and floodplains that are less frequently flooded. As channel incision propagates upstream and channelization at road crossings occurs every few miles, much of Elm Creek has become slightly entrenched. *BHR* was greatest in the headwaters (ranging from 1.5 to 3.0) because of channelization and proportionately greater hydrologic changes and near the river mouth (ranging from 1.2 to 2.2) (Figures 4 and 5).

Ditches

Surface drainage ditches, primarily located in the headwaters of Elm and Center Creeks, were highly entrenched because of dredging of the river bed. Entrenchment was exacerbated by the deposition of dredged material that formed berms along streambanks that further reduced floodplain connectivity. Ditches, which are a combination of channelized natural streams and created conduits, had *BHR* often greater than 2.0, greatly reducing floodplain deposition. As a result of ditch 'maintenance' or regular dredging, ditches have oversized channels relative to their flow. They usually have a high width-to-depth ratio within the created berm area, reducing their ability to transport sediment (Landwehr and Rhoads, 2003; Hansen *et al*., 2006). Consequently, much sediment is deposited within the channel as indicated by the depth of fine sediment (0.7 to 1.0 m of sand and finer) measured on ditch beds.

Elm Creek main channel

The greatest change to channel dimension in middle to lower Elm Creek was increased width. In comparing 26 channel widths measured at the same location in 1854 and again in 2005–2007, all sites increased in width with the mean increasing from 7.5 to 12.7 m. The average width increased by 77%. A paired *t*-test showed that the difference was significant at the $\alpha = 0.0001$ level. In addition to widening, the channel had downcut slightly in six relict channel surveys (Table 2, Figure 1). Channel incision occurred where the stream was straightened for bridge construction or agricultural channelization since the 1855 land survey maps. At these sites, the relict streambed ranged from 0.4 to 1.4 m higher than current streambeds.

Bank Erosion Hazard Index scores and channel evolution stages

In addition to width and depth changes, very high rates of bank erosion were indicated by the BEHI data, suggesting that the streams were not at geomorphic equilibrium from past and recent land-use, drainage and streamflow changes (Figure 2). The majority of BEHI scores ranked moderate to high for erosion risk (between 20 and 40 on a scale of 5 to 50). Simon's channel evolution model (CEM) observations indicated that 76% of Elm and Center Creek reaches surveyed were widening or aggrading (stage IV or V) depending on watershed location, land-use factors and history of channelization (Table 1). Stage IV (channel widening) was widespread in the mid-lower

Table II. Survey of recent channel cut-offs showing depth of bed entrenchment in current channels compared to historic channels that were cut off between 1855 and 1968

Site code	Stream name	Watershed location	Metres of bed entrenchment	Channel cut-off date[a]
JSF 560	South Fork Elm Creek	Headwater tributary	0.57	1949–1954
JSF 085	South Fork Elm Creek	Headwater tributary	1.07	1954–1962
JEC 080	North Fork Elm Creek	Headwater tributary	0.36	1954–1962
NEC 175	Elm Creek	Lower main channel	0.73	1855–1938
NEC 200	Elm Creek	Lower main channel	0.61	1855–1938
HEC 300	Elm Creek	Lower main channel	1.43	1962–1968

[a]Channel cut-off dates were determined by examining the General Land Office maps of 1855 and aerial photos from 1938 to 1968. The tributaries were channelized for agricultural drainage whereas the main channel sites were moved for road crossings sometime during the specified time interval.

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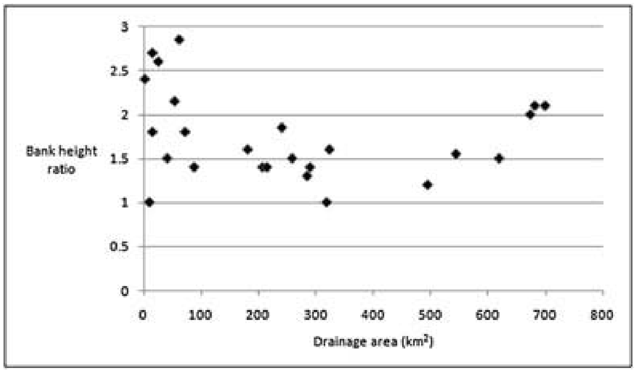

Figure 4. Bank height ratio (*BHR*) in Elm and Center Creeks with increasing drainage area. *BHR* is the bank height divided by the bankfull height measured at the 1.5-year recurrence interval flow. When the active channel height (bankfull) and the bank height are equal, the $BHR = 1$. Higher *BHR* scores indicate lower bank stability with ratios above 1.5 considered unstable. Using these criteria, about two-thirds of the sites surveyed were unstable.

watersheds, with the two lowest reaches (sites WEC 159 and WEM 607) appearing to be returning to a quasi-equilibrium (stages V–VI), after having downcut decades ago. (Paired relict and active channel surveys showed that bed downcutting occurred well below the historic bed elevations.) Some ditches that are not actively dredged and headwater streams protected by broad grassland buffers had also returned to a stable state (stage VI) whereas maintained ditches are in stage II, by definition. Two small tributaries, both steep artificial channels, were downcutting and described as stage III.

Figure 5. The photo shows slight entrenchment of an Elm Creek reach with a bank height ratio of about 1.3. The current active floodplain on the left of the photo lies 1–2 m below the terrace on the right. Following entrenchment, the channel has increased in width (as described in stage IV of the channel evolution model). Although entrenchment is slight, it is important because it reduced the frequency of overbank flooding. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

Bed materials and sediment transport

The streambed consisted mostly of silts and sand with some gravel (71% of reaches had a $D_{50} < 1$ mm) that are easily mobilized. The D_{84} ranged in size from 0.1 mm (very fine sand) to 53 mm (very coarse gravel) with the median value of 10 mm (medium gravel). Fine sediments were aggraded in depositional areas with a mean depth of 0.33 m at 24 sites, $n = 360$. Sediment is aggrading in most ditches from over-widening created by dredging that reduces shear force and transport capacity. Sites at or near the inlet of lakes and wetlands averaged about 0.7 m of fine sediment in the channel. Ditches averaged about 0.6 m of fine sediment depth.

Modelling showed that there is sufficient shear force to easily mobilize the median bed material (sand) at high flows. However certain reaches in the Elm and Center Creek watersheds may be aggrading because the sediment supply from bank and field erosion exceeds the transport capacity of these small rivers. Additionally, low flow (near zero discharge) in the late summer period promotes the accumulation of fine sediments at least temporarily, as evidenced by the depth of fine sediments that were measured. Some of the headwater streams are in the late channel evolution stages (stage 5 of Simon's CEM) and could return to a quasi-equilibrium if streamflow stabilized or declined and the aggraded areas were able to revegetate.

In the mid-main to lower-main reaches of Elm and Center Creeks (downstream of Creek Lake), channel incision, increased flows and decreased sinuosity from channelization have increased sediment transport efficiency and reduced aggradation of fine sediment. Reduced floodplain connectivity has decreased overbank deposition with little occurring except following large floods. Figure 6 shows how channel incision increased sediment transport capacity at one reach in the headwaters of Elm Creek. Sediment transport rates were found to drop by more than 25% once floodplain overflow occured at site JSF 560.

DISCUSSION

Channel adjustment and sediment load at Elm and Center Creeks

Channel adjustment in tributaries of the BER has followed a different timeline than some other regions of the upper Midwest. In contrast to the watersheds studied by Knox, Trimble and Fitzpatrick, the BER basin is now largely dominated by row-crop agriculture with an expansion of subsurface artificial drainage in the past three decades. During that same time period the watersheds of northern and western Wisconsin have experienced decreased rates of channel adjustment from the peak of agricultural land-use intensity and increased forest cover following the initial

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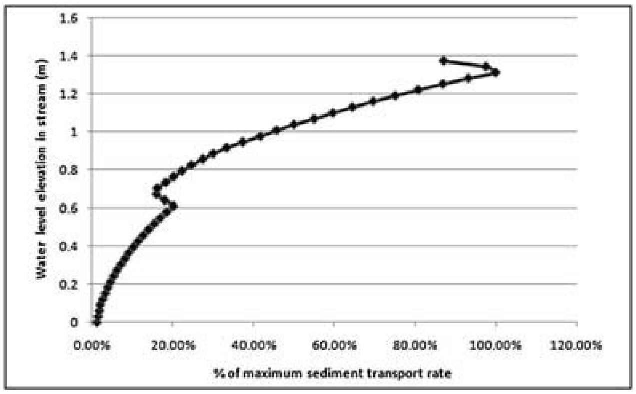

Figure 6. Sediment transport rate was modelled at all sites. At a headwaters site, JSF 560 shown above, we modelled transport in a historic channel cut-off in the 1950s and the current active channel. The transport rate increases with increasing water level until the water spills over the floodplain near 28.6 m. As water spills into the floodplain, sediment deposition occurs, reducing suspended sediment downstream. However channel entrenchment has reduced floodplain connectivity, increasing the rate of sediment transport compared to similar stream discharge under pre-European settlement conditions. If the channel was less entrenched as it was in pre-1950, floodplain overflow would occur at lower water elevations reducing the sediment transport capacity to about 50% of the current entrenched rate.

European development and/or logging (at least at the time they were studied by Trimble and Knox). Following improved soil conservation practices in the 1940s and 1950s, many streams began to aggrade and re-stabilize in northern and western Wisconsin. However, streams in the Driftless Area of Wisconsin continue to have turbidity problems because of erosion of high streambanks created by high rates of floodplain deposition. In contrast, streams in the Blue Earth and Minnesota basins have continued to adjust to hydrologic changes and to channelization that greatly slow their return to equilibrium (as evidenced by widespread distribution of channels in stages III–V of the CEM). Increased streamflow caused by tile flow, and in some locations increased precipitation, over the last three decades and continued channelization have contributed to greater sediment transport capacity increasing the amount of suspended sediment carried downstream (Figure 6). Higher flows have sustained channel adjustment preventing return to equilibrium.

Consequences for sediment transport and in-stream turbidity

The previously described land-use and drainage changes have caused increased flows and channel incision resulting in more efficient sediment transport from small tributary watersheds, increasing the sediment delivery rate where it was naturally fairly low. Even though entrenchment may be viewed as slight from a geologic perspective (0.4 to 1.4 m), it was hydrologically important, as the bank height in the headwaters streams was nearly doubled, drastically reducing the frequency of overbank flooding. Historically, watersheds of the prairie pothole region had a low sediment yield because of flatness and abundant depressional storage. Beach (1994) and Evans *et al*. (2000) found a similarly low sediment delivery rate in rivers within flat glaciated regions of the Midwest. In Elm Creek only eight to 13% of gross erosion from fields and channels was transported out of the watershed during 2005–2006 (Quade, 2000; MPCA, 2007; Lenhart, 2008). Although this is a low percentage, it is certainly much greater than it was historically, contributing to increased sediment loads downstream and habitat degradation for aquatic biota. Much of the sediment is still stored in ditches, lakes, floodplains, wetlands and headwater depressions. When this sediment is mobilized at high flows, it contributes to elevated turbidity in Elm Creek and downstream water bodies as indicated by frequent turbidity readings above the 25-NTU water-quality standard at even low to mean streamflow levels (Lenhart *et al*., 2010). Still sediment loading from Elm Creek, like many other small tributaries distant from the Minnesota River, is small compared with the large contributions from bluff and bank erosion along the larger channels of the Blue Earth, LeSueur and Minnesota rivers (Sekely, 2001; Gran *et al*., 2009).

Management implications

Widespread channel adjustment has led to increased sediment loading from channel sources in recent decades, although historically, field erosion was the dominant source. It is now necessary to reduce sediment loads both for turbidity and Index of Biotic Integrity impairment. However, reducing excessively high rates of channel erosion over thousands of square miles is a difficult task both from a socioeconomic and technical standpoint. Reduction of turbidity in streams of the prairie pothole region will require both watershed management and reduction of channel erosion. The challenge is to develop strategies for reducing channel instability on a large scale using a combination of restoration and management techniques to reduce streamflow levels, restore sinuosity and reduce highly erosive in-stream forces increased by entrenchment. Efforts to reestablish upland hydrologic storage via wetland restoration and re-establish floodplain function in incised channels may help to reduce sediment delivery and turbidity levels within tributary streams, the Minnesota River and the Mississippi River. Scientific investigations and management recommendations that ignore historic influences on channel form and process are not likely to be successful.

Future research

There is a need to establish long-term geomorphic monitoring sites to understand trends in channel migration over a

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period of decades, not just one or two years. Additionally, there is a lack of understanding of sediment depositional rates and processes, a critical issue when considering turbidity issues. Further sediment budget research is planned for the watershed including monitoring of current deposition rates, soil boring to determine depth of post-European settlement sediment and modelling of channel evolutionary processes with the CONCEPTS model. More research on entrenchment is needed as well to further refine estimates of flood frequency in different reaches of the watershed.

Finally there is a strong need to develop stream management and sediment reduction techniques that are more sustainable and applicable at the watershed scale to address the large quantities of channel-derived sediment contributing to downstream problems. Work is currently being done to prioritize channel erosion sites at a watershed scale with new funding from the Minnesota Department of Agriculture and the U.S. Environmental Protection Agency.

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