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Streambank erosion rates and loads within a single watershed: Bridging the gap between temporal and spatial scales

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ABSTRACT

The importance of streambank erosion to watershed-scale sediment export is being increasingly recognized. However few studies have quantified bank erosion and watershed sediment flux at the basin scale across temporal and spatial scales. In this study we evaluated the spatial distribution, extent, and temporal frequency of bank erosion in the 5218 ha Walnut Creek watershed in Iowa across a seven year period. We inventoried severely eroding streambanks along over 10 km of stream and monitored erosion pins at 20 sites within the watershed. Annual streambank recession rates ranged from 0.6 cm/yr during years of hydrological inactivity to 28.2 cm/yr during seasons with high discharge rates, with an overall average of 18.8 cm/yr. The percentage of total basin export attributed to streambank erosion along the main stem of Walnut Creek ranged from 23 to 53%. Large variations in individual site, annual rates and percentage of annual load suggested that developing direct relationships between streambank erosion rates and total sediment discharge may be confounded by the timing and magnitude of discharge events, storage of sediments within channel system and the remobilization of eroded material.

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1. Introduction

Sediment is considered the leading water quality problem in the United States (Simon et al., 1999), having been shown to cover critical fish spawning habitat, disrupt filter feeding and decrease species richness (Lemly, 1982; Gauge et al., 2004). Sedimentation also has economic effects, as flood control and water storage impoundments quickly fill with sediment, requiring expensive dredging projects that cost millions of dollars nationwide (Wesche and Isaak, 1999). Given the widespread ecological and economic impacts of excessive sediment loading it is of paramount importance that researchers develop a better understanding of how sediment flux is impacted by stream equilibrium status and channel evolution stage. Recent studies have contributed to a growing body of evidence that in watersheds with significant hydrologic alteration, the source of sediment in streams has shifted from uplands to gullies and stream channels (Simon and Rinaldi, 2000; Mulla et al., 2008; Simon and Klimetz, 2008; Wilson et al., 2008; Belmont et al., 2011). Improving our understanding of the relative contribution from different processes contributing to the sediment delivery within a watershed and the interacting factors of land use and hydrology is essential for directing management strategies to reduce sediment loads.

Recent studies have shown a wide range of relative streambank sediment contribution to watershed sediment loads. Up to 44% of the suspended sediment in the Blue Earth River has been attributed to streambank slumping (Sekely et al., 2002). A recent study of individual storm event sediment budgets on five Midwestern watersheds found that channel derived sediments totaled between roughly 50 and 80% of total sediment load (Wilson et al., 2008). Schilling et al. (2011) estimated that 38–64% of the annual suspended sediment load in Walnut Creek in south central Iowa could be explained by streambank erosion. Channel-derived sediment can also be an important source of downstream nutrient flux, with recent studies in Iowa finding that streambank erosion from riparian zones consisting of crop fields and continuously grazed pastures contributed up to 17 times more phosphorus to streams than riparian forested areas (Zaimes et al., 2004). These studies found that the establishment of riparian forest buffers could reduce sediment load to streams by up to 81% in comparison to row crop or grazed systems. An understanding of the source and magnitude of sediment sources across watersheds will help direct management efforts towards areas of critical need.

Much work has been focused on the driving mechanistic forces of bank erosion on individual sites (e.g., Simon et al., 1999; Simon and Collison, 2002; Pollen et al., 2004; Fox et al., 2007) with far fewer studies examining how bank erosion processes impact sediment loading dynamics at a larger spatial scale. For example, Couper (2004) identified 66 bank erosion studies conducted from 1959 to 2003 and reported

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that 59 of them focused at the site or reach scale and seven studies focused at the catchment scale. Linking spatial scales across time scales of years is rarely done for watershed-scale analyses (Couper, 2004; Florsheim et al., 2008). Considering the spatial distribution, extent, and temporal frequency of bank erosion at the watershed scale is important for understanding the impacts of bank erosion processes on channel geomorphology, stream ecology, and downstream sediment and nutrient flux (Florsheim et al., 2008).

In this paper, we report the results of a multi-year effort to evaluate streambank erosion at several sites within a single watershed. Our objectives were to 1) quantify the extent of severe streambank erosion along the main channel within a small, third-order Iowa watershed; 2) measure rates of annual and event-based bank erosion at representative sites; and 3) estimate the contribution of streambank sediment to watershed-scale suspended sediment loads. Study results are intended to bridge the gap between spatial and temporal scales in bank erosion

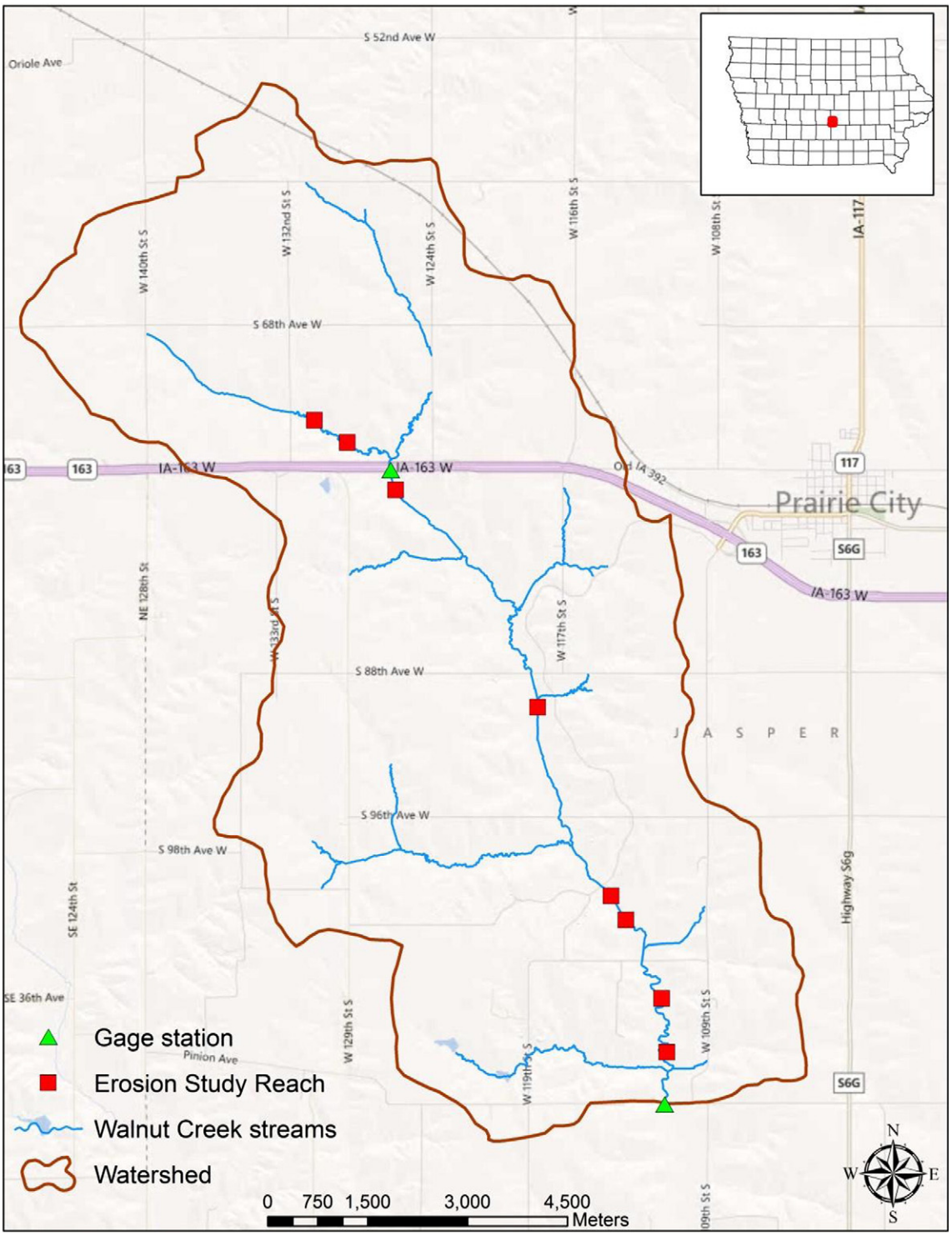

Fig. 1. Location of Walnut Creek watershed and monitoring sites.

research and link these scales together in a "coherent view of the whole" (Couper, 2004).

2. Site description and setting

Walnut Creek is a perennial, warm-water stream draining a 5218 ha (12,894 ac) watershed in Jasper County, Iowa (Fig. 1). The watershed is located in the Rolling Loess Prairies Level IV Ecoregion (47f), an area characterized by steeply rolling hills and well-developed drainage (Griffith et al., 1994). This ecoregion is a subdivision of the Western Corn Belt Plains Level III Ecoregion (47), which encompasses the majority of Iowa and is characterized by having 75% of the area used for cropland agriculture and much of the remainder in forage for livestock. The Walnut Creek watershed is in a humid, continental region with average annual precipitation of around 750 mm. Monthly rainfall totals are typically greatest in May and June, although large storms occurring throughout the summer can lead to rapid increase in discharge.

Walnut Creek is incised more than 3 m into its floodplain due to effects of historical agricultural practices, such as channelization, removal of riparian vegetation and increased drainage from tiles and ditches (Schilling and Wolter, 2000; Schilling et al., 2011). Several stages of channel evolution (Simon, 1989) were identified along the length of Walnut Creek, with areas of Stage III (degradation), Stage IV (degradation and widening), and Stage V (aggradation and widening) generally in the middle to lower stream reaches. Stream discharge tends to be flashy, displaying rapid responses to precipitation. Stream discharge at a stream gauge at the Walnut Creek outlet ranged from a high of 56,276 m^3/h to a low of 2 m^3/h from 1995 through 2005 (Schilling et al., 2006).

Soils within the watershed are primarily silty clay loams, silt loams, or clay loams formed in loess and till. Moderate to high erosion potential characterizes many of the soils, with 54% of them being classified as highly erodible (Schilling and Thompson, 2000). Loess mantled pre-Illinoian till typifies much of the upland geology whereas Holocene alluvial deposits are primarily composed of silt and clay (~84%; Schilling et al., 2009). The thickness of post Euro-American alluvium deposited in the stream valley ranges from 0.6 to 1.8 m (Schilling et al., 2009).

Land use in the watershed consists of 54% row crop agriculture (corn and soybeans), 36% grassland, and 4% forest, with the remaining lands comprising roads, farmsteads and urban areas (Schilling et al., 2006). Of the grasslands, 25.4% of the area is native tallgrass prairie planted by the U.S. Fish and Wildlife Service (USFWS) at the Neal Smith National Wildlife Refuge (NSNWR). Since NSNWR inception in 1991, a large portion of the Walnut Creek watershed is being converted from row crop agriculture to native prairie and savanna, with much of the early plantings concentrated along the riparian corridor (Drobney, 1994; Schilling and Thompson, 2000; Schilling et al., 2006). Land use along the riparian corridor of the main stem of Walnut Creek that includes both NSNWR and land outside of the refuge consists primarily of a mix of cool and warm-season grasses, grazed pastures and forest.

3. Methods

3.1. Stream bank erosion survey

We conducted stream surveys along the main stem of Walnut Creek on two occasions (November 2004 and December 2010) to identify the spatial distribution, lengths and heights of severely eroding streambanks. The surveys identified severely and very severely eroding streambank using the visual assessment criteria developed by the Natural Resources Conservation Services (USDA-NRCS, 1998). This visual assessment classifies banks that are predominantly bare with overhanging vegetation and exposed roots as severely to very severely eroding. Annual recession rate estimates specified in the USDA-NRCS method have been shown to closely approximate rates estimated using erosion pins in both Walnut Creek (Palmer, 2008) and other Iowa watersheds (Zaimes et al., 2008). However, in this study, we used the visual criteria solely to identify severely eroding streambanks. Banks that showed no evidence of severe streambank erosion were not monitored in this study because they were not considered significant sources of sediment to the total sediment load of Walnut Creek. Likewise we did not monitor sediment contributions from gullies in our study. During the 2004 stream survey, we mapped 96 gullies that entered the main channel of Walnut Creek but we did not classify them for size or sediment erosion potential. Future work in Walnut Creek will characterize sediment contributions from these gullies so that these source areas can be added to the overall sediment budget.

Bank heights were determined using a scaled height pole (accuracy 1 cm) approximately every 2 m along each eroding bank. Streambank lengths were calculated from the upstream to downstream distance between Global Positioning System (GPS) points taken at each identified streambank. All spatial and streambank attribute data collected during these surveys were recorded using Trimble Geo XM GPS units. Data collected during these surveys were incorporated into a GIS program (Arc View 9, ESRI INC. Redlands, California) for synthesis and evaluation. Results from the November 2004 survey were used to identify and select locations to monitor erosion rates.

3.2. Erosion pin plot selection

In order to select appropriate plots for pin measurements, a detailed assessment of riparian land cover was conducted early in the project (Palmer, 2008). Riparian land use within a 40 m buffer width on either side of the stream was identified and digitized using 2002 Color Infrared digital orthophotos (1 m resolution). Riparian land use was classified into segments with similar land use characteristics. A criterion for segment designation was that the channel had the same land use on both sides of stream to a width of at least 40 m, matching the minimum for installation of a riparian forest buffer (USDA-NRCS, 1997). Land uses along the main channel of Walnut Creek consist of riparian forest, grassland, grass-tree mix, grazed pasture and row-crop agriculture. Grassland, riparian forest and grazed pasture comprise equal percentages of the total stream length (15%, 16% and 16% respectively), whereas the dominant individual land use was considered to be a grass-tree mix (44% of the total length).

The main stem of Walnut Creek was broken into segments of equal length to identify spatial trends within the drainage system. We divided the stream into sections that equaled 30 times the average channel width of 4.9 m, or 149 m length segments. The length criteria was selected using the assumption that a single "natural" meander wavelength occurs over a distance of 14 times channel width (FISRWG, 1998) and we captured the length of at least two natural meander wavelengths. This selection process allowed for us to capture the natural erosion and deposition process which occurs along a meandering channel. Total eroding streambank length was determined for each segment. Stream segments with similar riparian land use characteristics were used to select reaches for installation of erosion pin plots to quantify bank recession rates. Selected stream segments were required to be at least 400 m in length and have the same land use on both sides of stream to a width of at least 40 m. Individual 400 meter segments were first identified as potential erosion study reaches for pin plot installation. Two reaches were available for each of the riparian forest, grazed pasture, and cool season grass treatments. Due to lack of land owner cooperation, no 400 meter segments in the row crop land use classification were available. A total of eight erosion study reaches were chosen in Walnut Creek (Fig. 1).

Within each study reach, we randomly selected a subset of eroding streambanks equal to at least 20% of the reaches total actively eroding stream length for erosion pin installation. To accomplish this, the total length of severely eroding streambank from within each 400 meter section was summed, and each eroding bank was assigned a number (1—X). Numbers were selected at random, the corresponding eroding

banks were selected and their length summed until at least 20% of the total eroding length for the site was reached. Erosion pins were installed in each selected eroding streambank (erosion plot), = with a total of 20 severely eroding streambanks selected for monitoring.

3.3. Streambank erosion measurements

In May 2005, we installed erosion pins along the bank face in a grid of two rows spaced vertically at 1/3 and 2/3 bank height and horizontally one meter apart along the entire length of the selected eroding bank (Fig. 2). Erosion pins were 762 mm long and 6.2 mm in diameter, the same size as pins that were used successfully in recent studies (Laubel et al., 2003; Zaimes et al., 2006, 2008). The frequency of pin measurements varied during the study, with more frequent measurement made early in the study as part of a student project (Palmer, 2008). These early measurements were compiled into annual erosion rates for 2005 and 2006.

Following the dedicated student work, a lapse in measurement occurred from May 2007 until measurement resumed in November 2008. For this study, we computed the total erosion occurring from 2007 through 2008 and report the average rate for the two year period. From 2009 to 2011, annual pin measurement was conducted late in the calendar year (late November to early December). On two occasions (April and May, 2007) bank erosion pins were measured soon after a storm event occurred in the watershed. Erosion rates for these two events are reported separately in this paper and also incorporated into the annual rates. Over the course of the project streambank pin measurements were conducted a total of eleven times.

During all measurement periods, we quantified erosion by measuring the change in exposed pin length between readings. Positive pin readings (lengthening of exposed pin) were considered erosion whereas negative pin readings (shortening of exposed pin) were considered deposition. All negative pin readings were incorporated into recession rate dataset development as true values (Couper et al., 2002). Exposed pins were reset to a length of 7.5 cm in order to restart the next measurement period with a standard pin length. In cases where erosion pins were missing, we assumed the recession rate for the pin to be 600 mm. This length was chosen due to numerous field observations of exposed pins in excess 600 mm in length protruding from the streambank face (Zaimes et al., 2006) and is similar to methods used in previous studies (Wolfman, 1959; Twindale, 1964; Hooke, 1977; Lawler, 1984). Buried pins were counted as deposition, with the length of exposed pin from previous measurement assumed to be the total deposition. We monitored the buried pin location and resumed pin measurements on any erosion pins that were re-exposed. The total number of pins measured on each measurement date ranged from 600 to 634. Individual numbers of pins measured at specific bank sites ranged from 10 (five columns of two pins each) to 70 (35 columns) (Table 1).

Erosion pin measurements at each plot over the six year period were analyzed for differences in erosion rates using a One Way ANOVA and Student's *T*-Test in SigmaPlot 12 from Systat. Comparisons for all pairs during both measurement periods were performed using the Turkey–Kramer Honestly Significant Difference test. Differences were considered significant at the $p < 0.1$ level.

3.4. Estimation of suspended sediment loads

Annual suspended sediment loads for the Walnut Creek watershed determined for water years 1995 to 2005 were previously reported (Schilling et al., 2006; Schilling et al., 2011). Monitoring of daily discharge, suspended sediment concentration and load was performed by the USGS using standard methods, and these data are publically available from the USGS in their annual water data reports (http://wdr.water.usgs.gov/). This monitoring however was discontinued late in 2005. Precipitation was monitored at a weather station located at the Prairie Learning Center of the NSNWR (Fig. 1).

Beginning in March 2007, suspended sediment sampling was resumed at the same gage sites by the U.S. Department of Agriculture's National Laboratory for Agriculture and Environment (NLAE). Discharge was calculated using a Waterlog bubbler (stage values every 10 min) and a rating curve developed for the weir. Three methods were used to collect sediment samples for suspended sediment concentration determinations. The first method used was grab sampling, a manual dip sample near the v of the weir. Grab sampling has been conducted on a weekly basis since March 2007. A second method utilized an

Fig. 2. Grid of erosion pins spaced vertically at 1/3 and 2/3 bank height and horizontally one meter apart along the entire length of the selected eroding bank.

Table 1
Summary of annual recession rates, precipitation, discharge and suspended sediment in Walnut Creek watershed.

	2005[a]	2006	2007–2008 AVG	2009	2010	2011	Overall average
Recession rate (cm/yr)	0.39	−0.64	19.24	34.2	27.0	13.59	18.84
Precipitation (mm)	767	835	1111	1108	1366	716	984
Departure P from Avg (%)	−13%	−5%	+26%	+26%	+55%	−16%	
Mean daily discharge (m3/s)	0.40	na	0.86	0.83	13.91	0.52	
Water volume (m3)	12,682,013	na	26,994,035	26,304,032	438,763,645	16,876,838	
Max discharge (m3/s)	9.8	na	19.3	15.9	34.8	23.2	
TSS load (Mg)	6172	na	11,447	18,814	25,815	17,541	15,958[b]
Total bank erosion sediment (Mg)	92	−151	4707	9921	7833	3943	5,299[b]
% of watershed sediment export	1.5%	0%	41%	53%	30%	23%	33%[b]

[a] Data for 2005 discharge and TSS loads were for the January to October period only (from Schilling et al., 2006).
[b] Average data excluded 2006 since total sediment load was not measured. % watershed export derived from average bank erosion sediment divided by average TSS load.

automated carousel sampler that collected composite water samples from a fixed intake during events. A third method utilized by NLAE was depth integrated transect sampling similar to traditional USGS methods. The depth integrated sampling was done at least monthly and at varying flow rates. Grab and carousel sampling was also conducted at the time of depth integrated sampling, allowing apparent bias in sediment concentrations measured using the grab and carousel methods to be corrected. The data gathered from the three sediment collection methods were then compiled into a mean daily sediment concentration used in this study. We calculated sediment loads as the product of mean daily discharge and mean daily sediment concentration.

In sum, daily suspended sediment concentrations and loads were collected from October 1995 to September 2005 (USGS) and from March 2007 to December 2010 (NLAE). Data for October 2005 through February 2007 are not available. Despite partial years, we assumed that sediment loads for years 2005 and 2007 approximate annual totals since the missing months in each case are not typically associated with major sediment export events. Based on 10 years of daily sediment monitoring (Schilling et al., 2006), missing months in 2005 (Oct–Dec) would account for approximately 1.5% of the annual total, whereas the missing months in 2007 (Jan/Feb) would account for 7.6% of the annual total. Hence, our bank erosion contributions to annual stream sediment loads in 2005 and 2007 are overestimated to some extent, but the amount is likely insignificant given the low flow conditions observed during these periods.

3.5. Quantification of sediment contribution

We estimated sediment contribution from streambank erosion using recession rates measured at pin plots in the Walnut Creek watershed. Heights and lengths measured during the 2004 and 2010 stream survey were used to calculate the total surface area of severely to very severely eroding streambanks. The surface areas of the eroding lengths were used in conjunction with pin plot recession rates and average streambank sediment bulk density to quantify total eroding streambank sediment contribution to Walnut Creek. Bulk density sampling was conducted by collecting soil samples at 1/3 and 2/3 bank height in the center each of the eroding bank lengths selected for erosion pin plot installation. Soil was collected using a 2.5 cm diameter, 38 cm long soil probe. Samples were dried at 105 °C for 24 h and weighed to determine the dry soil weight of each sample. Bulk density was determined by dividing the dry soil weight by the volume of the soil core.

We combined the recession rates estimated by erosion pins with the eroding length data collected during the 2004 and 2010 stream survey to quantify the effects of bank erosion on watershed sediment export. We averaged the recession plot data into a single recession rate value for the watershed, given that recession rate data were not available on all eroding segments in the basin. Thus, an average value based on all the measured plots was assumed to best represent the average condition for the entire basin. Recession rate data were used to calculate; 1) individual annual recession rates (cm/yr) by plot, including mean rates, maximum rates and standard deviation (Lawler, 1993a), 2) condition-based recession rates (cm/X (X = time)), and 3), overall average annual recession rate (cm/yr) from the entire duration of the sampling. Sediment loss calculations were performed using the following equation:

$$[(Bank\,height(m) * Bank\,length\,(m)) * \text{Recession}\,rate(m/time)] * Bulk\,density\left(kg/m^3\right) = kg\text{sediment}\,lost\,per\,defined\,\text{interval}.$$

Our estimates of the total sediment derived from streambanks were compared to the annual sediment loads to estimate the annual contribution of bank erosion to total sediment loads in the watershed. Calculations of streambank sediment contribution from 2005 to 2006 were based on the eroding lengths mapped during the 2004 streambank survey whereas the 2007–2011 comparisons were based on conditions mapped in the 2010 survey. This was done because the 2004 survey better reflected dry weather conditions experienced over this interval, while the 2010 survey was more representative of more recent wet weather conditions. Sediment contribution was estimated for each of the seven years of this study. Estimates of streambank sediment contribution to total suspended sediment loads were similarly calculated for single storm events in April and May of 2007.

4. Results

4.1. Hydrology

Precipitation during the study period was variable, ranging from below normal during three years (5–16% below normal) and 26 to 55% above normal during the 2007 to 2010 period (Table 1). Discharge was equally variable in Walnut Creek, with mean daily discharge ranging from 0.5 in 2011 to nearly 14 m^3/s in 2010. We do not have discharge measurements in 2006 but streamflow was observed to be very low during this time period. Discharge monitored through most of 2005 (Jan to Oct) averaged 0.4 m^3/s. Average flow through part of 2005 was similar to 2011 (0.5 m^3/s) for the same degree of precipitation (716 to 767 mm).

Mean annual discharge was considerably higher from 2007 to 2010, peaking in 2010 when nearly 440 million m^3 of water was exported from the basin (Table 1). Much of the 2010 water export can be traced to an exceptionally large three-day event when daily discharge ranged from 29 to 35 m^3/s (Fig. 3). Storm events of smaller magnitude were more frequent in 2008 and 2009 than in prior years. Maximum daily discharge from years outside of the 2008–2009 window ranged from 16 to 23 m^3/s and mean daily values were similar (~0.8 m^3/s).

4.2. Total length of severely eroding streambanks

Surveys of severely eroding streambanks along the main stem of Walnut Creek were completed in 2004 and 2010. The length of the

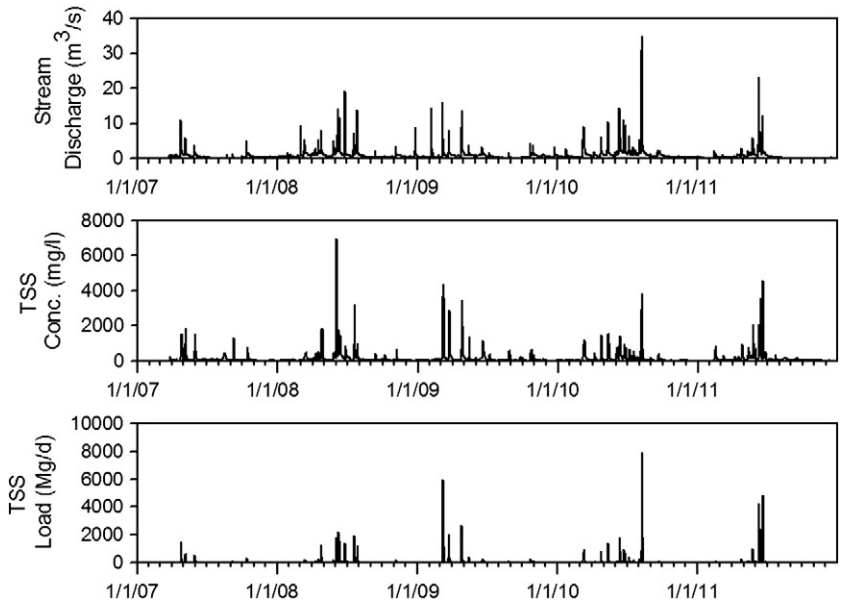

Fig. 3. Patterns of discharge, suspended sediment concentrations and sediment loads measured at Walnut Creek outlet.

channel surveyed was 10,295 m (or 20,558 m of bank on both sides of the stream) for both years. In 2004, 6707 m of streambanks considered to be actively eroding were identified, accounting for approximately 32.6% of the assessed channel. In 2010, 8204 m were considered to be severely eroding (39.9% of all streambanks), an increase of 22% from eroding length from 2004 to 2010 (Fig. 4). We consider the eroding lengths mapped in 2010 to be representative of the 2007 to 2011 period, whereas the 2004 survey results to be better representative of conditions in 2005 to 2006. The same eroding bank plots were measured throughout the study period but adjustments were made to the lengths of the eroding plots in 2008–2010 as some individual plots were seen to increase in length during this more active hydrologic period.

Although we used riparian land cover to initially select pin measurement sites, we did not evaluate eroding lengths by land cover type in this study due to the confounding effects of channel sinuosity and stream power. Several reaches in the watershed were channelized in the early 20th century and land covers were often associated with channelized versus unchannelized segments. Sites representing forested riparian zones were along some of the few meandering segments in this stream network located at the downstream end of the catchment, whereas grass was along straightened riparian reaches in the middle to upper portions of the catchment. Ultimately these differences in site sinuosity and drainage area were too great to make valid assessments of vegetation impacts on streambank erosion rates. Lawler (1992, 1995) noted similar challenges when he observed that stream channels in upper, middle and lower segments of a catchment basin are subject to different erosion processes. In our study, we focused on evaluating streambank erosion at a watershed scale rather than on individual reaches associated with differing land covers.

4.3. Streambank erosion rates

Bank erosion rates at 20 sites in the watershed were extremely variable across space and time (Fig. 5; Table 2). Maximum bank erosion rates exceeded 40 cm/yr at four sites, whereas negative pin measurements indicating deposition were recorded at every site at some point during seven year study. Among all sites, mean annual erosion rates ranged from 1.6 to 22 cm/yr, with a high standard deviation (5.3 to 22.7 cm/year). Mean erosion rates were greater than 18 cm/year at four sites and were less than 6.4 cm/yr at three sites (Table 2). Overall, total recession over the seven-year monitoring period at the 20 sites ranged from approximately 28 cm to more than 172 cm and averaged approximately 110 cm.

Bank erosion rates also varied by year, with significantly lower erosion in 2005 and 2006 compared to the 2007–2011 period (Table 2). Mean annual erosion rates at all sites during the first two years of the study were less than 0.6 cm/yr, but, increased during the latter five years to 11.3 to 28.8 cm/yr, 18 to 46 times the lower rate. Cumulative pin measured recession in 2005 and 2006 (combined) was 14.3 cm, but cumulative recession in 2009 alone was nearly 40 times greater than this two year total (547 cm). In any given year, bank erosion measured at the 20 sites was equally variable, although there was some consistency in minimum and maximum rates. Minimum rates were similar across years, ranging between −6.3 and 4.4 cm/yr, whereas maximum rates during 2007–2011 ranged from 37 to nearly 50 cm/yr. There was an upper limit of maximum annual bank erosion that approached 50 cm/yr, but we note that this maximum rate represents an average for a bank, not for an individual pin. In many cases, individual pins were missing at a bank, signifying that bank erosion exceeded the pins maximum measurement capacity of 60 cm.

The average recession rate from all plots through seven years of measurement was 18.8 cm/yr (Table 1). This rate was determined by dividing the total amount of recession at all pin sites by the total number of pins used and represents the best overall recession rate for the watershed. Recession rates observed in 2009–2011 were significantly higher than rates observed in the first two years of the study ($p < 0.001$) (data averaged for the combined 2007–2008 period were not included in the statistical comparison). The average annual recession rate observed during the study period ranged from −0.64 (cm/yr) in 2006 to 34.2 (cm/yr) in 2009.

Streambank recession rates, total streambank recession and total sediment export from Walnut Creek were all significantly related to high stream flow, as typified by maximum daily discharge (Fig. 6). This relation of maximum discharge to streambank recession (both recession rate and total bank erosion) was greatly affected by the higher rate of bank erosion occurring in 2009. Maximum daily discharge was a better predictor of total sediment export than average daily discharge (dashed line, Fig. 6). The distribution of recession rates varied depending on hydrologic conditions (Fig. 7). In 2006, when precipitation was near normal for the region, 59% of all pin measurements were recorded as ≤0 (indicating deposition) and only 0.5% measured ≥15 cm. In contrast, in 2009 when precipitation was 26% above normal, only 9% of all pin measurements were negative and 80% of all readings

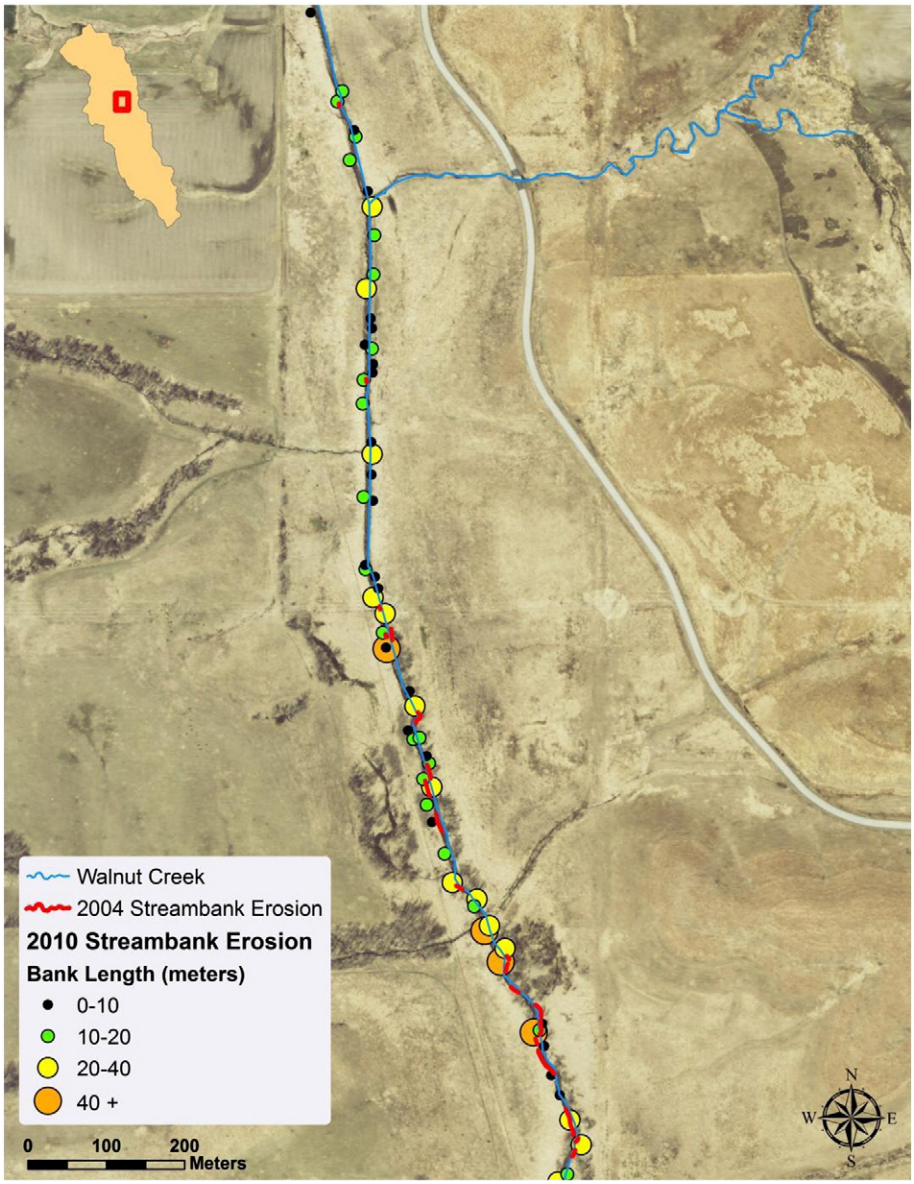

Fig. 4. Comparison of severe streambank erosion mapped in 2004 (red lines) and 2010 (circles). Expansion of locations classified as eroding clearly visible within this channel segment.

were ≥15 cm (Fig. 7). For the entire seven year period, 36% of the 7264 individual cumulative pin measurements were negative, 67% were ≤5 cm, and 22% were ≥15 cm.

4.4. Streambank sediment contribution to total annual loads

Annual sediment loads exported from Walnut Creek ranged from 6172 to 25,815 Mg, with loads from 2007 to 2011 approximately 2 to 4 times greater than loads in 2005 (Table 1). Total streambank sediment lost during 2005 and 2006 was estimated using eroding lengths evaluated during the 2004 survey and estimated to be 92 Mg and −151 Mg, respectively. The negative measurement in 2006 implies that net bank deposition occurred. In contrast, during the 2007 to 2011 period when we used the 2010 estimates of eroding lengths, the total mass of streambank sediment eroded ranged from 3943 to 9921 Mg (Table 1). A plot of streambank sediment loss versus total watershed export indicates that the two variables track similarly, as years with greater sediment export were accompanied by increased streambank sediment loss (Fig. 8). The proportion of annual sediment load attributable to streambank erosion ranged from approximately 1.5% in 2005 to 51% in 2009 (Table 1). The proportion decreased from a high of 51% in 2009 to 23% in 2011. Overall, the total streambank sediment contribution from Walnut Creek during the monitoring period (2005–2011) was 32,803 Mg and averaged 33% of the total sediment load.

4.5. Streambank erosion during storm events

On two occasions in 2007, pins were measured soon after a storm event in the watershed (Fig. 9). On April 25, stream discharge approached 11 m^3/s, and this event was followed by maximum stream discharge of 5.7 m3/s occurring 13 days later on May 7. Prior to pin measurement on April 30, pins were measured and reset on March 28 with no events occurring during the interim, so we can assume that bank erosion measured on April 30 was the result of the single event of April 25. Likewise, pin measurement on May 9 was assumed to be attributable to the storm event occurring on May 7.

Bank erosion rates measured on April 30 were higher than those measured two weeks later on May 14 (Table 3). Streambank recession from the April 30 event ranged from approximately 1 cm to more than 18 cm at the 20 sites (average of 6.5 cm) compared to erosion

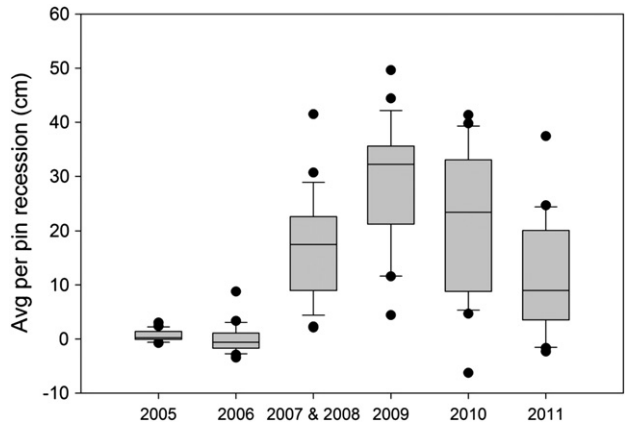

Fig. 5. Box plots of per pin recession data from each year of measurement in Walnut Creek.

measured two weeks later that ranged from net deposition (−0.33 cm) to maximum recession of 5.9 cm (average of 0.9 cm). Total bank recession at the 20 sites from the April 30 event (131 cm) was more than seven times greater than total recession from the May 6 event (~18 cm). The average recession based on the number of pins used was 9.77 cm on April 30 and 2.31 cm on May 6 (Table 3).

Recession data and eroding lengths were used to estimate sediment lost from streambanks during the two events (Table 3). Streambank sediment lost during the April 30 event (2835 Mg) was more than four times greater than the streambank sediment lost during the event 13 days later (671 Mg). During the April 30 event, more sediment was estimated to have entered the stream system from streambank erosion (2835 Mg) than was exported from the watershed (2445 Mg) (116%; Table 3). During the second event, bank erosion contributed an estimated 53% of the sediment load exported during the event. Streambank-derived sediment from the event on 4/30/2007 approximated the amount of sediment exported during a single year (2005) and was 30% of the two year total streambank sediment for 2007–2008 (9414 Mg). Streambank sediment losses from the two 2007 storm events represented 37% of the two year sediment total.

5. Discussion

5.1. Spatial and temporal scales

Streambank erosion varied considerably across spatial and temporal scales in the Walnut Creek watershed. Mean annual recession rates varied from 2 to 22 cm/yr across 20 streambanks in a single basin (spatial variation) and varied from −6 cm/yr (deposition) to 50 cm/yr over the seven-year monitoring period (temporal scale). At the temporal scale of storm events, we estimated that streambank erosion in just two consecutive events was equivalent to 37% of the total watershed sediment export over a two year period. At a longer temporal scale and at the spatial scale of a watershed, we found significant annual variation in mean annual recession rates, ranging from 0.1 cm during a dry year to nearly 30 cm during a wet year. Understanding this spatial and temporal variability in streambank recession in a watershed is critical to place bank erosion research in an appropriate context.

Couper (2004) eloquently discussed linking space and time in river bank research and noted that scale issues relate to both geographic and temporal scales. In our study, the location of erosion pin plots throughout the basin (Fig. 1) acts as a measure of geographic scale since recession measurements made upstream and downstream in the same basin reflect differences in drainage area and stream power, channel evolution stage, and riparian character (Lawler, 1992; Lawler et al., 1999). We used extrapolation, a common form of linkage used in bank erosion research (Couper, 2004), to link rates of recession observed on specific pin plots to the watershed scale. To accomplish this

Table 2
Erosion pin measurements at bank erosion monitoring sites.

Site	# Pins	2005	2006	07–08 (avg)	2009	2010	2011	mean	min	max	stdev	total
Pasture 1												
1–1	70	−0.74	−1.15	11.85	33.64	41.35	24.62	18.26	−1.15	41.35	17.83	132.77
1–2	12	−0.03	−0.86	6.5	13.27	4.68	−0.4	3.86	−0.86	13.27	5.51	36.16
Pasture 2												
2–1	44	−0.1	−0.39	20.03	37.35	28.9	−2.32	13.91	−2.32	37.35	17.18	123.53
2–2	18	−0.71	−2.14	7.87	32.22	18.23	22.52	13.00	−2.14	32.22	13.64	93.73
2–3	46	0.25	−0.79	23.27	35.93	25.66	37.43	20.29	−0.79	37.43	16.86	168.28
Woods 1												
1–1	20	−0.52	−2.9	25.15	34.68	9.72	15.73	13.64	−2.90	34.68	14.62	132.15
1–2	44	0.15	−1.15	14.72	32.83	25.14	6.9	13.10	−1.15	32.83	13.76	108.03
1–3	72	0.27	−1.82	20.3	49.63	39.79	23.79	21.99	−1.82	49.63	20.62	172.55
Woods 2												
2–1	62 (58)[a]	1.71	−3.44	30.69	44.41	34.44	3.56	18.56	−3.44	44.41	20.30	172.74
2–2	76	−0.03	0.19	27.07	38.83	26.77	20.09	18.82	−0.03	38.83	15.72	167.06
CS 1												
1–1	16	2.08	−2.56	10.09	4.41	−6.27		1.55	−6.27	10.09	6.31	27.93
1–2	12	0.41	0.18	7.62	11.73	12.41	6.14	6.42	0.18	12.41	5.30	53.72
1–3	26	0.42	0.8	17.35	25.13	7.63	9.74	10.18	0.42	25.13	9.64	95.77
CS 2												
2–1	20	1.09	−1.57	11.85	30.55	21.76	3.54	11.20	−1.57	30.55	12.73	90.92
2–2	12	2.38	8.78	2.29	11.57	35.57	14.91	12.58	2.29	35.57	12.32	80.08
WS 1												
1–1	12	1.9	3.34	17.59	30.32	23.38	11.58	14.69	1.90	30.32	11.23	123.29
1–2	22	−0.27	2.51	2.12	19.97	38.6	8.21	11.86	−0.27	38.60	14.99	75.37
1–3	14 (24)[a]	1.02	2.8	21.83	26.97	8.47	−1.67	9.90	−1.67	26.97	11.82	103.07
WS 2												
2–1	16	3.01	1.24	41.49				15.25	1.24	41.49	22.74	128.72
2–2	10 (20)[a]	0.05	0.95	21.33	33.65	6.3	−1.22	10.18	−1.22	33.65	14.20	103.71
	mean	0.62	0.10	17.05	28.79	21.19	11.29					109.48
	max	3.01	8.78	41.49	49.63	41.35	37.43					
	min	−0.74	−3.44	2.12	4.41	−6.27	−2.32					
	stdev	1.08	2.78	9.95	11.87	13.70	11.05					
	total	12.34	2.02	341.01	547.09	402.53	203.15					

[a] Number of pins modified during the study period to values shown in parentheses.

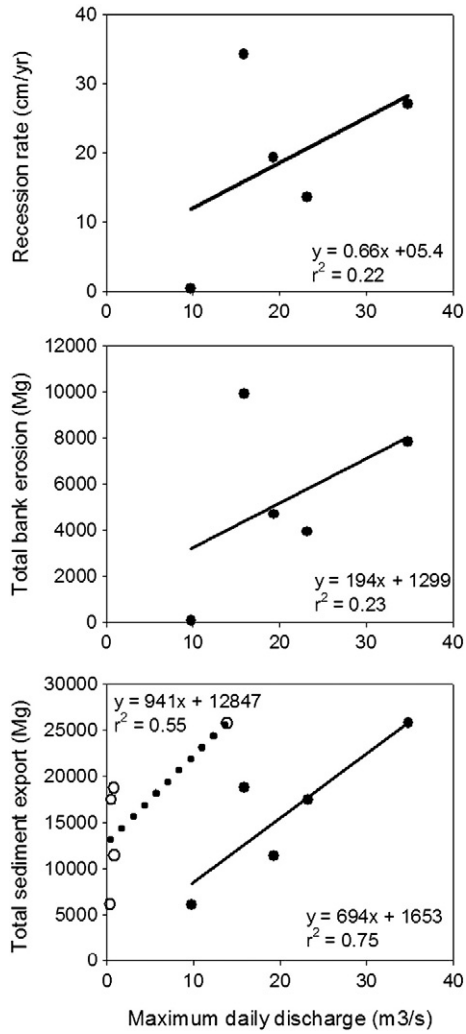

Fig. 6. Relation of recession rates, bank erosion loads and total sediment export to maximum daily discharge in Walnut Creek watershed. The relation of total sediment export to mean daily discharge is shown as a dashed line in the lower panel.

we monitored banks with similar characteristics and from varying geomorphic scales within this catchment. Similarly, we extrapolated our results across time. Our study represents a rare, long term study of bank erosion, allowing the assessment of the variability in bank erosion across a range of hydrological conditions. Previous research highlighted

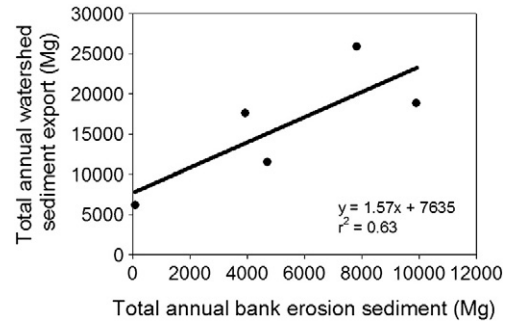

Fig. 8. Relation of streambank erosion loss to total annual sediment export in Walnut Creek.

problems with extrapolating short term bank erosion estimates to annual recession rates over a longer period (Wolfman, 1959; Twindale, 1964; Hooke, 1980). These studies identified problems associated with measuring bank erosion rates from a cross-section of time that may not be representative of a longer timeframe.

The timeframe of our study was marked by two very distinct hydrologic conditions. The early portion was characterized by below average precipitation, little hydrologic activity and very low rates of streambank recession. The latter portion was characterized by above normal precipitation, elevated hydrologic activity (including several out of channel floods), and high rates of recession. Hence, the cross-section of time represented in our study was particularly suitable for temporal extrapolation in a system estimated to be in a widening phase of channel evolution (Schilling et al., 2011). Clearly, our work supports the premise that many years to decades of monitoring are needed to quantify bank erosion rates that represent long-term averages.

5.2. Recession data

Average recession rates reported in this study are similar to other observations throughout the region. The overall annual average recession rate of 18.8 cm (±15.4 cm) falls within the very severe ranking category (>0.5 ft or >15.2 cm) reported in the visual assessment criteria developed by the Natural Resources Conservation Services (USDA-NRCS, 1998). This supports our initial mapping of streambanks in the watershed using the NRCS criteria. Results of our study also compare well with a three year erosion pin study conducted in Central Iowa which reported a recession range of 4.6 to 23.9 cm/yr on streams bordered by grazed pastures, row-cropped land, and grass and forested buffers (Zaimes et al., 2008). The highest recession rates from the Zaimes et al. (2008) study were from row

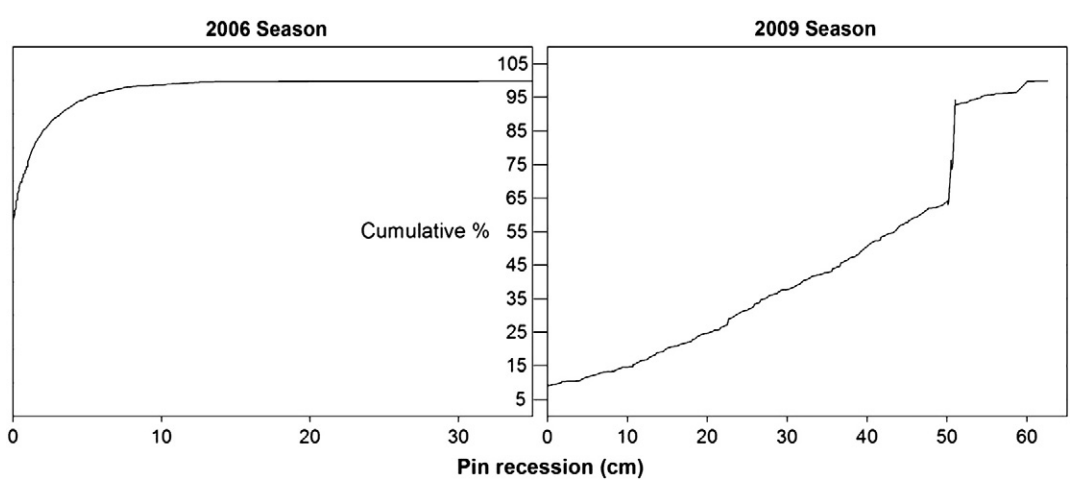

Fig. 7. Cumulative percentages of measurements from individual pins in 2006 and 2009.

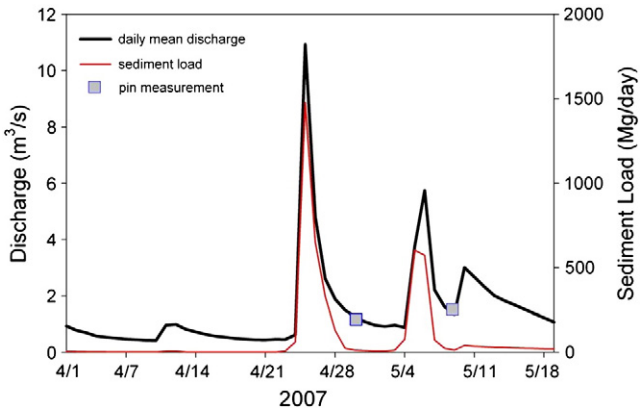

Fig. 9. Relation of erosion pin measurement to discharge and sediment loads measured during two storm events in 2007.

cropped riparian areas, but we were unable to monitor this riparian land use type with the Walnut Creek basin. It is possible that the lack of row crop monitoring in our study may have resulted in a slight underestimation of overall recession rates; however, row-crop land use occupies a relatively small proportion of the Walnut Creek riparian corridor (9%).

Streambank recession rates were better correlated with maximum discharge than average discharge conditions, which would be expected in incised channels such as Walnut Creek where hydraulic erosion is considered the dominant bank erosion process (Thorne, 1982; Rinaldi and Darby, 2007). Hydraulic erosion removes bank materials from the direct erosive action of the flow (Darby et al., 2010). During high flow events in incised Walnut Creek, streamflow is confined within the channel and scours the streambanks over the entire bank height. In addition to the direct hydrologic scour, the steep streambanks become saturated during channel-full events and, are subject to mass failure when stream flow recedes and they are no longer supported by the flow in channel (Simon et al., 2000; Simon and Collison, 2001). We have observed exceptionally flashy streamflow in Walnut Creek in response to precipitation when stage increased to the top edge of the channel and then decreased approximately 2.5 m within 8 h (Schilling et al., 2006). The evaluation of specific processes associated with bank erosion is the subject of considerable investigation (e.g., Rinaldi and Darby, 2007; Darby et al., 2010) with many studies focusing on quantifying variations in shear stress. While our study was not focused on evaluating bank erosion processes, our data suggest a close association between stormflow discharge and increased bank erosion.

Streambank recession has been quantified using erosion pins in many studies conducted world-wide (e.g., Hooke, 1980; Couper, 2004) and results from these studies exhibit wide variability in average and maximum rates. We observed similar spatial and temporal variability at the plot and basin scale. While mechanistic processes controlling bank erosion at individual sites have been well documented (e.g., Lawler, 1992; Simon and Collison, 2002; Pollen et al., 2004; Fox et al., 2007), understanding the distribution of variable bank erosion processes operating at the basin scale lags behind. For example, Lawler et al. (1999) interpreted the variability within individual eroding plots in the Swale Ouse river system as an indication of erosional processes and the variability among plots as an indication of longitudinal changes in the erosion process at the basin scale. Others have observed that changes in catchment area, width-depth ratios (Hooke, 1980), channel geometry (Odgaard, 1987), or landscape changes such as channelization (Simon, 1989) or agriculture (Knox, 1977) and urbanization (Trimble, 1997) contribute to basin-scale variability of bank recession rates. Fonstad and Marcus (2003) noted that it is difficult to separate factors contributing to local scale variation of streambank recession from those operating at a basin scale as they may be related in a self-organized critical system (i.e., fractal). If Walnut Creek operates similarly, then reach-scale variability in recession rates is not only a function of local scale processes but also a product of the basin-wide distribution of streambank failures. Hence, comparing recession rates among intra- or inter-basin sites is fraught with uncertainty as reach-scale or basin-scale dynamics reflect both local scale and regional conditions, including variations in topography, geology and/or climate. Our average recession rate data, based on seven years of monitoring at 20 sites, can be more reasonably extrapolated to similarly sized basins throughout the Western Corn Belt Plains Ecoregion (Schilling et al., 2011) with similar climate, land use and landform conditions.

Table 3
Sediment export and main stem streambank contribution from two storm events in the Walnut Creek watershed.

Date	Total precip.	Recession	Sediment export	Bank contribution	% bank
4/30/2007	78.6 mm	9.77 cm	2445 Mg 2695 tons	2835 Mg 3125 tons	116%
5/6/2007	55.4 mm	2.31 cm	1266 Mg 1396 tons	671 Mg 740 tons	53%

5.3. Pin measurements

The erosion pin method used in this study was chosen for its broad scale applicability in various fluvial environments (Lawler, 1993a) and high degree of sensitivity (Thorne, 1981). However, as reported in other studies, limitations such as the loss of pins and measurement disturbance likely affected the accuracy of erosion pin data (Hooke, 1977; Lawler, 1993a; Couper et al., 2002). During the first ~20 months of the study (a period of stable hydrologic conditions and relatively inactive erosion) activity on pin plots was limited to the loss of the friable granular surface of the upper streambank and subsequent deposition of this material at the toe of the streambank. This deposition of material resulted in the aggradation of soil on the bottom row of measurement pins and net deposition for the several measurement periods in 2005–2006. Frequent measurements during this timeframe may have disturbed the natural deposition process and artificially increased recession rates of the lower row of pin plots (Lawler et al., 1999). However, this source of error was relatively small since recession rates observed during this portion of the study were near zero or negative and the material accumulated at the toe of the streambank was easily mobilized by the first discharge events capable of inundating the bank toe. On the other end of the spectrum, maximum erosion rates were underestimated due to missing pins, indicating a rate greater than 60 cm/yr. Underestimating maximum bank erosion will underestimate the contribution of streambank erosion in overall sediment export.

Another source of error occurred during the latter period of elevated hydrologic activity and high recession rates. At several erosion pin plots very large planar and rotational failures resulted in the loss of streambank far exceeding the measurement capacity of the erosion pins. This is a common problem associated with this methodology (Lawler, 1993a) and likely led to the underestimation of recession rates on several pin plots during these wet periods. We lost erosion pins at different rates among the streambank sites, ranging from a rate of one percent of the total measurements at less active banks to 17% of the total measurements at an actively eroding bank. As noted earlier, recession rates were likely underestimated at sites where pins were lost.

5.4. Sediment budget

A major goal of this study was to derive a more accurate estimate of the contribution of streambank sediment to sediment export from the Walnut Creek watershed. Our effort incorporates over 16 years of

data, including data directly reported in this study (2007–2011) and a ten year study of suspended sediment transport within this basin (1995–2005) (Schilling et al., 2011). Such intensity and duration of sampling is rare. The range of streambank-derived sediment contribution to total sediment export from the basin was 6–53%. This range compares well with the findings of multiple studies throughout the region. Sekely et al. (2002) reported that 30–44% of the sediment load in the Blue Earth River in Southern Minnesota could be attributed to streambank erosion. Willett et al. (2012) reported that streambank erosion accounted for 79–96% of the total sediment discharge in two watersheds in northeast Missouri. Wilson et al. (2008) estimated that 54 to 80% of the sediment load was derived from streambanks at five sites in the Midwestern and southern U.S. Two previous studies in the Walnut Creek watershed estimated streambank-derived sediment comprised 38–75% of annual sediment load (Schilling and Wolter, 2000; Schilling et al., 2011). However, a weakness of previous studies within Walnut Creek was comparing a single annual estimate of bank erosion to highly variable measured annual sediment loads. Results from this study provide convincing evidence that bank erosion contributions to annual sediment loads can vary significantly during wet and dry years. Efforts to quantify streambank contributions at other watersheds should consider the role of hydrologic variability in reporting these estimates.

With our multiple year study, we are able to assess how streambank sediment contribution to total watershed export varied within and among years. The percentage of total load comprised of streambank sediments was found to be highly variable from season to season and largely driven by the frequency and magnitude of large discharge events. During the first two years of the study, streambank sediment contribution from the main stem of Walnut Creek was minimal and, in the case of 2006, estimated as negative (deposition outpaced recession). From 2005 to 2006 every bank measured in this study had at least one measurement period with net deposition. The contribution of streambank sediment to sediment export was approximately 0 to 1.5% during these dry years (2005 and 2006), highlighting that streambank erosion does not contribute significantly to annual sediment export under these conditions. However, it is possible that bank sediment mobilized during wet periods was stored in the channel, and incorporated into the sediment export during these dry years. A survey of streambed sediments conducted in 1998 estimated that under average sediment export conditions, it would take nearly 9 years for all the sediment stored in Walnut Creek stream bed to be transported out of the watershed (Schilling and Wolter, 2000).

The prolonged period of time before April 30 2007 without a hydrologic event in the basin allowed for an extended period of weathering to operate on the streambanks (Thorne, 1982; Lawler et al., 1997). Subaerial processes such as soil desiccation and freeze–thaw cycling causes cracking that significantly increases erodibility and reduces shear strength (Thorne, 1998; Wynn and Mostaghimi, 2006). During the nearly two years of low flows in Walnut Creek the banks were subject to intense drying which led to cracking in the soil profile (authors observations). In addition to prolonged dry conditions, the streambanks along Walnut Creek were also subject to two seasons of freeze–thaw cycles prior to the spring 2007 events. It has been shown that the growth and melting of ice crystals in a bank profile is highly effective in weakening bank material (Lawler, 1993b). The extended preparation process (weathering) that occurred in Walnut Creek helps to explain why the streambank erosion was so severe in the first of the two spring 2007 events. The first event in late April yielded streambank-derived sediments estimated to be greater than the total basin export for the event (116% of the total), compared to the second event in early May with far less recession (2.31 cm compared to 9.77 cm) and lower streambank contribution to watershed export (53% of the total).

Although streambank sediment is a major source of sediment discharged from Walnut Creek, the proportion across years and events varies considerably and appears to reflect pulses of sediment erosion and export in the watershed. The bank erosion proportion decreased from 116 to 53% in two consecutive events, and the two year average for the time period (2007–2008) was lower still (41%). Similarly, the sediment load in 2009 (18,814 Mg) increased by 7000 Mg in 2010 while the total bank erosion load over the two years decreased by approximately 2000 Mg and the percentage of watershed export decreased from 53 to 30% (Table 1). Similar variability in the contribution of single events to total sediment loads was observed by Wilson et al. (2012). The relation of bank erosion loads to maximum discharge (Fig. 6) suggests that other factors are important in predicting annual sediment budgets and that the timing of streambank sediment loss relative to discharge and total sediment loss is not necessarily synchronous. Fluvial erosion and subaerial processes may dislodge sediment from the banks, as measured by the recession rates, but some of this sediment is stored in the channel bottom on point bars or behind log jams or other flow impediments. Sediment loads during high flow events or during high flow years may result in export of this stored sediment. This remobilization of eroded sediment may be a major confounding factor in deriving annual bank erosion contributions. Additionally, variation in streambank sediment contribution to watershed sediment export is expected as a stream system works to reach equilibrium following disturbances (Lane, 1955; Schumm et al., 1984; Simon, 1989).

The complications of varied and transient sediment sources in overall basin loading have received far less attention than the impacts of climate. As pointed out by Schilling et al. (2011) "the response of fluvial systems to changes within channels or at the watershed scale is complex and even extensive changes in land use may not be adequate to reduce watershed sediment yield if peak discharges and stream power are not reduced". This problem is further compounded in unstable channel networks where major channel incision, flood plain sediment aggregation and/or channelization activities have occurred (Shields, 2009). The natural recovery process of these systems will include a period of widespread channel widening (streambank erosion) which will impact sediment dynamics within the system for the duration of this process (Lane, 1955; Schumm et al., 1984; Simon, 1989).

5.5. Future work

Studies such as this one provide much needed empirical data on the amount, source and location of severe streambank erosion in a single watershed over an extended period of time. As such, our study represents a rare data set available to researchers interested in testing theories of spatial patterns of bank erosion (e.g., Fonstad and Marcus, 2003, 2010) or identifying factors contributing to recession rate variability within a basin (e.g., Couper, 2003; Laubel et al., 2003; Henshaw et al., 2012). For example, Walnut Creek watershed results are being used to evaluate the effects of hydraulic disturbance (channelization) on the relations of channel sinuosity, stream power and occurrences of severe bank erosion. Spatial patterns of severe bank erosion mapped in Walnut Creek and our measured recession rates are also being used to calibrate the efficacy of using statewide 1-m LiDAR topographic data to identify severe bank erosion within unmonitored basins across the state.

Fonstad and Marcus (2010) stated that "…testing existing models and theories in different areas, at different scales, and for different potential applications is critical to large-area river observations and management." Using Walnut Creek data, validating and testing theories of spatial patterning of streambank recession can be extended from mountain west regions (Montgomery and Buffington, 1997; Fonstad and Marcus, 2010) to include Midwestern stream channels affected by more than a century of agricultural intensification (Jones and Schilling, 2011). Furthermore, watershed sediment budgets are often limited by

spatial and temporal variations in sediment yield, such that budgets typically utilize historical sedimentation records (i.e., Knox, 1987) rather than contemporaneous sediment transport. In the case of Walnut Creek, we are continuing to monitor daily sediment yield and annual streambank erosion, and will be assessing sediment delivered from gully and tributary sources in an effort to refine the annual sediment budget.

Erosion pin sites utilized in our annual bank erosion monitoring will be adjusted to reflect current conditions. While we will continue to utilize erosion pin techniques as our primary methodology, we will supplement this effort incorporating more advanced surveying techniques such as photo electronic erosion pins or PEEPS (Lawler et al., 1997) and ground based Light Detection and Ranging or LiDAR (Kovar and Russell, 2008). Erosion pin placement at new sites will be modified to target different Holocene alluvial members that typically comprise the exposed banks in the region (Schilling et al., 2009), including a post-settlement layer and underlying silt-dominated units. Refinements in methodology and techniques will increase measurement precision and allow for the broader inference of study results.

6. Conclusions

In this study, we evaluated streambank erosion at multiple sites within a third-order Iowa watershed. The study incorporated nearly 16 years of basin sediment discharge data and seven years of pin-measured streambank recession rates in order to quantify the rate and variability of streambank erosion and estimate the contribution of streambank sediment to watershed-scale suspended sediment loads. The data set used in this study is among the longest such record in the Midwestern United States. Our findings support a growing body of research that indicates that streambank derived sediment, while variable in timing and magnitude, makes up a significant portion of the annual sediment flux in Midwestern agricultural watersheds.

Annual sediment export and the relative contribution of streambank derived sediments to total watershed export varied widely thought the study period. Streambank recession rates measured at 20 sites in the watershed ranged from negative values during dry years (net deposition) to 40 cm/yr during a wet year. Over the seven year period, mean erosion rates were greater than 18 cm/year at four sites and were less than 6.4 cm/yr at three sites. The proportion of annual sediment load attributable to streambank erosion ranged from approximately 0% during dry years to 51% during wet years.

Our results highlight the challenges in developing direct relationships between streambank erosion rates and total sediment export. The relationship is confounded by the frequency, timing, and magnitude of discharge events, the storage of sediment within the channel system, and the remobilization of eroded material. Bank erosion estimates should be framed in proper context, as the driving geomorphic variables are not bounded by annual measures but by climactic and hydrologic processes. We recommend that researchers studying streambank erosion processes commit to the development of long term datasets. With time, such datasets will incorporate a broader scale of climatologic and hydrological conditions and improve our ability to evaluate how channel processes respond over geomorphic time.

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