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The influence of hydrologic and riparian factors on stream channel stability in a central Iowa stream

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ABSTRACT

Onion Creek, a 2^{nd} order stream in central Iowa, is the focus of research on stream channel stability and sediment movement. A field survey of Onion Creek (Chapter 2) found 24.5% of the total streambank length was severely eroding and some reaches of the stream had up to 50% severely eroding streambanks. Hydrologic factors such as watershed size, stream channelization, and flow restrictions were more significant than riparian land use in explaining the incidence of severely eroding streambanks.

An analysis of channel movement on Onion Creek from 1939 to 2009 (Chapter 3) found significant local changes, with landowners straightening stream channels in some sections and meander migration dominated by increases in stream extension in others. This predominance of channel extension in meandering sections indicates a stream that is adjusting to excess hydrologic energy.

Streambank erosion was directly measured on a subset of streambanks using erosion pin plots measured from October 2011 to April 2013 (Chapter 4). A drought during much of this period caused low levels of change, but study sites did show freeze-thaw destabilization during winter months followed by moderate erosion by fluvial entrainment in the springs of 2012 and 2013.

Water quality was measured at the outlet of Onion Creek between March 2012 and April 2013 (Chapter 5). An analysis of the loads and concentrations of sediment, phosphate and total phosphorus, and nitrate and total nitrogen exported from Onion Creek is presented. Finally, sediment loads discharged from Onion Creek are compared to estimates of sediment eroded from streambanks.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Sediment is a major cause of impaired water quality. Water-borne sediment can decrease gross primary productivity (O'Conner et al. 2012), impair stream ecology (Zimmerman 2003), and cause bed disturbance and reservoir siltation (Lawler and Dolan 1992, O'Conner et al. 2012). Further, sediment in water is a carrier of phosphorus, which in excess, has a negative effect on water quality and stream ecology (Laubel et al. 2003, Kronvang et al. 2012, Zaimes et al. 2008a, b).

Sediment loads can come from many sources, including surface runoff, gullying, and bed and bank erosion. Even when conservation measures decrease sediment loads from surface runoff and gully erosion, high sediment levels may persist, likely due to streambank erosion (Schilling et al. 2011). A review of several recent studies found that streambank erosion can contribute between 17 and 92% of the total sediment load in streams (Belmont 2011). Palmer (2008) obtained similar results in a survey of Iowa streams.

Excessive streambank erosion often occurs as a result of channel instability. Across much of the landscape, extensive land use change and stream straightening have increased stream slope and hydrologic loads. These changes increase the likelihood that a channel will destabilize and undergo a decades-long evolution towards a channel more in equilibrium with the changed agricultural landscape (Schumm et al. 1984). During this evolution, a stream contributes a large amount of sediment from its bed and banks (Schumm et al. 1984), seen in the high proportion of sediment from streambank erosion in the previous paragraph. Although the concept of channel evolution and its attendant streambank erosion are well-established, it is important to increase the knowledge of the triggers, processes, and specific effects of that erosion. With this knowledge, we should be able to better recommend practices to lessen the negative effects of streambank erosion.

Project Description

We have chosen the Onion Creek watershed as a case study of stream channel stability and sediment movement. The watershed is 5700 hectares with 42 km of stream channel. It is located on Wisconsin glacial till and flows through Boone and Story Counties in Iowa into Squaw Creek, a tributary of the Skunk River, which flows into the upper Mississippi in southeastern Iowa. A previous study of the Squaw Creek watershed, using RUSLE calculations for erosion from surface runoff combined with a sediment delivery ratio calculation, estimated that the Onion Creek watershed had the highest rate of sediment delivered per acre (0.134 tons/acre) compared to Squaw Creek's six other sub-watersheds (Wendt 2007). Wendt also conducted a survey of streambank condition on Onion Creek and found that it was not significantly more or less stable than the rest of the stream channels in the other sub-watersheds of Squaw Creek. However, she noted that bank erosion on Onion Creek was of serious concern in some areas and recommended stabilizing the channel by establishing perennial buffers and minimizing cattle access (Wendt 2007).

In response to these findings, the Iowa Department of Agriculture and Land Stewardship (IDALS) started a project encouraging in-field and riparian conservation practices to decrease the amount of sediment and nutrients exported from the Onion Creek watershed. To determine if these conservation practices are having an effect on stream condition and nutrient loads, IDALS partnered with Iowa State University to monitor sediment sources and water quality. Erosion from gullies and streambanks are the sediment sources being monitored. Suspended sediment, total nitrogen, nitrate, total phosphorus, and dissolved phosphate are the water quality parameters being measured. Many years of monitoring will be required to achieve a comprehensive picture of the effects of conservation measures on Onion Creek. This thesis offers preliminary results showing the state of Onion Creek as a case study on the general state of lower-order Iowa streams.

Thesis Organization

This thesis is arranged into six chapters. The first chapter is a general introduction to topics covered. The second chapter, "Effects of hydrological and stream-scale factors on streambank erosion within the Onion Creek watershed," presents the results of a channel assessment of Onion Creek, examining the influence of various factors on the incidence of streambank erosion. The third chapter, "Channel movement and change on Onion Creek, 1939 to 2009," examines stream movement on a decadal scale, while the fourth chapter, "Freeze-thaw action and deposition on Onion Creek streambanks," presents results from a shorter time-scale monitoring of severely eroding streambanks.

The fifth chapter, “Water, sediment, and nutrient export from Onion Creek,” examines the water quality of Onion Creek over one year and relates it to estimates of sediment loads described in the previous chapters. The sixth and final chapter provides a general summary and conclusion to the thesis.

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CHAPTER 2. EFFECTS OF HYDROLOGICAL AND STREAM-SCALE FACTORS ON STREAMBANK EROSION WITHIN THE ONION CREEK WATERSHED

Abstract

A field survey was conducted on Onion Creek, a 2nd order stream in central Iowa. The survey consisted of a Rapid Assessment of Stream Conditions Along Length (RASCAL), in which the riparian land use, points of interest for sediment and water movement, and severely eroding stream banks were mapped throughout the length of Onion Creek. 24.5% of the total bank length was severely eroding with up to 50% severely eroding banks in certain reaches. Severely eroding streambanks were more prevalent in areas with narrower perennial buffers, in meandering sections downstream of channelized reaches, and more downstream stream reaches. A lower percentage of stream banks were severely eroding on channelized reaches and upstream of flow restrictions such as bridges, culverts, and drop structures. No significant relationship was found between riparian land use and streambank erosion.

Introduction

Sediment and the phosphorus it carries are major causes of diminished water quality (Lawler and Dolan 1992, O'Conner et al. 2012) and cause bed disturbance and reservoir siltation (O'Conner et al. 2012). There is a growing body of evidence that much of the sediment and phosphorus delivered to the surface waters from agricultural landscapes originates from stream bed and bank erosion (Sekely et al. 2002, Wilson et al. 2008). Belmont et al. (2011), in a review of various studies, reported from 17 to 92% of sediment in streams originated from streambank erosion. In a study of the Neal Smith

Prairie Refuge in central Iowa, where large portions of the watershed have been converted to perennial vegetation, sediment export has remained high due to high rates of bank erosion, which accounted for 14-64% of exported sediment (Palmer 2008, Schilling et al. 2011). Accelerated bank erosion is the result of the combined actions of altered watershed hydrology, sediment accretion from historical agricultural erosion of uplands, and riparian land management (Rakovan and Renwick 2011, Schilling et al. 2011, Zaimes et al. 2008). In some conditions, streambank erosion has been estimated to exceed stream transport capacity, resulting in significant channel storage (Bull 1997). The resulting suspended and bedded sediment negatively affects stream integrity and ecology (O'Conner et al. 2012).

One potential factor increasing bank erosion is a historic increase in stream power. During European settlement of the Midwest, streams were channelized for faster water removal. This channelization continued into the 1950s (Yan et al. 2010) and even the 1970s (Simon and Rinaldi 2006). Channelization is the process of straightening and aligning a stream channel (Schum et al. 1984). Immediately following channelization, this decreases the turbulence of the water and reduces erosion (Hooke and Yorke 2010, McKenny et al. 1995, Nanson and Hickin 1986, Schilling and Wolter 2000). However, the removal of the natural meanders reduces the hydraulic roughness of the stream system, shortens stream length, and increases stream gradient (Langbein and Leopold 1967, Thorne et al. 1998). The increased gradient and decreased roughness increases velocity and sediment transport capacity which lead to channel incision and destabilization of the stream system (Nanson and Hickin 1986, Schumm et al. 1984, Simon and Hupp

1987). Further, conversion of forest and prairie to row crops has increased the amount of water flowing into streams during storm events (Fitzpatrick et al. 1999, Gilliam and Skaggs 1986, Raymond et al. 2008, Schilling et al. 2008). This increased stream power then erodes vulnerable bank material (Sekely et al. 2002, Simon and Rinaldi 2000, Simon and Darby 1997, Zaimes et al. 2004). Many studies have found that stream power is the variable most correlated with streambank erosion, as sediment transport capacity is proportional to stream power (Darby and Thorne 1996, Hooke 1979, Julian et al. 2012, Lawler and Dolan 1992).

However, sediment contribution from bank erosion depends on both sufficient stream power and the availability of erodible soil. Several studies have reported lower than expected sediment loads for observed discharges, possibly resulting from exhaustion of easily erodible soil (Lawler and Dolan 1992, Zaimes et al. 2006). Once banks are destabilized, bed and bank degradation is more influenced by factors controlling bank processes, such as bank height and slope (Darby and Thorne 1996). Further, substantial bank erosion can occur even during low flows (Zaimes et al. 2006).

Despite numerous studies on streambank stability and erosion, factors which affect the rate of erosion remain unclear. Fall 2010- spring 2011, an assessment of riparian and bank characteristics within the Onion Creek watershed was conducted to assess the effect of hydrological, streamside, and watershed-scale variables on streambank erosion. This assessment adds to the knowledge of what conditions promote greater streambank stability and should inform land managers in the watershed of best management practices for mitigating streambank erosion in Onion Creek and similar watersheds.

Methods

Study Site

This study is being conducted in the 5700 ha Onion Creek watershed (Figure 1) in central Iowa (42° N, 93° W). Of all the subwatersheds of Squaw Creek, Onion Creek has the highest estimated sediment load per acre (Wendt 2007). As a result, the Iowa Department of Agriculture and Land Stewardship initiated a project within the watershed focusing on conservation measures to improve water quality (see Chapter 1). Onion Creek is a second-order, 42 km stream system in Boone and Story Counties in Iowa, flowing through Wisconsin glacial till. Of Onion Creek's 5700 ha watershed, 86.6 % is planted in corn and soybean rotations. There are some forested areas near the watershed outlet, and a small amount of pasture and suburban development. Onion Creek enters Squaw Creek just upstream of Ames, Iowa.

Stream Survey

A survey of Onion Creek was conducted in fall 2010 and spring 2011. Ideally, the survey would have been conducted over a short period of time, but snow filled the channel and cut short our field work when we had completed 40% of the assessment in the fall. The remaining stream was surveyed the following spring. The assessment utilized the protocol *Rapid Assessment of Stream Conditions Along Length* (RASCAL), developed by the Iowa Department of Natural Resources and roughly following the methods of Schilling and Wolter (2000). The protocol consists of walking the entire length of Onion Creek and its tributaries, noting the riparian land use and recording the location of severely eroding streambanks. Severely eroding streambanks were defined as banks with very low vegetation cover, severe vegetative overhang, and fallen trees and slumps (NRCS 1998). We did not differentiate between severely eroding and very severely eroding banks, as the methods to distinguish between the two do not reliably predict differences in erosion rates (Palmer 2010). In addition to the location of the eroding streambanks, we recorded their length, height, and general characteristics (vertical or not, slumps present or not). We also marked the location of points of interest for sediment and water flow, such as tile outlets, sediment deposits, log jams, and bridges and drop structures. These points of interest and bank erosion points were marked on GPS devices and subsequently projected using ArcMap™ (ESRI 2012).

Within ArcMap, the stream course was digitized from 2009 color-infrared aerial photos viewed at 1:1500 scales (Iowa Department of Natural Resources 2009a, b). The stream was divided into segments based on riparian land use, with a stream segment length of 20-30 times the stream width, following Magner et al. (2008). In several locations the stream segment was shorter where restricted by confluences, bridges, or changes in land use. This resulted in 214 segments ranging in length from 34 to 667 meters, and an average length of 191 meters with a standard deviation of 96 m. These lengths were comparable to those used by researchers using fixed-segment lengths for similar studies (Burkart et al. 2004, Schultz et al. 1995, Kronvang et al. 2012, Nellesen et al. 2011, Zaimes and Schultz 2011). Stream segments of this length will adequately capture the sinuosity of a reach of stream and in channelized reaches will show the lack of sinuosity. Of the 42 km of stream, 0.7 km was dominated by beaver activity with deep, stagnant water and 0.4 km was in culverts or under bridges. These reaches were excluded from further analysis.

Factors Studied

Values were assigned for several factors to each stream segment as follows:

% eroding streambank: The length of eroding banks within each stream segment was summed and divided by the total bank length (segment length X 2) to provide a value for % eroding streambank. This was used as the dependent variable in subsequent statistical analysis.

Bank factors:

Riparian land use: Four major types of riparian land use were identified: Grass (ungrazed), pasture, grass-tree mix, and tree-shrub mix. Row crop, though originally noted as a riparian land use type in our survey, was not included in the final land use classification. This is in contrast to Wendt (2007), whose riparian land use classification was based on the dominant land use in the 55 meters on each side of the stream, resulting in cropland dominating as a land use category in much of the first order channels. However, for this study these sections were combined with those originally categorized as grass, as we assumed that the vegetation immediately adjacent to the stream is most relevant when assessing streambank stability (Peacher 2011). As a result, the riparian land use of “Grass” includes grass buffer widths ranging from 11 to 169 meters.

Width of riparian land use: The shortest distance from the two edges of the riparian land use on each side of the stream was estimated using Esri’s ArcMap™’s Measure tool on 2009 infrared photos. This was usually from row crop to row crop, though occasionally the edge was suburban development. This was averaged throughout each stream segment to get a representative width.

Hydrological factors:

Floodplain width: Average floodplain width was estimated using floodplain soils as boundaries (Iowa Cooperative Soil Survey and IDNR Geological Survey 1998). In one case, a complex of floodplain soils was roughly parallel to but somewhat offset from an Onion Creek tributary (Figure 2). Since these soils do not form without the presence of flowing water and no abandoned channel which could have formed these soils was noted during survey, we assumed that a mapping or projection error caused the offset and used the width of these floodplain soils to estimate floodplain width.

Stream order: Each stream segment was classified by stream order using the Strahler stream classification system (Strahler 1954).

Watershed size: Watershed size at each stream segment was estimated in ArcSWAT using the downstream endpoint of each segment as the outlet. Three m bare earth digital elevation models (DEMs) accessed from the Iowa Geological and Water Survey, DNR (2010, 2011) were used in watershed delineation.

Change in watershed size: As a potential measure of the effect of large increases in stream flow, we calculated the percentage change from the watershed size of the stream segment just upstream of the one being studied.

Gradient: Average stream gradient within each segment was calculated using Dilt's tools within ArcMap™ (ESRI) (<http://arcscripts.esri.com/ details.asp?dbid=16305>), using the 3 m DEMS used in the watershed assessment above.

Sinuosity: Sinuosity was calculated by dividing each stream segment's length by the straight line distance between its endpoints.

Channelization: Stream segments were assigned a nominal variable (yes or no) for channelization (channel straightening and alignment) (Simon and Hupp 1987) based on a lower sinuosity threshold of 1.25 (Yan et al. 2010).

Stream-level variables

Because stream segments are not entirely independent variables as assumed in standard regression analyses (Haan 2002), we also evaluated the effects of factors characterizing upstream and downstream reaches.

Distance from nearest upstream confluence: To assess the influence of a stream confluence on downstream streambank erosion, the distance from the upstream end of each segment to the closest upstream confluence was measured for any second order stream (19.5 of the 41 km).

Distance from nearest flow restriction: To assess the effect of engineered structures restricting water flow on streambank erosion, we measured the distance from the segment endpoint to the nearest upstream and downstream flow restriction, creating two data points for each segment. Flow restrictions were bridges (unless specifically marked as not being control points), culverts, drop structures, field crossings, dams, and any other point noted as control points. When a segment did not have an upstream flow restriction, it was not analyzed, removing 3.3 km of stream. When a stream segment was just upstream or downstream of a flow restriction, the distance from the flow restriction to the segment endpoint was given a value of zero for that factor (upstream or downstream, as appropriate). When a stream segment was bisected by a flow restriction, it was given a value of zero for both variables and the stream distance from the flow restriction was measured to each adjacent segment. When a segment had an upstream confluence prior to any flow restrictions, the distance to the flow restriction on the tributary with the larger watershed size was used as it was assumed this would have a greater effect.

Distance below channelized reach: The stream length from the upstream end of each reach to the nearest upstream channelized reach was calculated. Stream segments which didn’t have an upstream channelized reach were not included, removing 2.2 km of stream. When measuring upstream beyond a confluence, the tributary with the larger watershed was used.

Length of upstream channelized reach: The length of the upstream channelized reach was measured for each stream segment. For this assessment, all culverts and bridge underpasses were considered to be part of a channelized reach if the stream segments on each side of these structures were channelized.

Analysis of Factors' Effect on Streambank Erosion

The correlation of potential causative variables with the dependent variables was assessed using R (R Development Core Team 2011). A correlation matrix of all factors was generated to examine trends in the distribution of values for those factors, remove factors which had an R^2>0.75 with any other factor, and carry out a bivariate analysis of each factor's effect on % severely eroding streambank.

A best-fit model was built using a stepwise multiple linear regression of explanatory factors' effect on % eroding streambank. In addition to the factors mentioned above, we also included two potential interaction effects in our model building: Upstream channelized reach length with channelization and distance from upstream channelized reach with channelization. These interaction effects were included because we expected channelized and meandering reaches to behave differently in response to upstream channelized reaches.

Because of the difference in stream lengths, we weighted our stream segments according to their length when carrying out regression analyses. After construction of the final statistical model, the residuals of % streambank erosion were plotted based on distance of the stream reach from the mouth of Onion Creek (Haan 2002) to test for autocorrelation of streambank erosion in nearby stream segments.

In our analysis, we used an overall α-value of 0.1. However, as the number of factors analyzed increases, the probability of random numbers producing a significant correlation for any one of those factors increases when using the multiple tests of stepwise regression. To counteract this effect, we performed a Bonferroni correction, which takes the original α value and divides it by the number of factors being analyzed. In our case, we are studying 13 factors and two interaction effects, so our corrected α value is $0.1/15=0.0067=\alpha_{corrected}$. This is a conservative means of analyzing our results which increases the likelihood of failing to detect relationships which do exist. However, this factor is used to avoid implying confidence our analysis method does not warrant. While α values greater than 0.0067 may indicate a significant relationship, I suggest that future research examine that relationship and will not report such results as significant.

Results

General Stream Characteristics

1799 points of interest were mapped along 41 km of stream. The most common mapped points were sediment bars and islands (764), gullies (132), log jams (155), animal crossings (147), riffles (142), and tile outlets (115).

1676 severely eroding streambank segments were noted, for a total length of 20.1 km and an average of 24.3% of total bank length severely eroding (Figure 3). 93% of the eroding streambanks on Onion Creek were vertical, 73% had slumps at the time of sampling, and 14% cut into valley walls. The average bank height was 2.05 m. Based on estimates from NRCS's Erosion and Sediment Delivery Worksheet's (1998) of a recession rate of 0.122 meters/year and an average soil density of 1.36 Mg/cubic meter, severely eroding streambanks in Onion Creek contribute 5100 cubic meters or 6800 Mg soil to the stream system in an average year.

Correlation Analysis

On Onion Creek and its tributaries, 15.5 km of the stream flowed through grass, 10.2 km through a grass/tree mix, 12.1 km through trees/shrubs, and 3.0 km through pasture (Figure 4). There was significant collinearity between the factor of riparian land use and other factors (Table 1). Trees/shrubs and Grass/tree mix reaches were more prevalent on the downstream end of the watershed while Grass and Pasture were clustered on 1st order streams. Average riparian land use widths, or the distance between row crops on each side of the stream, were 54 m for Grass, 153 m for Grass/tree mix, 188 m for Trees/shrubs, and 199 m for Pasture.

In addition to having a narrower vegetation width, roughly 72% of grass reaches were channelized, compared to 24% of grass/tree, 17% of tree/shrub, and 10% of the pasture reaches (Figure 5). 16 km of the total 42 km were channelized. The longest continuously channelized stream reach is 3.7 km and the longest stream reach without any straightening was also 3.7 km. The tree/shrub section had a 60% higher gradient than the grass section ($p<0.001$) and the grass/trees section had a 40% higher gradient than grass reaches ($p=0.0035$). A significant number of stream flow restrictions were identified (Figure 6). Most of the factors had some collinearity, but none had an $R^2>0.75$, so we included all factors in our subsequent analysis.

A significant bivariate relationship was found between % eroding streambank and the following variables: Riparian land use, stream order, watershed size, channelization, distance from downstream flow restrictions, and distance below upstream channelized reaches (Table 1). The bivariate regression between riparian land use and % eroding streambank illustrated that forested reaches (Grass/tree mix and Trees/shrubs) had 8% more eroding streambank than the grass reaches, while pasture was not statistically different from any other riparian land use group (Figure 7). 27% of second-order streambanks were severely eroding, compared to 21% of 1st order streambanks. With every 530 ha increase in watershed size, severely eroding streambanks increased by 1%. 19% of streambanks in channelized reaches were severely eroding, compared to 26% in unchannelized reaches. A stream segment increased in % severely eroding streambank by 1% every 490 m upstream of a flow restriction. Finally, severely eroding streambank increased by 1% with every 365 m increase in the distance from an upstream channelized reach.

Multiple Linear Regression of Factors in Relation to % Eroding Streambanks

The best overall model created using stepwise addition and elimination of factors, explained 28.8% of the variance in % severely eroding stream bank. The model contained six factors: width of riparian land use, watershed size, distance to downstream flow restrictions, channelization, length of upstream channelized reach, and an interaction effect between channelization and length of upstream channelized reach (Table 2). The model for the amount of severely eroding stream bank for a given reach of stream is shown below:

*% severely eroding streambank= 20.6 – 0.03 * [meters width of riparian land use] + 0.0025 * [watershed size (hectares)] + 2.47 * [km upstream from a downstream flow restriction] + 4.1 * [km of upstream channelized stream reach] - if channelized, (2.5 + 5.5 * [km of upstream channelized stream reach])*

To explain this equation, for every 400 ha increase in watershed size, bank erosion increased by 1%. For every 400 m increase in distance from a downstream flow restriction, bank erosion increased by 1%. In other words, closer to a downstream flow restriction, stream banks were less likely to be severely eroding. Channelized reaches had 2.5% less erosion than the non-channelized reaches. With every 240 meter increase in upstream channelized reach, the % eroding streambank increased by one percentage point. The interaction effect of the upstream channelized reach and channelization was that if a stream reach was channelized, the rate of streambank erosion would *decrease* by 1.3 % for every 240 meters upstream channelized reach ($p<0.001$). This interaction effect counteracted the marginal effect of the upstream channelized reach factor when a stream was channelized. In other words, an upstream channelized reach increased erosion, but only in reaches that were still meandering. There was no substantive autocorrelation among the residuals of this model.

Finally, though width of riparian land did not have a significant zero-order correlation with % severely eroding stream bank, it was significant when included in a multiple linear regression model, once collinearity among land use width, watershed size, and channelization was resolved. With every 33 meter increase in the width of riparian land use (or every 17 meter increase in distance from row crop), erosion decreased by 1%. Although it may seem illogical to include width of riparian land use in a model that does not include land use, all land uses were perennial vegetation, so their width, or the distance from the stream to row crops was still considered a meaningful factor even if the type of perennial vegetation was not included.

The inclusion of the above factors to the multi-factor model decreased the effect of vegetation to such an extent that it was no longer significant. The forested reaches still had a greater % of eroding streambank than the grass section, but rather than the 8% difference of the bivariate analysis, if riparian land use were included in the model, forested reaches only increased the eroding streambank by 4.8% (Grass/tree mix-P=0.012) and 2.9% (Trees/shrubs-P=0.20) over the grass land use. Pasture again was not significantly different from other land uses. Theses contrasts did not meet the Bonferroni-corrected α value of 0.0067 and so were not included in the model.

Other factors which were significant in our bivariate analysis were not significant when added to the final model. The distance from the upstream channelized reach lost any significance once the channelization factor was included in the model. This is likely because all but the most upstream channelized segments were given a value of zero for the distance from upstream channelized reach, so segments with lower distances from upstream channelized reaches were more likely to be channelized, and thus have less erosion. Stream order was significant when included in the place of watershed size in the model. However, the two factors are different ways of explaining stream size. When watershed size is included in a model with stream order, stream order no longer has a substantial correlation with bank erosion. Other variables, such as floodplain width, change in watershed size, and distance from upstream confluence were not significant in the bivariate or the multiple linear regression, indicating that either they do not have an effect on streambank erosion, or that either the variability of these variables within this watershed, and/or measurement errors inherent to this study, did not allow detection of a significant effect on erosion.

Discussion

The objectives of this study were to quantify the extent of streambank erosion in the Onion Creek Watershed and assess the effects of riparian and watershed-scale variables as controlling factors in that erosion. In Onion Creek and its tributaries, 24.3% of the banks were severely eroding. This is similar to Wendt's (2007) study of random reaches on Onion Creek, which found less than 40% severely eroding streambank on 90% of surveyed reaches. As a comparison, Zaimes et al. (2008) found an average of 25% severely eroding bank length in a watershed with a similar land use to Onion Creek and Tufekcioglu (2012) found an average of 23% severely eroding stream length on other lower-order Iowa streams with largely row-crop watersheds. These numbers are all close to but somewhat higher than the 20% cutoff below which a stream can be considered stable (Simonson et al 1994). Below a 20% severely eroding streambank level, erosion that occurs will not overwhelm a stream system but will instead provide important structural diversity (Florscheim et al. 2008, Piégay et al. 2005). Because Onion Creek's % of severely eroding streambank is near the 20% level, it is relatively healthy according to the metric of Simonson et al., especially given that our survey of severely eroding streambanks was conducted in the months following a major flood in the Onion Creek watershed (Barnes and Eash 2012). However, there are significant reaches of the creek with values much higher than 20% (Figure 3), indicating these sections are not in equilibrium.

In the model of streambank erosion created from this study, important factors were width of riparian vegetation, watershed size, distance to downstream flow restrictions, channelization, length of upstream channelized reach, and an interaction effect between channelization and the length of upstream channelized reach.

The factor which explained the most variation in percent eroding streambank was watershed size. Prestegaard (1988) and Lawler et al. (1999) also noted the importance of watershed size in bank erosion and a multi-stream study in Canada that related increasing stream size with increased rates of channel movement (Nanson and Hickin 1986). As to the width of riparian land use, many researchers have found no significant correlation between riparian vegetation width and streambank recession rates (Laubel et al. 2003, Kronvang et al. 2012). However, the data from Onion Creek indicates a significant negative correlation between riparian vegetation width and the extent of streambank erosion. While stream water only contacts the roots and shoots of vegetation right on the bank, a possible explanation for our results is that vegetation not directly in contact with stream water will have a hydrological effect on the stream bank. Nearby perennial vegetation will remove more water from the soil than an annual cropping system, stabilizing streambanks by increasing the matric suction of the soil (Simon and Collison 2002). The wider the zone of perennial vegetation is, the greater its hydrologic effect. In addition to any potential hydrologic stabilization, a wider zone of perennial vegetation will increases wildlife habitat (Bentrup and Kellerman 2004), and reduce pollution from overland flow (Bren 1998, Lee et al. 2003, Tomer et al. 2003). This latter function would help reduce the high delivered sediment load within Onion Creek predicted by Wendt (2007).

Another significant factor explaining streambank erosion within Onion Creek was channelization. Yan et al. (2010), in discussing historical decreases in sinuosity, mentioned how straightening meandering channels increases channel slope and thus likely increases erosion. According to traditional models of channel evolution, this erosion will occur within channelized reaches (Schumm et al. 1984, Simon and Hupp 1987). However, at the site of channelization, streams are straight, with lower turbulence, counteracting the increase in gradient. As a result, many studies have found less erosion and channel migration in straighter stream sections (Hooke and Yorke 2010, Robbins and Simon 1983, Schilling and Wolter 2000), similar to the survey on Onion Creek. Palmer (2008), in attempting to explain increased erosion in lower-watershed, forested sections of Walnut Creek in central Iowa, speculated that perhaps the increased erosion was a result of the increased stream power caused by a large amount of channelization upstream of those forested sections. This relationship was inferred in our results with the inclusion of "Upstream channelized reach length" in our multiple linear regression model of streambank erosion.

Our observations within Onion Creek also indicate a relationship of decreased erosion approaching a downstream flow restriction. These observations are in line with Martin and Pavlowsky (2011), who found that just upstream of dams, stream segments were more likely to be accumulating sediment and less likely to be migrating. Simon and

Darby (2002) and Julian et al. (2012) also found that erosion was reduced upstream of grade control structures. However, caution should be taken in interpreting these results as a prescription for drop structures and other stream grade control structures, since if a stream is already destabilized, there may be increased erosion downstream of such structures (Simon and Darby 2002).

Other factors which we thought may be important explanatory factors for the extensiveness of severely eroding streambanks were not included in the multiple linear regression model. Chief among these was the type of riparian land use. Riparian vegetation type is often a primary concern in bank restoration and our failure to find a significant effect of vegetation type contrasts with a good deal of other research in Iowa and Missouri. For example, a study on a central Iowa stream using the same RASCAL assessment found the lowest bank erosion rates in riparian forest buffers, as compared to row crops, pasture, and grass (Zaimes et al. 2006). Other studies have also supported these results, showing forested reaches to be most effective in reducing erosion as compared to pasture and row crops (Laubel et al. 1999, Zaimes et al. 2008), and in some studies, more effective than grass buffers (Kronvang et al. 2012).

In addition to studies of the overall effect of riparian vegetation, other studies have shown the benefits of specific vegetation types. Several studies have demonstrated that woody riparian vegetation will increase streambank stability due to the relative strength of tree roots (Simon et al. 2006, Simon and Collison 1992), their hydrologic stabilization of bank soils (Bosch and Hewlett 1982), and insulation from freeze-thaw destabilization (Stott et al. 2111). Further, the deep tree roots of many riparian species have been found to be useful in bank stabilization (Simon et al. 2006, Tufekcioglu et al. 1999). The effect of tree root strength was visually noted in our assessment, as tree roots were better able to slow the rate of recession compared to pasture grass (Figure 8).

However, the optimal species composition is subject to considerable debate (Montgomery 1997). Figure 8 also shows tree roots being undermined by the channel depth. When a stream cuts below the rooting zone of riparian vegetation, the tensile strength provided by roots is no longer effective, as noted by Thorne et al. (1998). Further, Tufekcioglu et al. (2003) documented greater amounts of fine live roots in riparian soils dominated by switchgrass (*Panicum virgatum* L.) compared to poplar (*Populus* x *euroamericana* “Eugenei”), indicating that grass roots may provide greater streambank stability than woody species. In the field, many studies have found reaches with riparian forests to have greater rates of streambank erosion (Boothroyd et al. 2004, Davies-Colley 1997, Murgatroyd and Ternan 1983, Trimble 1997). This observation has been attributed to the destabilizing weight of large trees along banks (Thorne et al. 1998), the turbulent effect of large woody debris (Abernethy and Rutherfurd 1998, Ebisemiju 1994, Trimble 1997), and the shading of undergrowth vegetation leading to exposed, vulnerable banks (Keim and Schoenholtz 1998). Allmendinger et al. (2005) have further noted that grassy riparian vegetation promotes more sediment deposition than forest because dense stands of grass will better trap flowing sediment. Trimble (1997) has gone as far as promoting the removal of trees in favor of grass to reduce sediment export from streams.

In contrast to the studies above, data from Onion Creek found that riparian land use was not correlated with the incidence of streambank erosion. Moreover, an apparent bivariate relationship between riparian land use and streambank erosion was no longer significant when other factors such as watershed size and channelization were considered. The relationship between riparian land use and streambank erosion warrants further study, but researchers should be aware of other factors which may cause both a change in vegetation and erosion frequency. Landowners may prefer grass along a channelized reach to maximize row-crop acreage and trees are a more common riparian land use along larger water bodies. Both of these trends were seen on Onion Creek and a careful consideration of multiple factors and an awareness of the social and economic causes of riparian land use should lead to a clearer picture of the causes of increased erosion.

In the RASCAL survey, two important points of interest were sediment bars and log jams. These are factors we did not consider in our analysis but which may be quite important when examining movement and storage of sediment in stream systems. The frequency and size of sediment bars can be a sign of sediment overload from overland flow or other upstream sources and can also show a stream's stage in the channel evolution process, with more bars in an aggrading channel and less in an incising one (Schumm et al. 1984). Log jams are also potentially important factors in stream hydrology and sediment movement (Figure 9), creating structural diversity and locally increasing the turbulence and erosiveness of a stream (Anderson et al. 2004, de Paula et al. 2011, Murgatroyd and Ternan 1983, Sovell et al. 2000, Trimble 1997).

Unfortunately, there were no *a priori* criteria assigned to designate a log jam or sediment bar and the degree to which flow was restricted by log jams was not recorded. While the work of de Paula et al. (2011), where researchers noted the length and diameter of each piece of woody debris, is likely too precise for stream assessment such as RASCAL, some intermediate level of precision, such as an estimate of the percent of bankfull area blocked by a logjam, could be useful in the analysis of the effect of large woody debris in a stream system.

Similarly, in future RASCAL assessments, a size cutoff should be established for deciding whether to mark sediment bars, and ideally, the height, length, and width of the bar should be noted along with defining characteristics. Further, to avoid variation in the data set caused by inundation of sediment bars, the assessment of all reaches should be carried out as much as possible at similar flow levels, ideally at ones low enough to note major sediment bars. By more carefully surveying sediment bars and log jams, better conclusions could be made about their relation to bank and channel instability.

Soil type is another potentially important factor in the rate and nature of streambank erosion (Hooke 1980, Knapen et al. 2007, Schilling et al. 2009, Simon and Rinaldi 2000), but it was not considered as an explanatory variable in this study since 38 of Onion Creek's 42 km were bordered by Coland and Spillville, two very similar alluvial soil mapping units (Iowa Cooperative Soil Survey and IDNR Geological Survey 1998). However, it is nearly certain that there is actually more variation in streambank soils than is shown on the Soil Survey. For example, Schilling et al. (2009), in a study on bank soils in Walnut Creek in central Iowa, noted that the channel had cut through multiple alluvial members, including paleosols and post-settlement alluvium and that each alluvial member would have a different resistance to bank erosion. Though we have not yet completed a survey of bank soils, we have found evidence of soil types other than Coland and Spillville, noting horizons with high clay content and strong angular blocky structure. Soil mapping units do not appear to accurately represent the alluvial members present on the streambanks of Onion Creek and similar stream systems and an analysis of the effect of soil type may require a field assessment of actual streambanks.

A final issue with the RASCAL survey is a lack of precision in the erosion assessment. One of the major markers of severe erosion is bare banks (NRCS 1998), which indicate vegetation has been washed away. However, in densely forested reaches, shade from trees may prevent an understory from growing. This lack of vegetation may cause banks to be more vulnerable to erosion, but it does not necessarily mean that banks are actively eroding. In a study on streams throughout Iowa, banks marked as severely eroding in riparian forest buffers had lower recession rates than other riparian land uses (Zaimes et al. 2008). The forests on Onion Creek are not planned riparian forest buffers and it is possible average recession rates of eroding streambanks may not follow a similar pattern to that seen by Zaimes et al. 2008. Other pin plots established on banks mapped as severely eroding have shown effectively the same rate of bank recession throughout vegetation types (Willet et al. 2012). However, banks mapped as severely eroding may not all have the same recession rate of 0.122 meters/year given by the NRCS (1998), but vary depending on vegetation type or other stream characteristics. The use of RASCAL to assess stream conditions is, in some regards, just a starting step in the analysis of stream and bank conditions. In our final multiple linear regression model, only 29% of the variation in severely eroding streambank incidence was explained, leaving 70% unexplained by the factors we used. By combining a RASCAL survey with assessment methods at other temporal or spatial scales, researchers should be able to better explain the erosion occurring on a stream system.

Summary and Conclusions

Approximately one quarter of Onion Creek streambanks were severely eroding. In analyzing the variation in the distribution of these severely eroding streambanks, we created a five-factor model showing greater amounts of erosion when a stream segment had a narrower buffer from row crop, a greater distance above a downstream flow restriction, a larger watershed, and if the reach was not channelized, when preceded by a longer upstream channelized reach. This indicates that, at least in Onion Creek, the effect of vegetation type on erosion is not as pronounced or apparent as that of hydrologic factors. Streambank stability and erosion should be checked on other streams and using other assessment methods to gain a better picture of the way in which streambanks are affected by their riparian and hydrological conditions.

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Tables and Figures

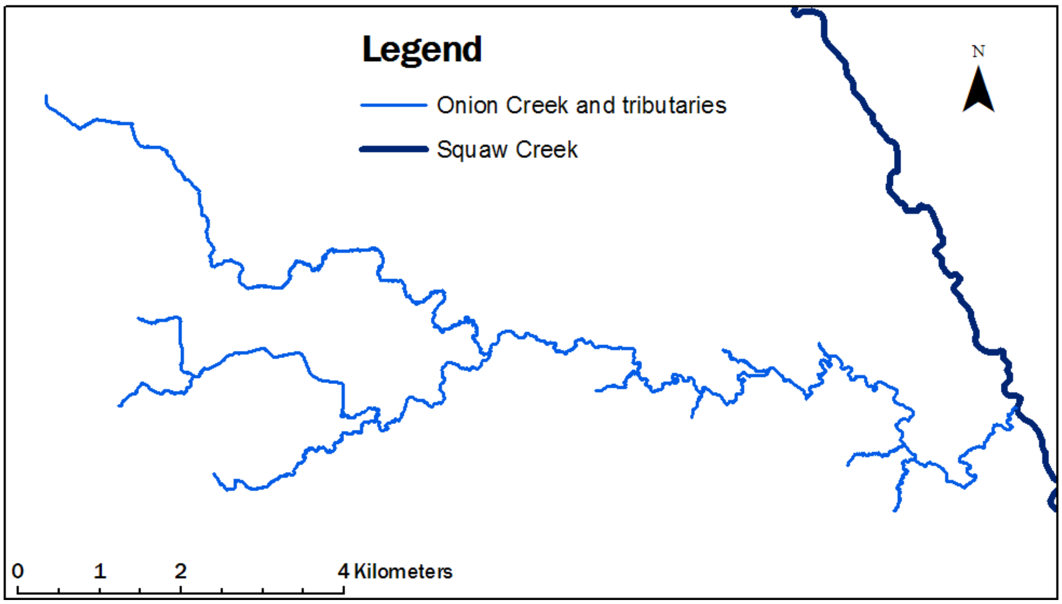

Figure 1: Onion Creek and tributaries, traced on ESRI's Arcmap™ from 2009 infrared photos.

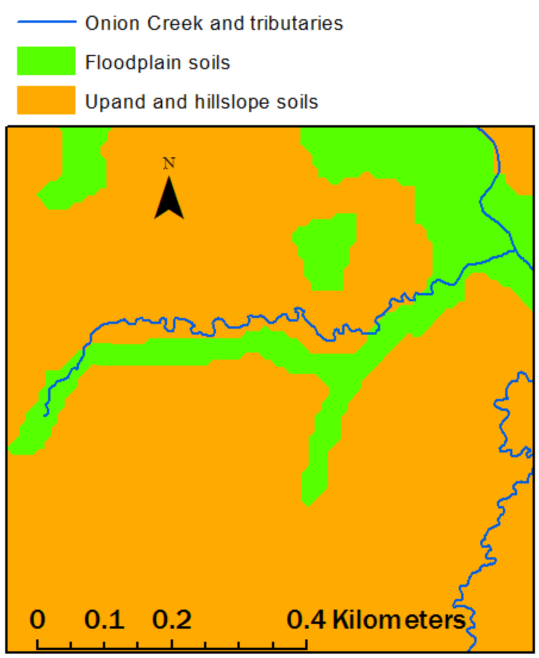

Figure 2: A section of Onion Creek overlaid on soils data. The western tributary was assigned floodplain width values based on the floodplain soils to the south.

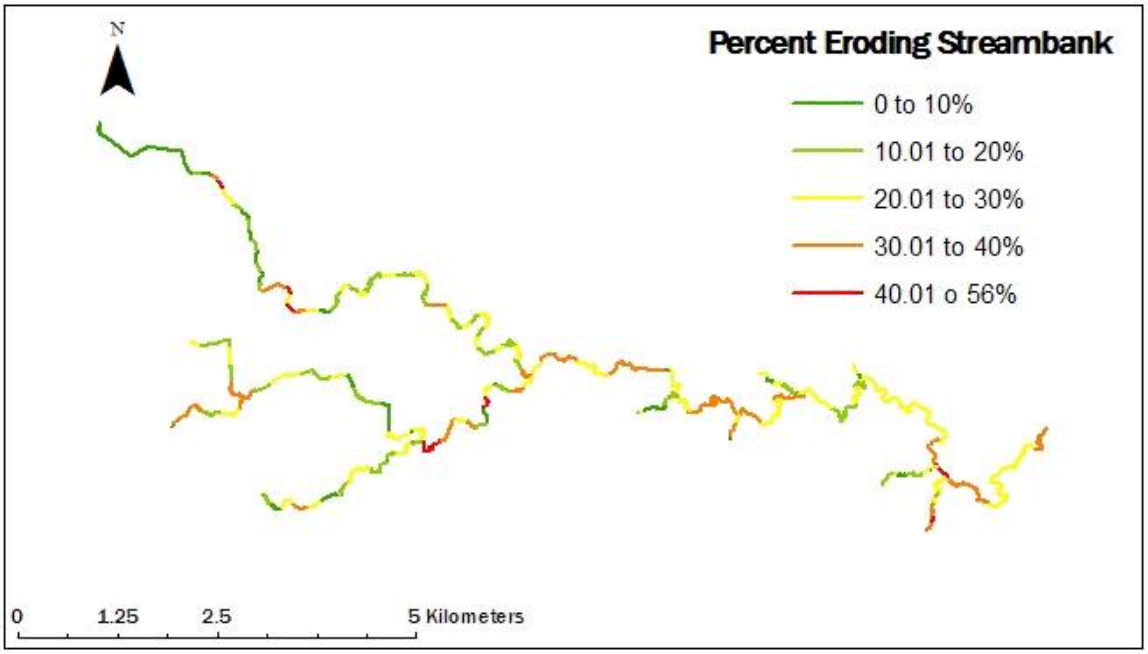

Figure 4: Percent severely eroding streambank, according to a RASCAL survey conducted fall 2010-spring 2011.

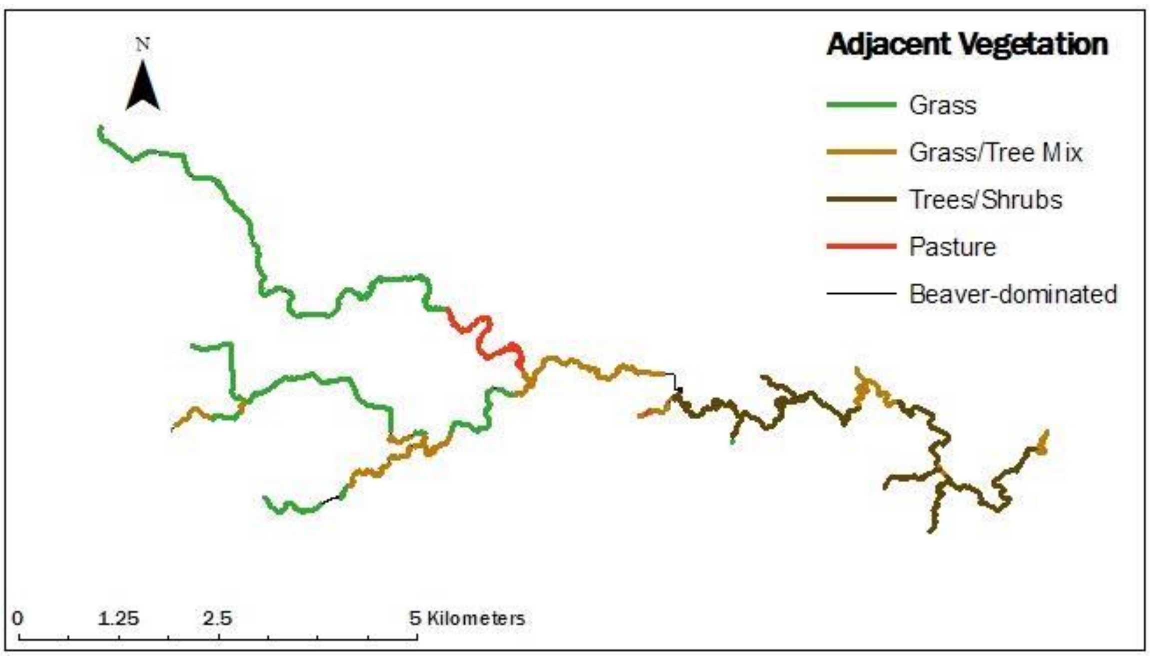

Figure 3: Riparian land use of Onion Creek and tributaries, based on fall 2010-spring 2011 survey, checked using 2009 infrared photos.

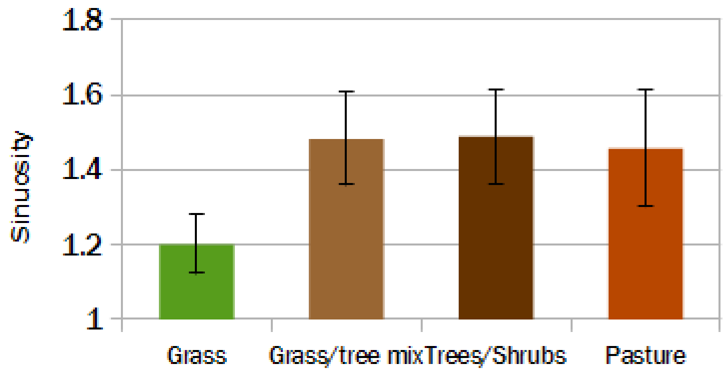

Figure 5: Sinuosity, measured as the ratio of stream length to distance between stream segment endpoints. Error bars show a 90% confidence interval. Grass sinuosity values are significantly less than the other riparian land use types (p<0.001).

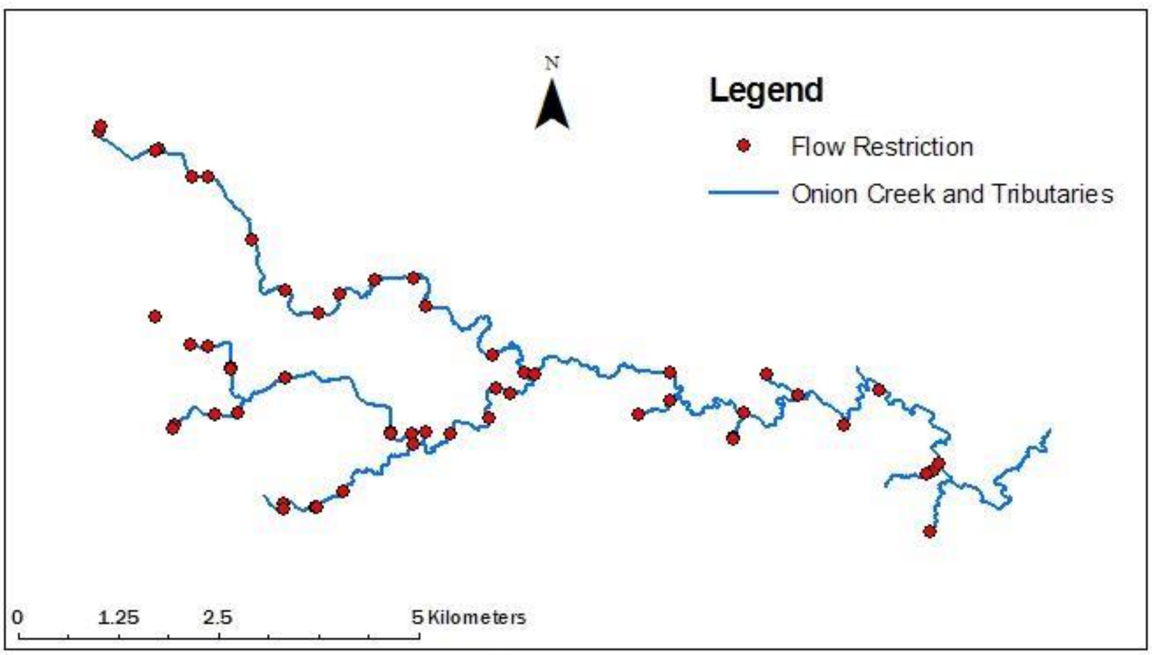

Figure 6: Flow restrictions on Onion Creek and its tributaries (bridges, culverts, drop structures and other points noted as flow restrictions are shown in red).

Table 1: Individual r^2 values showing correlation among % severely eroding streambank and explanatory factors, with p-values shown in parentheses. Values for which there is >90% confidence (α<0.0067) are bolded.

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 - % eroding streambank	**0.14 (<0.001)**	0.02 (0.065)	0.02 (0.06)	**0.11 (<0.001)**	**0.11 (<0.001)**	0.01 (0.12)	0 (0.6)	0.02 (0.02)	**0.06 (<0.001)**	0.08 (0.02)	0 (0.4)	**0.06 (<0.001)**	**0.06 (<0.001)**	0 (0.94)
2 - Riparian land use	1	**0.29 (<0.001)**	0.03 (0.08)	**0.20 (<0.001)**	**0.29 (<0.001)**	0.01 (0.62)	**0.13 (<0.001)**	**0.23 (<0.001)**	n/a	0.09 (0.03)	**0.11 (<0.001)**	**0.15 (<0.001)**	**0.23 (<0.001)**	**0.18 (<0.001)**
3 - Width of riparian land use		1	**0.14 (<0.001)**	**0.15 (<0.001)**	**0.44 (<0.001)**	0.02 (0.06)	0.01 (0.23)	**0.18 (<0.001)**	**0.18 (<0.001)**	0.02 (0.24)	**0.16 (<0.001)**	**0.18 (<0.001)**	**0.09 (<0.001)**	**0.07 (<0.001)**
4 - Floodplain width			1	**0.19 (<0.001)**	**0.38 (<0.001)**	0.03 (0.007)	**0.05 (<0.001)**	0.03 (0.01)	0.01 (0.056)	0 (0.52)	**0.23 (<0.001)**	0 (0.4)	**0.14 (<0.001)**	0 (0.6)
5 - Stream order				1	**0.61 (<0.001)**	**0.05 (0.001)**	0.03 (0.01)	0.03 (0.016)	n/a	n/a	**0.17 (<0.001)**	0.03 (0.011)	**0.13 (<0.001)**	0 (0.7)
6 - Watershed size					1	**0.05 (<0.001)**	**0.05 (0.001)**	**0.09 (<0.001)**	**0.09 (<0.001)**	0.05 (0.06)	**0.28 (<0.001)**	**0.08 (<0.001)**	**0.27 (<0.001)**	0.03 (0.014)
7 - Change in watershed size						1	**0.10 (<0.001)**	0.01 (0.06)	0.01 (0.092)	0.02 (0.25)	0.03 (0.023)	0 (0.43)	0.02 (0.057)	0.02 (0.026)
8 - Gradient							1	0 (0.33)	0.01 (0.31)	0 (0.6)	0.03 (0.018)	0.03 (0.011)	0 (0.6)	**0.05 (0.001)**
9 - Sinuosity								1	**0.40 (<0.001)**	0 (0.72)	0.03 (0.015)	0.01 (0.15)	**0.11 (<0.001)**	**0.04 (0.004)**
10 - Channelization									1	0 (0.61)	0.02 (0.044)	0 (0.99)	**0.15 (<0.001)**	**0.05 (<0.001)**
11 - Distance from nearest upstream confluence										1	0.09 (0.012)	0.04 (0.09)	0 (0.90)	**0.17 (<0.001)**
12 - Distance from nearest upstream flow restriction											1	0 (0.95)	**0.11 (<0.001)**	0 (0.95)
13 - Distance from nearest downstream flow restriction												1	0.01 (0.15)	0.03 (0.009)
14 - Distance below channelized reach													1	**0.04 (0.003)**
15 - Length of upstream channelized reach														1

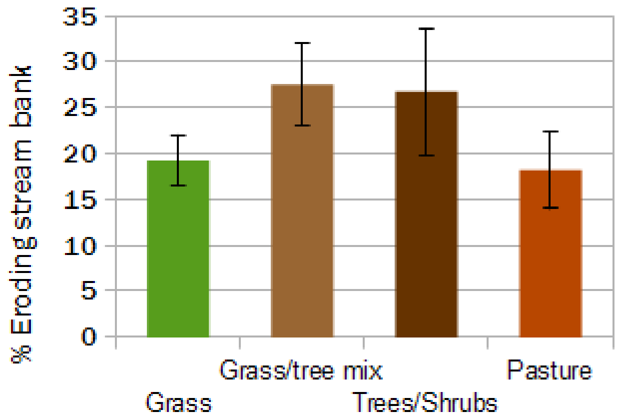

Figure 7: % Eroding streambank for all surveyed riparian land use types. Error bars represent the 90% confidence interval. Grass/tree mix and Trees/shrubs have essentially the same value, but both are significantly different from Grass (p<0.001).

Table 2: Standardized regression coefficients of each factor of the final multiple linear regression model represent the amount of variation explained by each factor in the model. The coefficient of multiple determination (0.29) is not the sum of the standardized regression coefficients because of substantial multicollinearity among the explanatory factors. All factors have a p-value <0.001.

Correlation coefficients of factors in the multiple linear regression model	
Factor	Standardized regression coefficient (r^2)
Width of riparian land use	0.07
Watershed size	0.11
Distance from downstream flow restriction	0.07
Channelization	0.30
Length of upstream channelized reach	0.10
Interaction effect: Length of upstream channelized reach, if segment is channelized	0.17
Coefficient of multiple determination (R^2) = 0.29	

Figure 8: Tree roots stabilizing bank soils. The 10-foot high bank, however, was deeper than the tree's roots. Photo taken August 2012.

Figure 9: One of the larger log jams on Onion Creek. Photo taken March 2011.

CHAPTER 3. CHANNEL MOVEMENT AND CHANGE ON ONION CREEK, 1939 TO 2009

Abstract

An analysis of decadal stream movement is presented for Onion Creek, a 2nd order Iowa stream. Changes in channel length and position are assessed using aerial photographs from 1939 and 2009 and channel evolution stage is determined by examining channel cross sections. Total stream length increased just 1.5% but there were significant local changes in channel length and position. Channelization (channel straightening and alignment) significantly reduced channel length and sinuosity in certain sections of the stream. Natural meander migration also occurred and channel extension was the most common result of that meandering. This predominance of meander extension and channels in the threshold and aggrading stages of the channel evolution process indicates a stream that is adjusting to excess energy. Stream reaches which were channelized prior to 1939 moved less in the next 70 years as did downstream reaches and those with narrower floodplains.

Introduction

The previous chapter described the effect of riparian vegetation, channelization and other factors on streambank erosion and deposition. However, these effects were observed at very short temporal scales. As noted by Couper (2004), studies based on short temporal scales should be aware of larger-scale processes, which may complement or counteract processes occurring during the short temporal scales. To better assess channel dynamics on Onion Creek, a longer-term analysis of change in stream channel morphology was warranted.

Three major ways in which stream morphology changes over time are meander migration, anthropogenic channelization, and channel evolution (Schumm et al. 1984). Channelization is the practice of digging a new, relatively straight channel, removing all meanders from a stream reach (Simon and Hupp 1987). In Yan et al.'s (2010) 1939-2002 study on the South Fork of the Iowa River, 28% of the change in the channel position of the main channel and 47 and 64% of the change in two of its tributaries occurred as a result of channelization in the 1950s, causing a reduction of sinuosity throughout the studied stream system. Channelization results in a decrease in channel length, an increase in channel gradient, and a decrease in channel roughness. The reworking of a stream channel during channelization also often includes the digging of new drainage ditches to further accelerate the removal of water. Dredging and channelization increase stream power, which can destabilize stream systems (Schumm et al. 1984).

Meandering occurs as outside bends in the stream are undercut by the water column, causing the bend to move outward and downstream. The movement of meander bends can result in a number of different changes in channel position, conceptualized by Martin and Pavlowsky (2011) (Figure 1). The classic meander bend will extend until its ends eventually meet each other and form a cutoff. In a translation movement, the bend will migrate downstream as sediment collects at the upstream end of the meander bend, pushing the water column away from the old channel location (da Silva et al. 2006). Occasionally, a buildup of sediment in the center of a relatively straight reach will create a megabar. In response, the channel migrates laterally, creating a new bend (Martin and Pavlowsky 2011). Meandering does not usually occur at the same rate on all sections of a river, but is focused on certain rapidly moving active reaches, while other, usually straighter reaches, remain more stationary (McKenny et al. 1995).

Unlike channelization, meandering is a natural process, but the rate at which it occurs can be affected by human activities. The conversion of permanent cover such as forests and prairies to row crops causes an increase in the amount of water streams convey (Schilling et al. 2008). This additional water along with hydrologic alterations such as channelization, dredging, and tile drainage accelerate the rate and extent of meander migration and generally destabilize a stream channel (Knox 2006, Martin and Pavlowsky 2011, Schottler et al. 2013, Schumm et al. 1984).

A destabilized stream system will often go through a characteristic process of channel evolution to adjust to its new hydrological conditions. This process was characterized by Schumm et al. (1984), further developed by Simon and Hupp (1987) and others, and proceeds as follows: Following channelization or other changes which increase the amount or intensity of water flowing through a stream channel, the stream bed will typically incise until the banks reach a threshold height of bank stability. At this point, the beginning of the threshold stage, mass failures of bank materials produce high levels of sediment which is then carried away by the stream. The threshold stage is followed by the aggradation stage, in which sediment supply and stream power become more balanced, sediment from mass failures begins to accumulate in the bed of the channel in alternating bars, and a meandering thalweg develops. In the final restabilization phase of the channel evolution process, this meandering thalweg matures and forms a new meandering stream in quasi-equilibrium with its environment.

This process of evolution is a model and streams may change differently depending on soil type, land use, and other factors (Andrews 1984, Nanson and Hickin 1986). Still, by comparing a stream channel's current condition to the model, an assessment can be made of that channel's stability (Simon and Darby 1997, Zaimes et al. 2006).

In addition to an assessment of channel evolution stage, there are several different ways of measuring changes in channel morphology. In the very long term, studies of floodplain form and sediment deposits can be used to interpret a stream's history at levels up to 15,000 years, as described by Lawler (1993). At a shorter time scale and requiring less field work, researchers have also compared changes in streams using aerial photos. On large rivers, mappers trace the banks of the channel and determine the change in channel width over time, such as in Bartley et al.'s (2006) study of the 140 km Daintree River in Northern Australia. Another method, used by Yan et al. (2010), measures change in the position of the channel centerline. This method was also used to measure change in Squaw Creek and its tributaries by Wagner and Gobster (2005). Results from Wagner and Gobster's study indicated that channelization and reductions in sinuosity have occurred in the Squaw Creek watershed during the last seventy years. Our study focuses on Onion Creek, one of the tributaries of Squaw Creek. This study quantifies the changes Onion Creek has undergone in the past decades and analyzes the characteristics of meander migration on the creek. This should aid in the interpretation of our stream survey from the previous chapter and strengthen our recommendations on conservation measures for the watershed.

Methods

As part of an assessment of current stream conditions, the 2009 Onion Creek stream channel was traced from color-infrared aerial photographs (Iowa Department of Natural Resources 2009a, b). Aerial photographs taken spring 1939 were developed into a mosaic by the Iowa Department of Natural Resources (2006a, b), downloaded from the Iowa State University GIS facility, and traced to create the 1939 stream map. Where county images overlapped, the ortho-rectified images for Boone County were used rather than the less precise geo-rectified Story County images. The same 1:1500 scale was used in both sets of photographs. The 2009 channel map was broken into stream segments with lengths 20-30 times the stream width (Chapter 2). The 1939 stream channel map was divided into segments with endpoints in the same location as in the 2009 channel map in order to better compare changes in length and sinuosity (Figure 2). The major differences in mapping methods between the 2009 and the 1939 stream course was the higher resolution of the 2009 photographs. Also, headwaters and other locations of interest on the 2009 photographs could be field-checked, but no such option was available for the 1939 photographs. When the 1939 channel was unclear because of concealing tree cover or when it was ambiguous where the stream started, those sections of the 1939 channel and their 2009 counterparts were not included in subsequent comparisons.

Following Yan et al. (2010), we used the feature-to-polygon tool on ESRI's ArcMap 9™ to show the area of land the stream had moved across. Polygons created using this tool were classified according to the type of movement: undetermined, channelization, and meandering. The undetermined class was used where it was difficult to differentiate between mapping and digitization errors and stream movement, when the 1939 stream course was unclear because of tree cover, and for most polygons less than 200 m^2 (0.02 ha). Polygons were classified in the channelization group where newly dug ditches in the stream channel removed meanders, leaving behind a relatively straight stream reach. When the polygons created were due to natural meandering, they were further classified according to the scheme used by Martin and Pavlowsky (2011) (Figure 1): If the channel length decreased by more than 10%, it was labeled as a cutoff, if it increased more than 10%, an extension. When channel length didn't change, if the channel shape was shifted up or downstream it was labeled as a translation and if the change in the channel position was more of a lateral shift, a megabar.

The sinuosity of each stream segment was calculated by dividing the stream segment length by the linear distance between segment endpoints. The change in sinuosity from 1939 to 2009 was calculated for each stream segment. Also, the percentage change in each segment length from 1939 to 2009 was recorded and the absolute value of that change was calculated and reported as channel activity. To compare these results with those from a 2010-2011 survey of eroding streambanks and riparian characteristics (Chapter 2), the effect of factors noted in the previous chapter (watershed size, floodplain width, and sinuosity) on change in length and channel activity was examined. Any sections channelized between 1939 and 2009 were removed from this examination, since the change in channel length was not due to the erosional and depositional processes of meander migration, but to the digging of a ditch. In doing this, the focus of analysis was on change which occurred as a result of natural meander migration. When segments were not clearly mapped in 1939, these segments were removed from the analysis as well. As a result, the analysis of the change in channel length and channel activity was carried out on 30 of the 42 total stream km.

As another method of analyzing decadal change, channel evolution stage (Simon and Hupp 1987) was assessed using channel cross sections, an analysis of bank characteristics, and evidence of channelization. Cross sections were measured at 33 points throughout the channel April 2013. In these cross sections, channel depth was measured every 0.5 meters moving across the stream channel. The presence or absence of mass wasting was assessed during a survey conducted fall 2010-spring 2011. Channelization was assigned as a characteristic when the stream shape was essentially straightened and broken into “new” and “old” channelization. New channelization had occurred between 1939 and 2009, while old channelized reaches were already straightened in 1939 and remained relatively straight until 2009. The width: depth ratio of each cross section was calculated and the difference in width: depth ratios among the above channelization groups was analyzed using Microsoft Excel spreadsheet software. Photos were taken at each cross section to aid in assessing the channel characteristics. From this data, we assigned a channel evolution stage to each assessed stream reach, following Simon and Hupp (1987).

Results and Discussion

As mentioned in the methods, certain sections of the 1939 stream channel were not possible to map accurately, as tree cover obscured the channel location. They and their 2009 counterparts, which had a cumulative length of 4.3 km (10% of the total channel length), were not included in comparisons of sinuosity and channel movement. Also, 544 meters of first-order channels existed in 1939 but not 2009, most of which (508 m) was from one tributary. Although field work to verify 1939 channel endings was not possible, this suggests that those channels were likely buried in tile. One 273 meter long tributary mapped in 2009 did not exist in 1939. This increase represents a lengthening of 1^{st} order channels (Figure 3).

Despite the loss of channel length at the ends of tributaries between 1939 and 2009, on the 90% of the channel examined, the total length of the Onion Creek channel system increased by 1.5% from 1939 due to a 2% increase in the length of segments which existed in both 1939 and 2009. First order channel length of the Onion Creek stream system increased by 8 % and second order channel length decreased by 4%. This corresponds to an increase in average sinuosity for first order channels and a decrease for second order. Looking at the average sinuosity of the entire stream, for segments that existed in both time periods, the average sinuosity (1.4) was effectively the same, unsurprising given the small change in total length. These results contrast with Wagner and Gobster (2007), who found that the entire Squaw Creek stream system had a 4% decrease in stream length for channels that existed in 1939, but an overall length increase of 9%. This length increase was from extension of headwaters, which counteracted stream length lost as a result of a 12% decrease in sinuosity (Wagner and Gobster 2007). On a different lower-order Iowa stream system, Yan et al. (2010) also saw a decrease in channel sinuosity from 1939 to 2002.

Though overall, Onion Creek's stream length changed by just 1.5% from 1939 to 2009, there were substantial changes in local stream length and morphology (Figure 4). Forty-three percent of the 2009 stream segments were essentially the same as in 1939 (2009 length was between 90.01 and 110% of the 1939 length). Generally, these sections did not have a balance of extension and cutoffs as much as a complete lack of movement (Figure 5). Fifty seven percent of the stream channel substantially changed in length. Nineteen percent of the 2009 stream was shorter than its 1939 equivalent, largely due to channelization (90% or less of the 1939 length) (Figure 2). Thirty-three percent had 110-150% the length than the 1939 stream, and 5% had over 150% of the length of their 1939 counterpart (Figure 6). After removing stream segments which experienced channelization between 1939 and 2009, the average increase in stream segment length in 2009 was 11% and the average channel activity was 16%. In other words, the average stream segment that only experienced meander migration between 1939 and 2009 changed in length by 16%. That change was more likely to be an increase in length as meander bends extended.

Classification of polygons created by overlaying the 1939 and 2008 channel confirm results from the analysis of change in channel length. The sum area of undetermined polygons was 7 ha. Eleven ha, or 39% of the determined polygon area was due to channelization. Of the 61% of the polygon area from meander migration, the greatest total polygon area was from extension. Extension, which increases channel length, accounted for 7.5 ha or 27% of the determined polygon area. Translations (4.1 ha, 15% of the polygon area) and megabars (2.8 ha, 10%), which result in no net change in channel length, created the next largest polygon areas. Finally, cutoffs of meander bends, which decrease channel length, accounted for 1.4 ha of polygon area, just 9% of the total determined polygon area.

The various types of channel movement are clustered in zones throughout Onion Creek (Figure 4). As mentioned above, most reductions in sinuosity and stream length were due to anthropogenic channelization. Most of this channelization occurred on a long second-order section of the southern tributary of Onion Creek (Figure 2). A 1.5 km section of some of highest percent increases in stream length (Figure 6) is just downstream of this channelized reach. This is unsurprising, as the channel has dissipated energy concentrated in the channelized reaches by increasing the length and decreasing the gradient of downstream reaches, also seen by Palmer (2008) and in Chapter 2 of this thesis. On the rest of the stream, zones of channel length increase are interspersed with relatively stable reaches such as that shown in Figure 5. This pattern of active and stable reaches has been reported in several other studies (Knox 2006, Martin and Pavlowsky 2011, McKenny et al. 1995).

As noted above, channelization in certain sections of the stream system and extension of meanders in others resulted in little change in the average stream length and sinuosity on Onion Creek. Seeing a similar lack of change in sinuosity and stream length in their studied river system, Martin and Pavlowsky (2011) attributed this to a self-organizing process of a system in equilibrium, as new meanders extend and others are cut off. Similarly, according to the channel evolution model (Simon and Hupp 1987) a stable sinuosity and stream length indicate a stream which has not been disturbed or has recovered from disturbance.

However, the changes on Onion Creek do not indicate stability. Where stream length and sinuosity decreased, it was usually because of the creation of a new channelized reach. This is stage 2 of Simon and Hupp's (1987) channel evolution model, which tends to be followed by incision, bank erosion, and channel instability. When the stream was allowed to migrate naturally in response to hydrological pressures, the dominant type of channel movement was channel extension. In other words, when changes are occurring as result of the energy-balancing process of meander formation, the stream is creating more meanders and increasing in length and sinuosity, which decreases the channel gradient. Over time, a straightened stream will move towards its original sinuosity to return to a quasi-equilibrium condition (Schumm et al. 1984). Although meander migration has increased sinuosity on Onion Creek in the past 70 years, landowners have dug new ditches to counteract this process. The average sinuosity has remained the same and the channel slope remains higher than its pre-modified condition. Because of this, Onion Creek has likely not reached equilibrium, especially as extensive changes in land use and drainage accentuate channel instability (Schottler et al. 2013, Schumm et al. 1984).

The analysis of channel evolution stage also showed a stream that was not in equilibrium. Most of the analyzed cross sections showed a stream in the threshold or aggradation phase of the channel evolution process (Simon and Hupp 1987), as seen in extensive slumping and near-vertical banks (Figure 7). These phases are also associated with meander belt development, which is seen in the way extension dominates meander migration.

As mentioned above, 43% of the channel stayed essentially the same length (Figure 5). Many of these inactive reaches were already channelized in 1939 (Figure 8) or started out straight as recently dredged drainage ditches. Such cases represent channelization, but channelization which was not included in the quantitative assessment of change, as it occurred prior to 1939. The effect of that channelization can be seen in that the channelized reaches in Figure 8 have seen little change, while the section to the west, which still had some meander bends in 1939, saw those bends migrate and amplify. On the 30 km of analyzed stream, the average increase in channel length was 8 % less for reaches which were straightened in the 1939 photos ($p=0.022$), and the channel activity, or absolute value of the change in segment length, was 10 % less for channelized reaches ($p<0.001$), a trend of inactivity on straight reaches similar to that seen by McKenny et al. (1995).

We were not able to make many conclusions about variability in the width: depth ratios because of the small number of cross sections taken and the high variability in their dimensions. Among the channelization groups, reaches which were channelized before 1939 and remained straight until 2009 had lower width: depth ratios than those that had never been channelized, but no other comparisons were significantly different (Figure 9). This indicates, again, that channelization destabilizes a stream, though it was interesting that sections channelized more recently had width: depth ratios nearer those that had never been channelized. It is difficult to compare width: depth ratios found on Onion Creek with that of other literature, as the value of a stable width: depth ratio depends on the parent material and hydrology of a site (Schumm et al. 1984). Still, the fact that the channels appear to be in the threshold and aggrading phase of the channel evolution model and the extending meanders of the stream channel indicate that the cross sections noted here are not stable.

This assessment was carried out to observe Onion Creek at a broader temporal scale than the previous chapter and compare the results of analyses at these two scales. Chapter 2 noted that streambank erosion was more prevalent in stream reaches with a narrower buffer, a greater distance above a downstream flow restriction, a larger watershed, and when preceded by a longer upstream channelized reach. Because buffer vegetation, buffer width, and flow restrictions changed between 1939 and 2009, the effect of these variables on the degree of change from 1939 to 2009 could not be analyzed according to our methods.

However, we saw lower amounts of both erosion and change in channel length on channelized reaches and noted substantial meander migration on already meandering reaches (Figure 6), confirming the effect of channelization on stream dynamics. The percent change in channel length and channel activity in this period both decreased with increasing watershed size ($p<0.001$ for both statistics). This contrasts with the results of the previous chapter as well as with the results of other researchers such as the 21 year study by Nanson and Hickin (1986), who saw increased channel migration with increasing watershed size. This could be due to variation in the units of analysis. Stream segments had lengths 20-30 times the bankfull width. Downstream reaches, having wider channels, had longer segment lengths and so would require a greater amount of bank erosion to substantially increase that length. Also, upstream reaches of Onion Creek are generally more channelized and so erosion will act to reintroduce meanders to these reaches, following the channel evolution process (Simon and Hupp 1987). The downstream sections are also adjusting to the changed hydrology of Onion Creek, but were historically less channelized, so their adjustment process may be characterized less by channel migration and more by widening. A final reason for the difference between the two chapters' results is potential errors in the characterization of severely eroding streambanks. The downstream reaches are more likely to be forested, which causes shady, bare banks, which may falsely appear to be eroding. Whatever the reason for the difference in conclusions between the two scales of analysis, that difference calls for caution when interpreting results at either scale of analysis.

Though floodplain characteristics had no significant effect in Chapter 2, an increased floodplain width was correlated with average increase in stream segment length and increased channel activity ($p<0.001$). Martin and Pavlowsky (2011), seeing similar results, concluded this was due to the confining nature of their bedrock valley walls. Except for at the far downstream portions of the watershed, valley walls consisted of glacial sediment rather than bedrock, but the relation seen indicates these valley walls also confine and slow channel movement. Also, where the stream bed reaches bedrock, the stream cannot easily expand bankfull area, and so if the stream is not restricted by the bedrock valley walls, it is more likely to migrate to deal with excess stream energy. The restricting effect of valley walls was not seen at the shorter time scale of Chapter 2, possibly because the marking of eroding streambanks may not accurately portray the rate of channel movement, as in narrower valleys, the stream is likelier to butt against valley walls which then appear to be rapidly eroding, but are actually slowing both erosion and channel movement. Further work examining the actual erosion rate of valley walls may be necessary to assess this factor.

Looking at a direct comparison between the measures of channel change in Chapter 2 and 3, stream segments which had a greater increase in segment length between 1939 to 2009 were likely to have a higher percentage of severely eroding bank length than other stream segments in the 2010 stream survey (r^2=0.037, p=0.017). There was a similar but less significant relationship with channel activity (r^2=0.023, p=0.061). These results indicate that processes causing change in the channel in the last 70 years continue to be in effect on the present-day stream channel. However, the small correlations, as well as the contradictions seen in results in regards to watershed size and floodplain width, indicates that one method of analyzing channel activity cannot be taken as a proxy for the other. In other words, the rate of past erosion and channel change may not relate to current or future change.

Beyond this, the metric of change in channel length may not fully encompass that change. Although all the types of channel meandering in Table 1 occur through streambank erosion, only extensions and cutoffs result in a change in channel length and when the two occur together, their effect on channel length will cancel each other out, despite the fact that this would be indicative of greater channel activity. Many of the sections with no apparent change did actually have little change (Figure 5), but there were stream segments where channel activity was not captured because of cutoffs (Figure 8). Again, bank erosion may cause channel widening rather than meander migration. Finally, as noted above, the assessment of the eroding streambanks may not accurately assess the rate of bank erosion, something that will be explored as this project continues and in the following chapter.

Summary and Conclusions

From 1939 to 2009, average sinuosity and stream length stayed essentially the same on Onion Creek. Locally, there were zones of significant channelization and extension-dominated meandering, while 43% of the stream showed very little movement (Figure 5). In regard to sections that weren't altered by channelization between 1939 and 2009, meander migration which changed channel length was greater in areas with greater sinuosity, wider floodplains and smaller watersheds. The first result confirms the relationship with sinuosity shown in the one-time stream survey of the previous chapter, while the latter two show differences which were not found by or contradict the results of the previous chapter. In other words, watershed size and floodplain characteristics effect channel movement measured at the 70-year timescale differently than that measured at one point in time, emphasizing the importance of using multiple means of analyzing change in a stream system. Finally, the predominance of extension as a meander movement type and channels largely in the threshold stage of the channel evolution process indicates that Onion Creek is adjusting to an excess of stream energy, suggesting continued channel instability. Riparian conservation practices on Onion Creek would do many useful things, including intercepting sediment and nutrients and providing habitat, but these conservation practices may not fully protect stream banks because of the destabilizing excess stream power.

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Figures

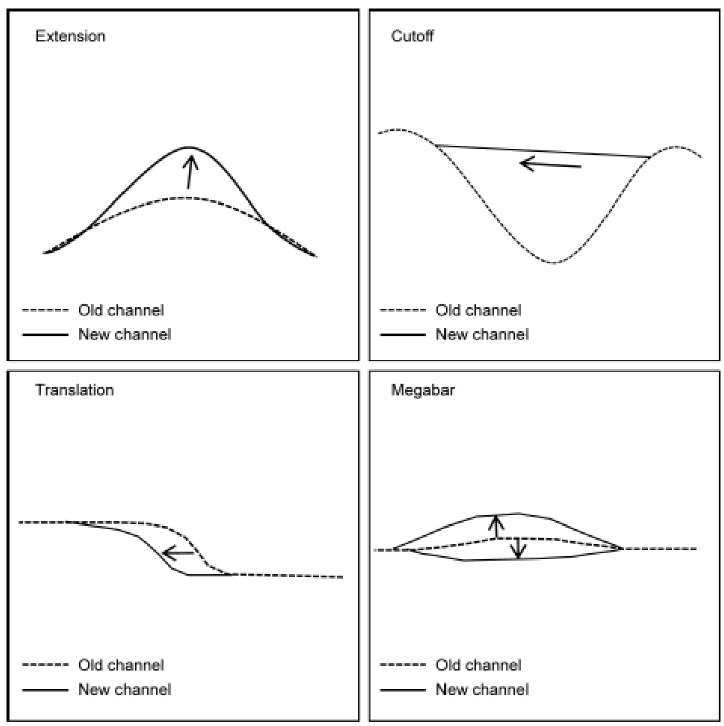

Figure 1: Models of meander migration from Martin and Pavlowsky (2011).

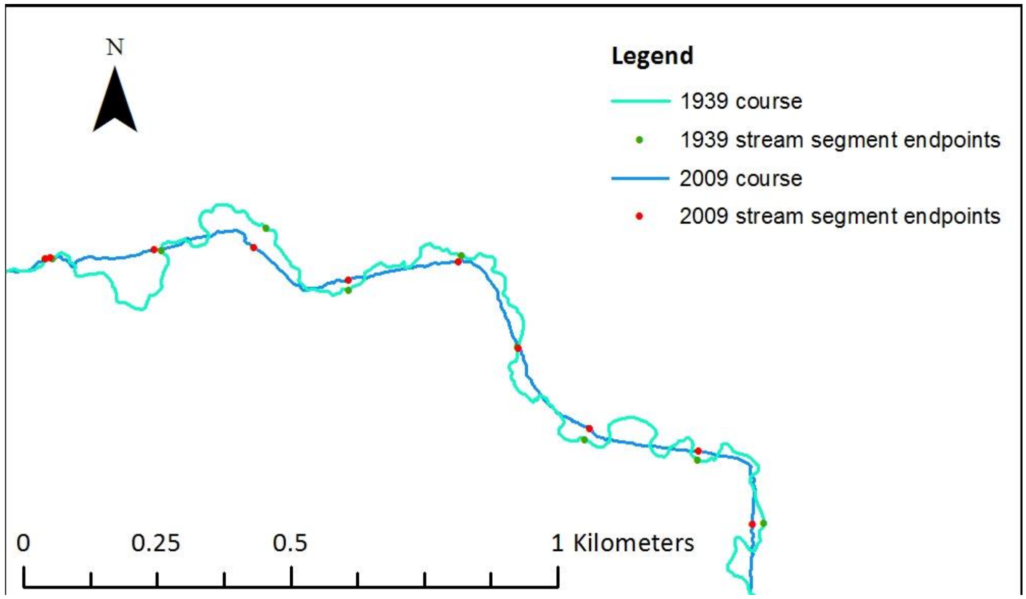

Figure 2: A section of Onion Creek channelized between 1939 and 2009. Green dots show the endpoints of 1939 stream segments and red dots show the endpoints of 2009 stream segments. The fall 2010-spring 2011 survey showed a low percentage of severely eroding streambanks in this section.

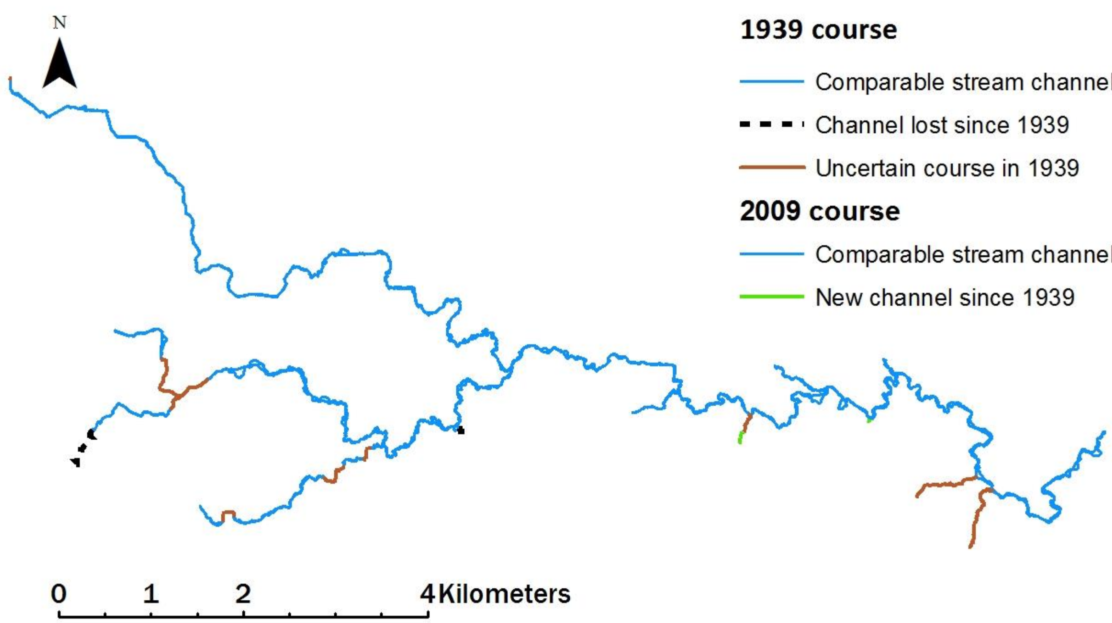

Figure 3: Onion Creek stream course. Red sections show areas not mappable for 1939. Dashed section (mainly one tributary) shows channel headwaters lost since 1939, green section (one tributary) shows a headwater extended since 1939.

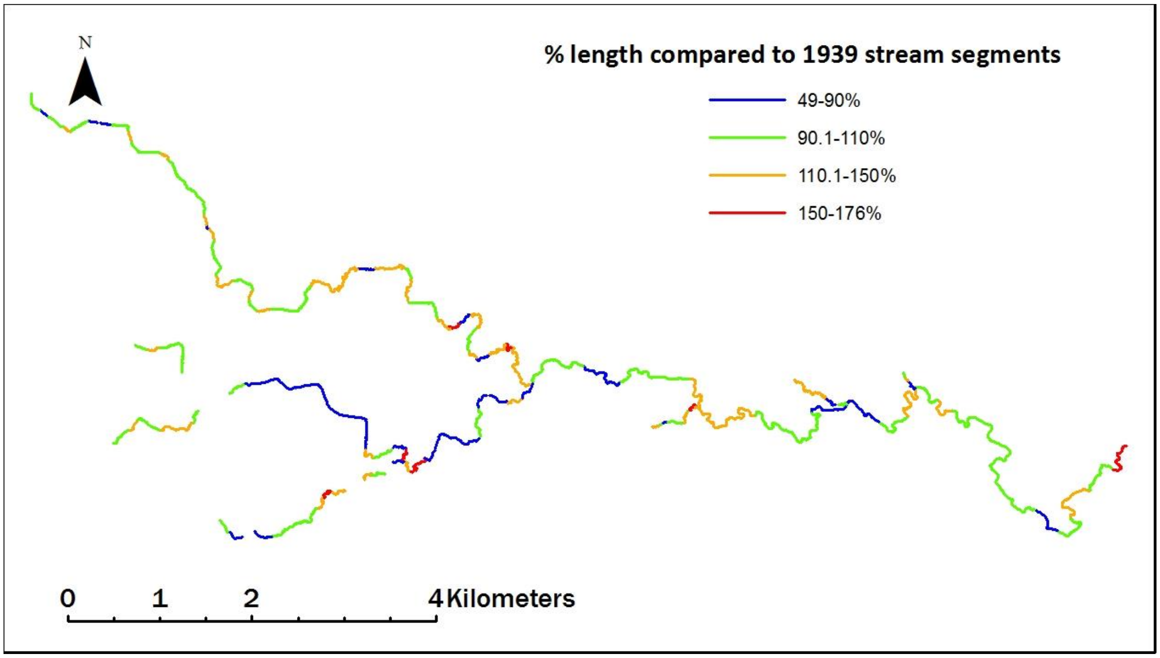

Figure 4: 2009 stream course, color-coded to show difference in length from 1939 course. Sections not mappable in 1939 are not shown.

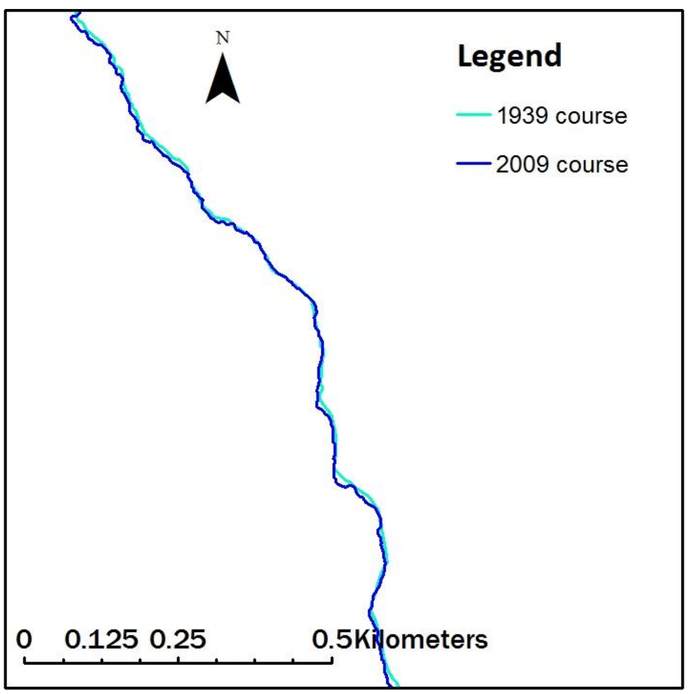

Figure 5: A first-order stretch of the Onion Creek stream system. This stretch is representative of stream sections which changed by less than 10% in length from 1939-2009, with little apparent meander migration.

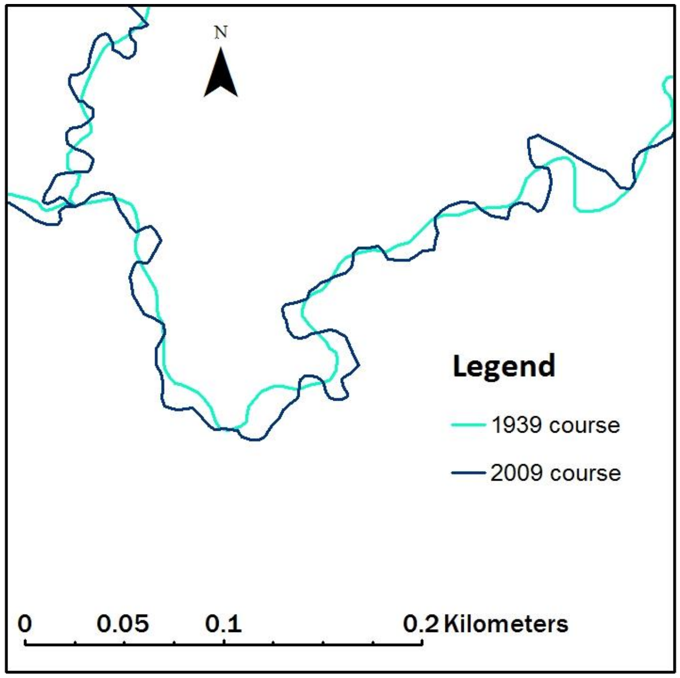

Figure 6: A second-order length of the Onion Creek stream system. 2009 channel shows extensive creation and extension of meander bends in the past 70 years.

Figure 7: A second-order section of Onion Creek with numerous slumps falling or fallen into the channel. Photo taken October 2012.

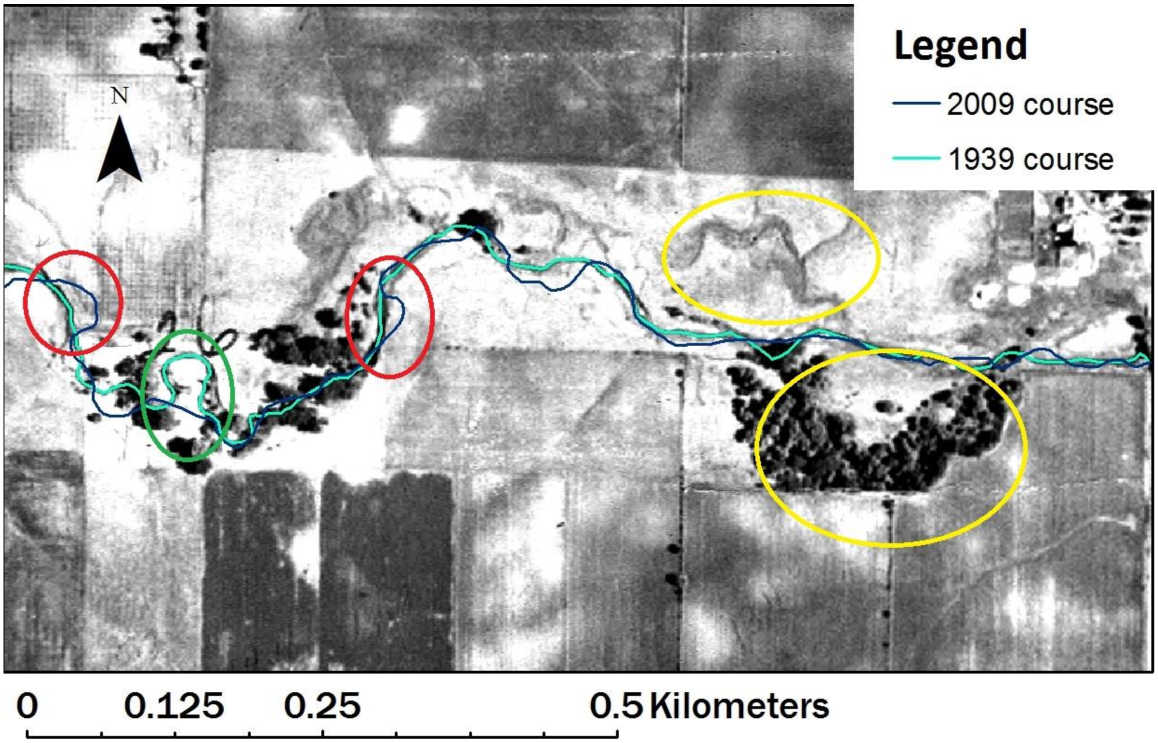

Figure 8: 1939 and 2009 Onion Creek stream course, overlaid on a 1939 aerial photo (Iowa Department of Natural Resources 2006, 1). A cutoff is circled in green, extensions in red. Two oxbows removed from the stream by channelization are circled in yellow.

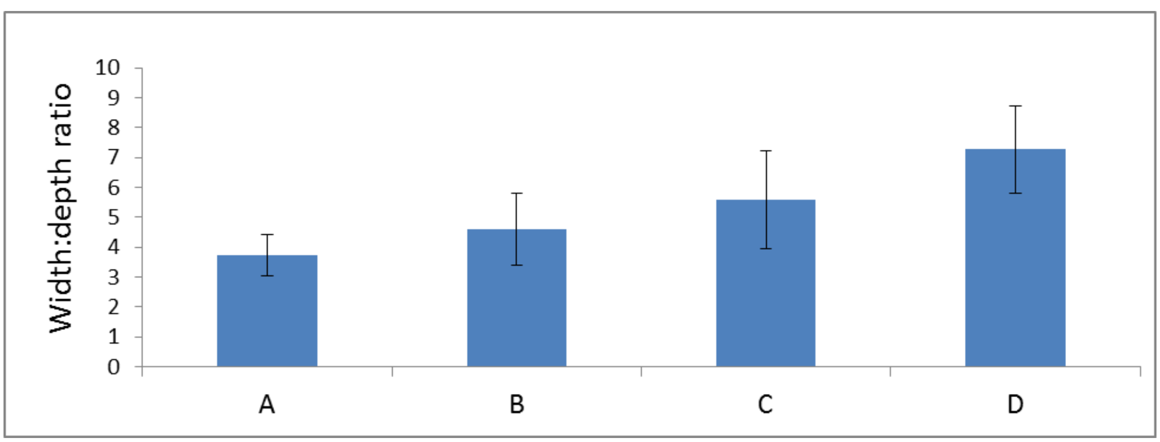

Figure 9: Width:depth ratios of channel cross sections on Onion Creek. A represents stream sections channelized before 1939 and remaining relatively straight in 2009, B represents stream sections channelized before 1939 but which developed meanders and increased by over 10% in length by 2009, C represents stream sections channelized between 1939 and 2009, and D shows cross sections that did not appear to be channelized before or after 1939. Only A and D were significantly different.

CHAPTER 4. FREEZE-THAW ACTION AND EROSION ON ONION CREEK STREAMBANKS

Abstract

A one and a half year study of erosion and deposition on severely eroding streambanks was conducted on Onion Creek, a central Iowa stream. A survey of streambank erosion on Onion Creek was followed by installation of erosion pin plots on a subset of severely eroding streambanks. These pin plots were measured October 2011, March 2012, October 2012, and April 2013. A subset of these pins was measured once a month and after major storms. A drought through much of the study period caused low water levels and low levels of streambank erosion. During winter months, the sub-aerial process of freeze-thaw action led to full or partial burial of many lower pins. Erosion by fluvial entrainment was measured on lower pins in the springs of 2012 and 2013, adding an estimated 1030 Mg of sediment to the stream system in 2012, with an additional 1290 Mg added from January to April 2013. South-facing erosion pins saw more activity as a result of freeze-thaw action during the second winter period but no significant differences were found between aspects in the summer or first winter periods. Adjacent vegetation and longitudinal pin position were not related to total erosion or erosion activity, though this may be due to the low amount of measured bank erosion.

Introduction

Suspended sediment and phosphorus are major causes of water quality impairment. Landscape-level conversion from perennial to annual vegetation, extensive drainage systems, and straightening of stream channels have altered the hydrology of Iowa streams and greatly increased channel instability (Schilling et al. 2008, Schottler et al. 2013, Schumm et al. 1984, Simon and Rinaldi 2000). This instability causes streambank erosion to contribute up to 92% of the sediment load of a stream system (Belmont et al. 2011). One Iowa study estimated that 14-64% of suspended sediment loads come from streambank erosion (Palmer 2008).

Other factors may also affect the rate of channel recession. North-facing banks were found to be more susceptible to freeze-thaw collapse than south-facing by Reid (1985), although Gatto (1995) suggested south-facing banks may experience more frequent freeze-thaw events. More generally, other researchers have found that factors such as discharge rates, bank soil type, and a stream's stage in the channel evolution process have an important effect on the rate of stream bank erosion (Schilling et al. 2011, Willet et al. 2012, Van Haaveren and Jackson 1993, Zaimes and Schultz 2011).

Although high rates of bank erosion are often caused by watershed-scale channel instability and increased peak discharge, streambank erosion may be mitigated with proper riparian management. Although there is some dispute about the optimal riparian land use (Montgomery 1997), planting a buffer of dense, deep-rooted vegetation has been found to reduce the rate of streambank erosion (Brown 1943, Haygarth et al. 2009, Prosser 2000, Schilling et al. 2011, Zaimes et al. 2008).

Because of the importance of streambank erosion to water quality, we are monitoring bank and channel instability on Onion Creek, a central Iowa stream. Onion Creek is the focus of an Iowa Department of Agriculture and Land Stewardship (IDALS) watershed project, as the watershed contributes high levels of sediment to downstream water bodies (Wendt 2007). Two major objectives of the IDALS Onion Creek Watershed Project are to assess streambank recession rates under different riparian land uses and to present an assessment of stream channel instability. In Chapters 2 and 3, stream channel instability in Onion Creek was measured at two temporal scales: using a rapid assessment of stream channel condition along length (RASCAL) and an analysis of multi-decade change in channel position and length.

Another, shorter-term method of measuring streambank change is erosion pin plots. According to Saynor and Erskine (2006), erosion pins were first used by Ireland et al. (1939) to measure erosion on gully banks. In this method, steel pins are installed horizontally into a bank and the change in the length of the exposed pin is used to measure the amount of erosion or deposition on that bank. This method gives a high temporal and spatial resolution (Zaimes et al. 2006), accurate within 5 mm with operator variance (Simon et al. 1999). A disadvantage of erosion pins is they measure change at one point on a bank and often neglect change on the bed, toe, and top of a bank, where pins are seldom placed (Figure 1, from Bartley et al. 2006). It has also been suggested that frost action or other disturbances may change a pin position (Couper et al. 2002), though this was not found to be a major factor in several studies (Couper et al. 2002, Hooke 1979, Stott et al. 2011). More seriously, erosion or deposition can entirely remove or bury a pin, increasing measurement error. Couper et al. (2002) discussed possible methods in the case of burial, one of which, used by Willet et al. (2012), is to give the exposed pin length a value of zero, ignoring any burial beyond the initial covering of the pin. This method underestimates deposition, as it does not account for further deposition after pin burial. For pins which have eroded away, researchers usually give an exposed pin length slightly less than the actual length of the pin, assuming that before the entire pin is entirely exposed, its own weight will pull it out of the bank (Kang 2012, Lawler et al. 1999, Willet et al. 2012, Zaimes et al. 2004, 2006, 2008). This, again, likely underestimates total bank activity, as erosion could have occurred beyond the length of the pin.

Even with these limitations, erosion pins are an efficient means of measuring short-term changes in streambanks. To that end, we installed and measured erosion pin plots on a sample of severely eroding streambanks in the Onion Creek stream system. This short-term measurement complements the results of the RASCAL stream survey from Chapter 2 and the historical assessment of channel movement from Chapter 3, provides an estimate of recession rate of severely eroding streambanks in Onion Creek, and determines the effect of land use and other riparian factors on that recession rate.

Methods

Onion Creek is a second-order, 42 km stream system in Boone and Story Counties in Iowa, flowing through Wisconsin glacial till. Its watershed is 5,700 hectares, 86% of which is in row crops, which are concentrated in the upper portions of the watershed. In fall 2010 and spring 2011, the riparian land use and location of severely eroding streambanks was mapped through the length of Onion Creek and its tributaries in a RASCAL survey following the methods of Schilling and Wolter (2000) (See Chapter 2).

Severely eroding streambanks were defined as banks with very low vegetative cover, severe vegetative overhang, and fallen trees and slumps. Banks with these characteristics are estimated to erode at 0.12 m (0.4 feet) per year (NRCS 1998).

Following methods used in similar studies in the Northeastern Missouri Claypan Region (Peacher 2011, Willet et al. 2011), we randomly picked 9 surveyed stream reaches ranging from 375 to 403 meters within each riparian land use of Grass, Grass-Tree Mix, and Tree-Shrub Mix on each side of the channel. Surveying both sides of the stream in each ~400 m reach, this resulted in a total bank length of ~7200 meters per land use. Pasture sites were not included since they did not cover enough stream length to be representatively studied. One site originally mapped as Grass was occasionally used as a pasture, resulting in only eight reaches with Grass as their riparian land use. In selecting the reaches, we made an effort to have a balance of first and second-order stream reaches for each riparian land use type. However, because grass dominated the upper reaches of the stream channel and forest the lower, the study design was not completely balanced between stream order and land cover type.

Erosion pin plots were installed in summer 2011 and measured October 2011, March 2012, October 2012, and April 2013, resulting in measurement of change through two winters and one summer season. A subset of the biannually monitored pins was chosen for a more intensive monitoring, similar to the methods of Lawler et al. (1999). Two random stream reaches within each of the three riparian land uses, representing 313 of the total 1609 pins, were more intensively monitored. On these reaches, we measured pin lengths after each major flow event and once a month when high flows did not occur. This monitoring was initially intended to assess the effect of individual flow events, but also allowed the assessment of the effect of bank soil desiccation during a drought and freeze-thaw action during winter. These intensively monitored sites were measured a total of 19 times during the 18-month monitoring period.

Random placement of pin plots throughout a stream reach can capture subtle changes and is more likely to note sediment storage (Kronvang et al. 2012). However, because the focus of our study was on the sediment contribution of streambank erosion, we focused on erosion occurring on severely eroding streambanks. Similar to the methods of Willet et al. (2012), we installed pin plots on randomly chosen eight-meter long stretches of severely eroding banks until 20% of the severely eroding bank length within each 375 to 403 meter long reach was pinned. If a section of eroding streambank selected was 8 meters long or shorter, we pinned the entire length. The location of the 8 meter stretch within an eroding length was also randomly selected, thereby incorporating the influence of longitudinal location on erosion rate (eg. within a stream meander) (da Silva et al. 2006, Hooke 1980).

On each pin plot, we installed 76.2 cm long, 6.2 mm diameter rolled steel pins. This length was used because longer pins may stabilize streambanks (Hooke 1979) and shorter pins are more likely to be lost in a major erosion event (Kang 2012). One row of pins was inserted at ½ bank height for banks less than one meter in height, two rows at 1/3 and 2/3 bank height for banks from one to two meters high, and ¼, ½, and ¾ bank height for banks over two meters in height. At a few sites, mainly valley walls over 4 meters, it was not possible to place pins throughout the full height of the bank, and so the pins were placed at 1, 2, and 3 meters from the bed, leaving the upper parts unmonitored.

To maintain consistency, pins were inserted to leave approximately 10 cm exposed, though all initial lengths were measured at installation to incorporate any variability in installation. If greater than 15 cm was exposed when pins were re-measured, pins were reset to again leave approximately 10 cm exposed.

During measurement, pins assessed as buried were given a length of zero, as if they had been just buried with no additional sediment deposition. This underestimates sediment deposition, but avoids the confusion of multiple pins in one location and prevents an overestimate of erosion. If a second pin had been installed, this would count erosion of recently deposited sediment as a net sediment contribution to the stream. Until the pins were re-exposed, no data was entered for these pins at subsequent measurements. When we were unsure if a pin was eroded away or buried, it was replaced, and no value was entered for the change in exposed length. Changes in pin length for each period, whether negative or positive, were averaged to give an estimate of net erosion. Because any change on an erosion pin represents sediment movement, and thus bank instability, the absolute value of change on each pin was averaged to give "bank activity" (Couper et al. 2002). Finally, the streambank recession rate, total eroding bank length and height, and NRCS (1998) estimates of soil bulk density were used to estimate the sediment contribution from stream erosion. For all these statistics, 95% confidence intervals were calculated using Microsoft Excel spreadsheet software.

In addition to determining the streambank recession rate and its sediment contribution, the effect of pin position, aspect, and riparian land use on the recession rate were analyzed. Pins were assessed based on their vertical position (upper, middle, lower) and the longitudinal position of pins along the eroding streambank (da Silva et al. 2006). We also measured each pin plot's aspect and assessed its effect on streambank erosion, as the level of solar exposure has been found to be important in the destabilization of banks during winter months (Gatto 1995, Reid et al. 1985). We used the linear model function on R (R Development Core Team 2011) to analyze the effect of these factors on both net erosion and bank activity.

Results and Discussion

Streambank Erosion Summary and Seasonal Variation

In total, 4800 measurements of pin length change were made as part of the biannual observations. 5300 measurements were made of the intensively measured pins on 19 separate dates. On average, the overwhelming majority of the pins saw very little change, with little difference by season (Figure 2). Deposition was slightly more common in the first winter period, with an average deposition of 1.7 +/- 0.2 cm (this and all subsequent error ranges give 95% confidence intervals). In the summer and second winter period, there were some moderate flows, which resulted in an average of 0.9 +/- 0.3 cm of erosion in summer and 0.8 +/- 0.3 cm of erosion in the second winter. The cumulative change throughout the entire period was effectively zero. The difference in erosion between the two winter periods is likely due to higher flows from snow melt in

March 2013. Average bank activity was 3.4 +/- 0.2 cm in the first winter biannual measurement period, 3.7 +/- 0.3 cm in the summer biannual period, and 3.5 +/- 0.3 cm in the second winter period.

The intensively monitored pins showed a pattern of erosion and deposition that is consistent with the biannual pins, but provides a much more detailed picture of deposition than that suggested by the biannual monitoring (Figure 3). In the second winter period, the intensively monitored pins exhibited a similar pattern of deposition as that seen in the first winter period, but this change was not captured in the biannual pin measurements, as snow melt had eroded away much of the deposited sediment before biannual measurements of all pins occurred in April 2013. This contrast shows the value of more frequent measurement, as we were able to capture a cycle of deposition and erosion which otherwise would have been missed.

The intensively monitored erosion pins also showed a more complete picture of bank erosion than the biannually measured pins. In 2012, the majority of erosion measured by the intensively-monitored pins occurred from February 29 through May 4th, 2012, when erosion pins, on average, showed bank recession of 1.8 cm (+/- 0.7 cm). In the second winter period, 2.3 cm (+/- 0.5 cm) of erosion was measured on the intensively monitored pins between Jan 31 and April 5, double that found using the biannually collected data. Using these recession estimates, a standard bulk density of 1.36 Mg/m^3 (NRCS 1998), a measured total of severely eroding stream length of 20.1 km, and an average bank height of 2.05 m, this results in 1030 Mg (+/-380 Mg) of net soil lost to the stream from March to October 2012 and 1290 Mg (+/- 410 Mg) of soil from October 2012 to April 2013.

Estimates of soil erosion from streambanks using this methodology depend on a few simplifying assumptions. First, in this calculation, we are disregarding periods of deposition and summing only intervals in which the recession rate was positive. We are using this method because deposition was observed to come from bank collapse and not storage of fluvial sediment from upstream, as will be discussed later. A second assumption we are using in our estimates of sediment loads is that streambanks not identified as severely eroding in our survey were assumed to not have contributed any sediment, which is undoubtedly an underestimate. However, bank erosion tends to follow a distribution where most of the sediment comes from severely eroding sections (Laubel et al. 1999, 2003, Kronvang et al. 2012). Finally, our approach uses a bulk density estimate of 1.36 g soil cm^{-3}, as per the USDA-NRCS's Erosion and Sediment Delivery protocol (1998).

For the majority of the time erosion pins were measured on Onion Creek, the watershed experienced a severe drought. The Onion Creek watershed received 88 cm of precipitation from October 2011 to March 2013, 22 cm less than the historical average. Data for October 2011-November 2012 from a weather station two km south of the Onion Creek watershed were obtained from the National Climatic Data Center: NOAA <www.ncdc.noaa.gov/>. Data from this site were not available December 2012 to March 2013, so data from a weather station six km southeast of the Onion Creek watershed were obtained from the Iowa Environmental Mesonet:

<http://mesonet.agron.iastate.edu/>. As a result of this low precipitation, discharge was less than 0.1 m^3/second and usually zero from July 2, 2012 to January 2013, except for a four hour period following a storm in early August.

As a result of this drought, erosion recorded for both spring periods was relatively small. Streambank erosion estimates during this study period (1.88 cm in 2012, 2.3 cm so far in 2013) are much lower than the NRCS estimated erosion rates for severely eroding streambanks of 12.2 cm per year, reflecting the effect of drought and subsequent low water flows. Studies of severely eroding streambanks in similar lower-order, agriculturally-dominated watersheds in the Midwestern United States also found recession rates which were higher than those seen in Onion Creek: 5.6 cm/year (Peacher 2011), 10 cm/year (Zaimes et al. 2008), and 22 cm per year (Tufekcioglu et al. 2012).

Looking at studies of banks which were not severely eroding, Bear et al. (2012), in a study of streams in the Loess Flats and Till Plains ecoregion of Iowa, measured bank erosion of 6.7 cm per year in sites with pasture as a riparian land use. Two studies of 1st and 2nd order streams flowing through glaciated, agriculturally dominated terrain in Denmark found 2.4 cm bank erosion per year (Kronvang et al. 2012) and 1.1 cm bank erosion per year (Laubel et al 2003). However, these three studies used erosion pins in randomly chosen locations rather than severely eroding streambanks, so their averages represent the entire length of a stream, rather than the sites of highest erosion. Since the bulk of streambank erosion comes from a small subset of severely eroding banks, with little activity on other stream reaches (Laubel et al. 1999, 2003, Kronvang et al. 2012), the fact that these studies still found similar or higher rates of bank erosion than those seen on Onion Creek underlines the effect of drought on streambank erosion rates.

Erosion activity on Onion Creek was also lower than in similar studies of severely eroding streambanks. Compared to the annual activity of 7 cm measured on Onion Creek, Couper et al. (2002) measured 13.4 cm annual bank activity in a larger-order river in the midlands of England, and Zaimes et al. (2008) measured an average bank activity of 17.2 cm in a study of lower-order streams in agricultural landscapes similar to the Onion Creek watershed in central Iowa. Again, the small values seen on Onion Creek are likely a result of drought conditions.

The timing of bank activity in Onion Creek is similar to that seen by many other researchers. On Onion Creek, there were periods of deposition in both the first and second winter periods due to freeze-thaw loosening of streambanks. Freeze-thaw action is a sub-aerial process in which needle ice expands, then melts in soil, disrupting the macrostructure of soil and leading to bank collapse. Evidence for freeze-thaw action can be found in pin activity that occurred despite the stream being entirely dry or frozen. Additionally, where deposition was noted, the soil had a similar structure and color to the bank soils above it, rather than the structure-less sediment expected with fluvial deposition. Further, much of the deposition was observed in the winter, again pointing to freeze-thaw action. Although Prosser et al. have noted that bank desiccation can have a similar soil-loosening effect to freeze-thaw action (2000), very little change was observed during the drought in the summer of 2012 (Figure 3).

Freeze-thaw action creates an easily eroded layer of soil and erosion of this layer of freeze-thaw destabilized soil often provides the majority of sediment contributions from streambank erosion (Couper et al. 2002, Ferrik and Gatto 2005). On Onion Creek streambanks, all observed bank erosion occurred during the springs of 2012 and 2013. Bear et al. (2012) also found the bulk of bank erosion on a southern Iowa stream occurred in the later winter and early spring and attributed this to spring storm flows entraining freeze-thaw loosened soil. Other researchers (Lawler et al. 1999, Willet et al. 2012, Stott et al. 2001, and Zaimes et al. 2006) found similar results, again attributing their results to winter-freeze-thaw action followed by high flow events in the spring.

Pin Position

Vertical pin position was found to influence bank activity but not net erosion in each biannual period. In the first winter period, the upper pins had 0.7 cm less activity than the lower pins' 3.8 cm ($p=0.004$), and the middle pins had 0.5 cm less ($p=0.047$). In the summer period, there was an average of 4.8 cm erosion activity for the lower pins, 3.3 cm for the middle pins, and 2.9 cm for the upper ($p<0.001$ for all summer comparisons of vertical pin positions). In the second winter period on the lower pins, 0.6 cm more erosion activity was measured than the upper pins' 3.2 cm ($p=0.033$), while the middle pins were not significantly different from either set. For each biannual interval and for change from October 2011 to April 2013, the effect of vertical pin position on net erosion was not significant ($p>0.05$). Looking at bank activity across all the periods, the lower pins had an average bank activity of 7 cm, the middle 1.2 cm less than the lower pins ($p=0.004$), and the upper 1.7 cm less than the lower pins ($p<0.001$).

This pattern of bank activity can be explained by sub-aerial processes loosening soil on the upper banks with subsequent deposition lower on the bank (Figure 4A, C). The greater activity within the lower pins in the summer and second winter period point to fluvial action as the main erosion agent during these periods, with limited spring flows entraining the particles at the base of the bank which were already detached by freeze-thaw action (Zaimes et al. 2006, Laubel et al. 2003, Lawler, 1986). This was supported by field observations. In many of the places where we noted erosion, it usually occurred as moderate erosion on the base of the bank, rather than as a result of mass wasting (Figure 4). Only one or two instances of mass wasting were observed, which is not surprising given the low water flows. These conditions were unlikely to cause enough incremental disturbance to destabilize bank soils. Further, drought conditions resulted in low water content in bank soils, which likely increased bank stability through higher matric suction (Simon et al. 2000).

Longitudinal pin position was not found to have a significant effect on the rate of bank erosion or on erosion activity for any of the biannual measurement periods or for overall change. This is in contrast to the results of Hooke (1980) and da Silva et al. (2006), who found that the downstream end of an eroding meander bend will erode faster than the upstream end. The reason we did not see any significant relation is likely because little erosion occurred throughout our study period.

Aspect

Streambank aspect did not affect bank erosion or activity as observed during biannual measurements in the first winter period or in the summer period. However, higher erosion rates were observed in the second winter period on south facing banks (0.013 cm more erosion for every degree closer to due south, $p<0.001$) as well as more total activity (0.010 cm more activity for every degree closer to due south, $p<0.001$). This relationship was not significantly affected by vegetation cover or stream order.

Similar results were observed in the intensively monitored pin plots (Figure 5, 6). There was no difference in streambank erosion or activity between south-facing and north-facing pins until the second winter, when less erosion was observed in north-facing pins. Similar to the biannual measurements, a difference in erosion activity within intensively-monitored pins was only observed for a short interval during the winter of 2012-2013.

Past research has found aspect to have an important effect on streambank erosion, though the results have been inconsistent. Reid (1985) observed greater erosion on north-facing banks, attributing the result to more severe cold. On the other hand, Gatto (1995) predicted that south-facing banks would be more vulnerable to freeze-thaw action, as direct solar exposure on the south-facing banks will cause more frequent changes in temperature.

It is likely the effect of aspect will be different under different conditions, and our data illustrates that aspect may only be important in some cases. There was little snow cover the winter of 2011-2012, while in the 2012-2013 winter, snow covered some banks almost all the time from November to March. It is possible that in the 2012-2013 winter, the south-facing banks experienced faster melting of snow, while the north-facing ones had a longer duration of snow cover. This snow, as suggested by Reid (1985) could have reduced the freeze-thaw action by insulating the soil from temperature variation. However, the difference was only seen on one measurement date. Further research under a range of conditions is needed to determine the effect of aspect.

Riparian Land Use

Riparian land use was not observed to be an important factor for any of the measurement periods for either the biannually- or intensively-measured pins. However, since there was little overall erosion and activity during our measurement period (Figures 2, 3) care should be exercised in extrapolating these results to periods of greater stream flow and streambank erosion. Other studies which did see higher rates of bank erosion than those reported here have also not found difference between riparian land use groups (Schilling et al. 2011, Willet et al. 2012). However, riparian land use has been found to effect rates of bank recession by many other researchers. Zaimes et al. (2008) found increased rates of bank erosion in streams with row crops or pasture as a riparian land use, compared to grass or forest buffers and other researchers have also noted that banks that were more protected by vegetation erode less (Prosser et al. 2000, Stott et al. 2001, Tufekcioglu et al. 2012). However, the main process seen in this study was freeze-thaw colluvial actions on banks. We did not find that vegetation had an effect on this process, but as this study continues, we will likely observe more substantial erosion events and be better able to determine the effect of riparian land use and other factors on the rate of that erosion.

Summary and Conclusions

Because of a drought and resultant low stream flows, average streambank erosion on severely eroding streambanks in Onion Creek, as measured using erosion pins at two temporal measurement scales, was very low from fall 2011 through spring 2013. Observed streambank erosion was 1.8 cm during the spring of 2012 and 2.3 cm from January to early April 2013, much less than the 12.2 cm recession rate predicted by the Natural Resource Conservation Service and less than that found by researchers studying change in similar stream systems. During this period, there was significant deposition of soil due to the sub-aerial process of freeze-thaw action during two winter periods, followed by minor fluvial entrainment of that sediment in one or two early spring flows. Both of these processes were more prominent at the base of the streambanks, and to a very minor extent in the late winter of 2013, on south-facing banks. Results to date reinforce the usefulness of erosion pins for monitoring the recession rate of severely eroding streambanks, especially when that monitoring includes an intensive-measurement component.

Because of the low amount of measured erosion, we did not make any conclusions about the effect of riparian land use on streambank erosion. We will continue to monitor changes in the pins installed on Onion Creek as stream flows increase and examine how those changes are related to riparian land use and other riparian characteristics.

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Figures

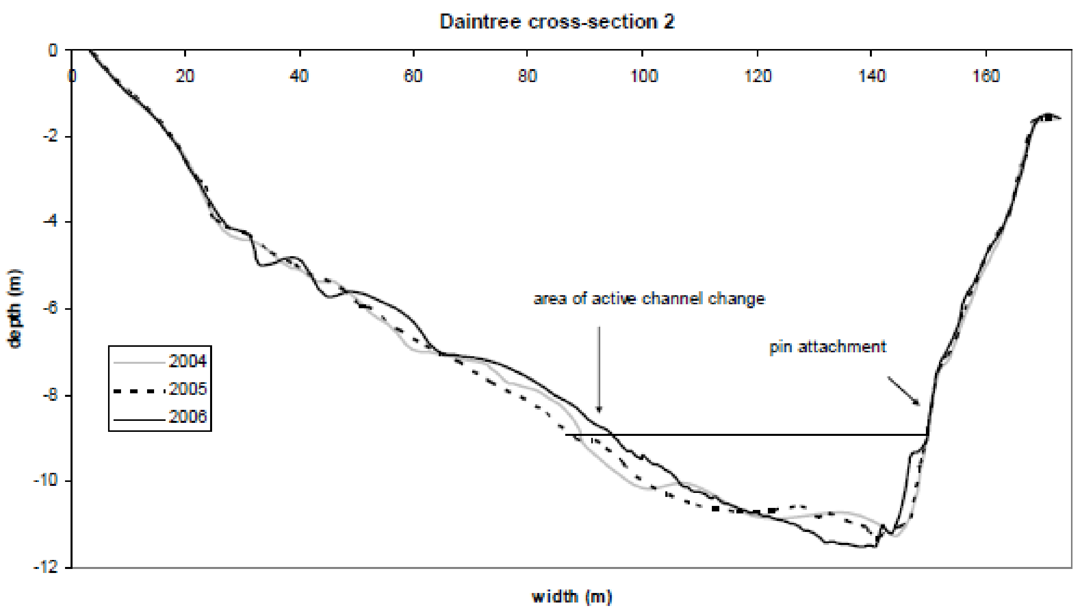

Figure 1: From Bartley et al. (2006), showing little change at the site of an erosion pin despite significant bed erosion and deposition on the opposite bank.

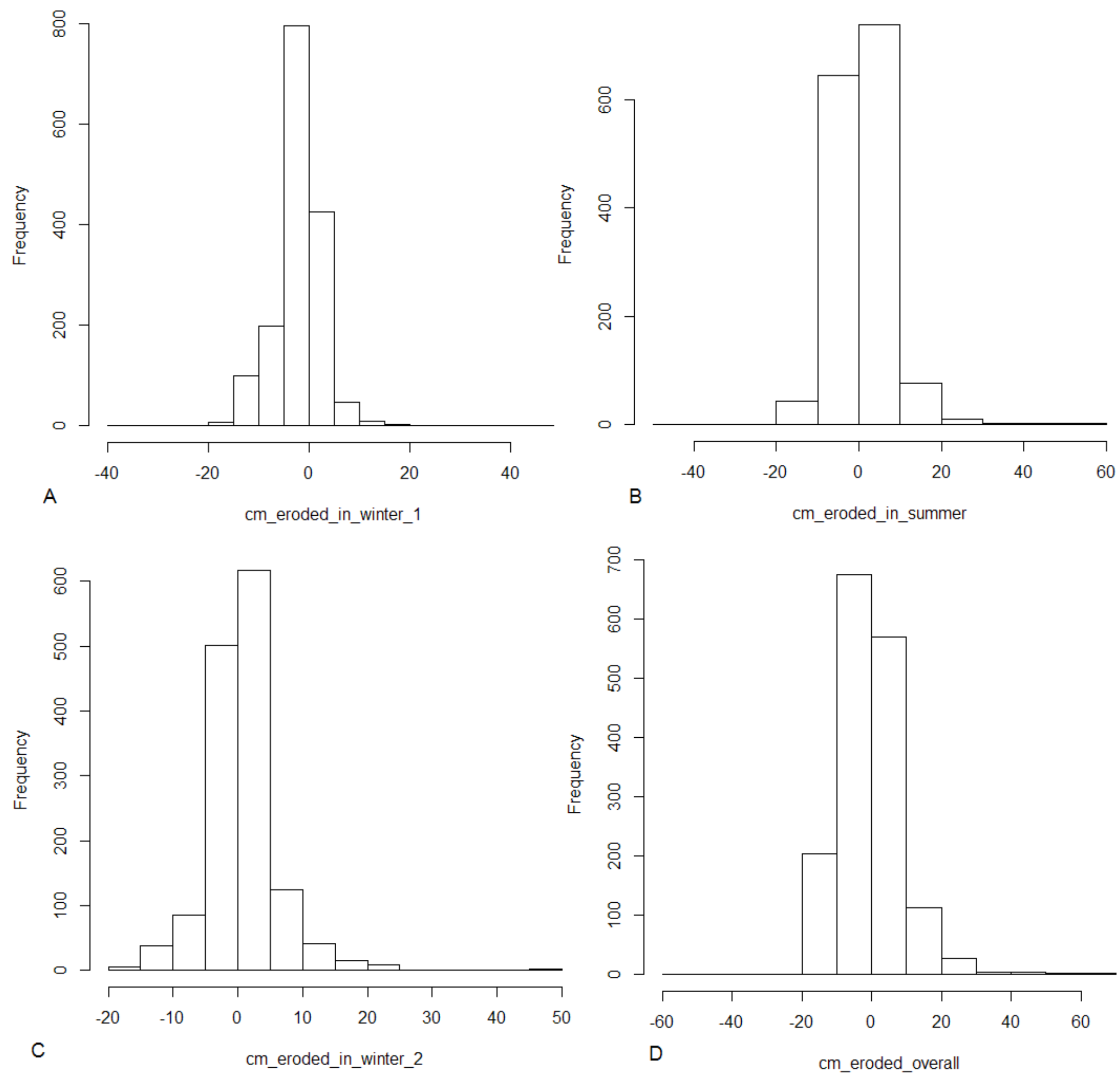

Figure 2: Histograms of change in pin lengths for each season (A-C) as well as the overall change October 2011-April 2013 (D).

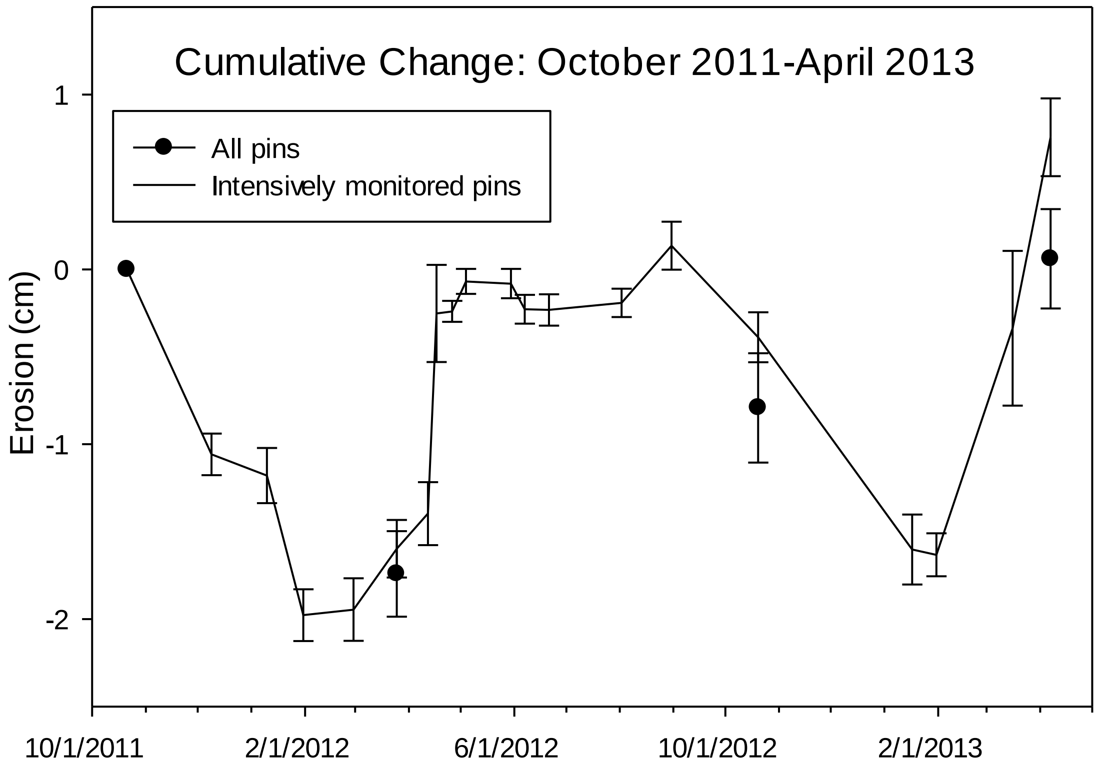

Figure 3: Cumulative deposition (negative) and erosion (positive), Oct 2011-April 2013. The continuous line shows measurement of change on our intensively measured pins and the black dots show average change for all pins, measured biannually. Error bars show a 95% confidence interval of the change from the previous measurement date.

Figure 4: Freeze-thaw action and fluvial entrainment on one Onion Creek streambank. A: Buildup of freeze-thaw-loosened soil at the base of a streambank, January 10, 2012. B: Following spring storm flows, June 7, 2012. C. Freeze-thaw deposition in the second winter period, January 17, 2013. D. Fluvial entrainment following snow-melt flows, April 25, 2013.

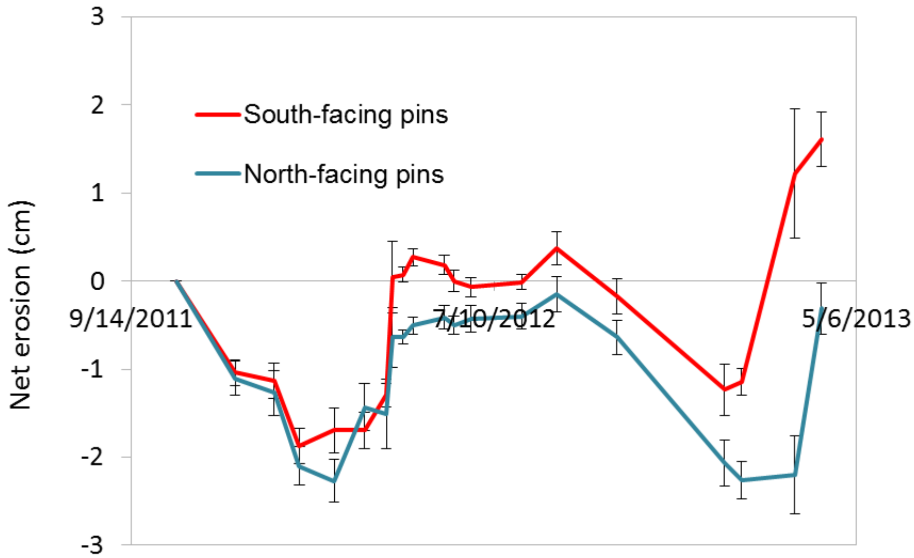

Figure 5: Cumulative deposition (negative) and erosion (positive) for intensively monitored pins. South-facing pins had aspects from 91-270 degrees; north-facing pins had aspects from 0-90 and 271-360 degrees. Error bars show a 95% confidence interval of the change from the previous measurement date.

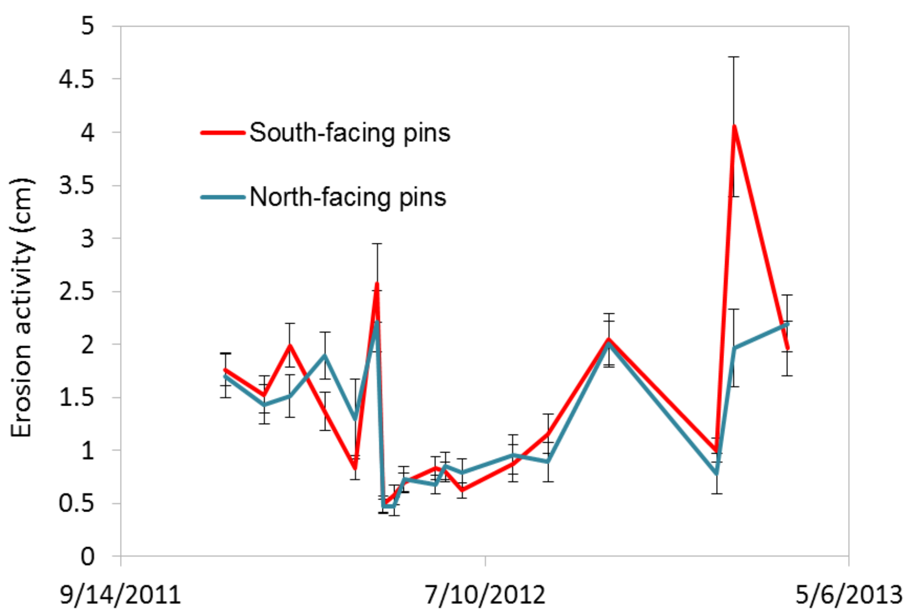

Figure 6: Erosion activity for intensively monitored pins. Error bars show a 95% confidence interval.

CHAPTER 5. WATER, SEDIMENT AND NUTRIENT EXPORT FROM ONION CREEK

Abstract

Water quality was measured on Onion Creek between March 2012 and April 2013, a period in which significant streambank erosion was measured. An analysis of the loads and concentrations of sediment, phosphate and total phosphorus, and nitrate and total nitrogen exported from Onion Creek is presented, showing concentrations frequently above EPA recommended criteria. Finally, a comparison is made between sediment loads and streambank erosion for one storm event in spring 2012 and for the entire water sampling period.

Introduction

Streambank erosion is a major contributor to sediment in streams (Belmont et al. 2011, Walling et al. 2005). This sediment causes impaired water quality (Laubel et al. 2003, Simon and Klimetz 2008, Zaimes and Schultz 2011). In 2007, Wendt estimated sediment export from Onion Creek, a second-order stream in central Iowa, based on a RUSLE assessment and a sediment delivery ratio calculation. According to this estimate, 677 Mg of sediment from sheet and rill erosion was delivered annually to the confluence of Onion Creek with Squaw Creek. Wendt also surveyed streambank erosion along 15 of the 42 km of Onion Creek and reported that streambank erosion was not particularly severe compared to the six other watersheds she had studied, but that it could still be a major source of sediment. As described in Chapter 2, a Rapid Assessment of Stream Channel Along Length (RASCAL) survey of both sides of all 42 km of Onion Creek (for 84 km total bank length) conducted Fall 2010-Spring 2011 estimated that 24.3% of the total length of streambanks, averaging 2.05 m in height, were severely eroding. Severely eroding streambanks were defined as banks with very low vegetative cover, severe vegetative overhang, and fallen trees and slumps. Banks with these characteristics are estimated to erode at 0.122 m/year and have a bulk density of 1.36 Mg/m^3, according to estimates used by the NRCS (1998). Based on these estimates, bank erosion from Onion Creek adds 6800 Mg/year to the stream system (see Chapter 2); over ten times the amount of sediment Wendt estimated would come from sheet and rill erosion. Erosion pin plots measured from March 2012 to April 2013 showed two periods of bank erosion totaling 4.1 cm. Assuming this erosion is representative of the 24.3% of the stream channel mapped as severely eroding, erosion from streambanks between March 2012 and April 2013 added 2320 Mg of sediment to Onion Creek (Chapter 4). Assuming a sediment delivery rate of 80% (NRCS 1998), this represents 1850 Mg of sediment from streambank erosion reached the confluence of Onion Creek and Squaw Creek between March 2012 and April 2013. This level of sediment from bank erosion is much less than that predicted based on our bank survey, likely as a result of a severe drought (see the US Drought Monitor: <http://droughtmonitor.unl.edu>). Still, this sediment is a significant threat to water quality.

However, calculations made by Wendt and in Chapters 2 and 4 of this thesis may give an inaccurate measure of sediment export from Onion Creek. For example, in a multi-decade study, roughly one quarter of the sediment loads from upland, gully, streambank, bluff, and bed erosion did not reach the outlet of a Wisconsin creek due to floodplain and channel storage (Fitzpatrick et al. 1999). Similar results were noted by Bull (1997) and Walling et al. (2002). Wendt's estimates for sediment contributions from surface runoff included a sediment delivery factor (NRCS 1998) to estimate the amount of sediment reaching the confluence of Onion Creek and Squaw Creek. However, this factor depends on broad, simplifying assumptions. Sediment from sheet and rill erosion is largely delivered to channels through gullies, and the connectivity and size of those gullies has a large effect on their ability to deliver sediment to a channel (NRCS 1998). Further, gullies themselves are important sources of sediment (Foster 2005, Ohde 2011) which have not been studied within the Onion Creek watershed.

With respect to stream bank erosion estimates, the erosion pin plots we used to measure streambank recession may neglect or overemphasize certain sections of streambank activity (Bartley et al. 2006, Kronvang et al. 2012). Also, a focus solely on erosion ignores bed, bank, point bar, and floodplain storage which can occur before suspended sediment leaves a channel (Walling 2005, Trimble 1983, 1999, Walling 2005, Kronvang et al. 2012).

In general, the relationship between gross erosion and sediment yield is highly complex, and the calculation of a sediment delivery ratio requires "[c]onsiderable technical judgment" (NRCS 1998). Trimble and Crosson (2000) have noted that because of the difficulty of accurately calculating a sediment delivery ratio, any such calculation requires validation to determine the amount of sediment actually exported from a stream system.

Because of uncertainty in the estimates for both erosion and sediment delivery, we have begun a long-term project monitoring suspended sediment loads exported from Onion Creek. As phosphorus and nitrogen also have a significant effect on water quality (Iowa Department of Agriculture and Land Stewardship et al. 2012), we are also monitoring their concentrations and loads. Data from the first year of monitoring is presented in this chapter.

Methods

Data reported here includes samples collected in Onion Creek between March 1st, 2012 and April 12, 2013. Periodic water samples were collected every two weeks 0.75 km upstream of the confluence of Onion Creek and Squaw Creek. These periodic samples were collected by hand from the thalweg of the stream channel. Samples were assayed for suspended sediment, nitrate-nitrogen, total nitrogen, dissolved phosphate, and total phosphorus. Nitrate samples were preserved with sulfuric acid to a $pH < 2$. Stream stage was measured at the time of each sampling.

Storm flow has been found to carry large portions of the sediment loads within small streams such as Onion Creek, so periodic sampling alone likely would not capture important sediment movement events (Horowitz et al. 1990, Lawler and Dolan 1992, Kronvang and Bruhn 1996). To supplement periodic samples, we installed a Teledyne ISCO 6712 (Teldyne ISCO, Lincoln, NE) automatic water sampler at the same sampling location to collect samples from storm flow. The sampler was installed in accordance with USGS recommendations for automatic water samplers detailed in Edwards and Glysson (1999).

Stream stage was recorded every 5 minutes from April 2, 2012 to Aug 14, 2012, using a Teldyne 750 model area velocity flow module (Teldyne ISCO, Lincoln, NE). The automatic water sampler was removed during winter to protect it from low temperatures and was removed early fall 2012 due to a lack of flow. Sensor readings from the area velocity module were validated using the periodic stage measurements. Stream discharge was estimated over a range of stream stages using a Marsh McBirney Flo-mateTM 2000 stream velocity meter. Stage measurements were converted to discharge using a stage-discharge curve developed according to procedures described by Turnipseed and Sauer (2010).

The automatic water sampler was programmed to collect water samples whenever the stage increased 5 cm above base level, following methods described by Kronvang et al. (1997). This base level was reset to the current stage at least once every two weeks to account for changes in base flow throughout the year. Once water sample collection was started sampling continued for the next four days, filling one bottle every 3 hours for the first 33 hours, then every 6 hours for the next two and a half days. At completion of the sampling cycle, water sampling was restarted immediately if water levels were still above base flow stage.

Suspended sediment concentration was measured by filtration (Standard Test Methods 1997). A 50 mL sub-sample was vacuum-filtered through an oven-dried, pre-weighed 0.45 µm cellulose membrane filter, which was then dried and weighed to calculate the suspended sediment. For periodic samples, three water samples from each date were assayed individually. For storm samples, only one bottle of stream water was collected every three or six hours, so suspended sediment concentration was assayed on three subsamples. For all samples, 50 mL of deionized water was filtered through three separate filters as a control.

Filtered samples were analyzed for dissolved phosphate using the ascorbic acid photometric method from Murphy and Riley (1962) with modifications from the American Public Health Association (1998). The filtered deionized water from suspended sediment analysis was used as a tare sample in this phosphate assessment to correct for any phosphate introduced during the filtering process. Nitrate-nitrogen was analyzed using second-derivative spectroscopy as per the method of Crumpton et al. (1992). Nitrate-nitrogen was assayed on filtered samples to prevent the high levels of sediment in storm samples from interfering with the spectrophotometer, again measuring the nitrate content of filtered deionized water as a tare. Total nitrogen and phosphorus were analyzed using persulfate digestion (American Public Health Association 1998). Digested samples were analyzed using the methods described above for nitrate and dissolved phosphate.

When the concentration of total nitrogen was less than nitrate-nitrogen, likely due to losses of gaseous N prior to collection of the field samples, the measured nitrate-nitrogen value was used for total nitrogen. Several measured total phosphorus concentrations were lower than those for dissolved phosphate. This only occurred with samples with relatively low levels for both phosphate and total phosphorus and was likely a result of a lack of precision at the low end of our standard curves or contaminants introduced during our filtration process. As this difference never exceeded the 95% confidence interval for our sample values, all dissolved phosphate and total phosphorus values were considered to be the best possible estimate and left as measured.

Concentration and discharge values were multiplied to calculate loads exported from Onion Creek to Squaw Creek. 95% confidence intervals were calculated using Microsoft Excel spreadsheet software for concentrations of individual water samples and also multiplied by the discharge to illustrate the precision of load estimates. The concentration of sediment and nutrients between sampling times was estimated using a simple linear interpolation method (Kronvang and Bruhn 1996). When the automatic water sampler was not installed, the concentration and discharge measured when taking periodic samples was used for the entire two-week period.

Relationships between sediment and nutrient concentrations were analyzed by testing their covariance using the linear model function on R (R Development Core Team 2011). For a direct comparison between sediment exported and streambank erosion, the total length of severely eroding streambanks were surveyed and their recession rate was measured using erosion pins (Couper et al. 2002, Lawler et al. 1999, Zaimes et al. 2008) over the same time period (Chapter 4). The rate of sediment loss from these streambanks was then compared to the total flux of sediment exported from Onion Creek.

Results and Discussion

Sediment and Nutrient Concentrations and Loads

Figures 1-4 show the cumulative discharge of water, nitrate-nitrogen, total nitrogen, dissolved phosphate, total phosphorus, and suspended sediment from Onion Creek from March 1, 2012 to April 12, 2013. From July 5, 2012 to January, 2013, stream flow stopped as a result of drought conditions (Figure 5, also see the US Drought Monitor: <http://droughtmonitor.unl.edu>). When rainfall occurred during this period, the storm flow was quite short. For example, a storm on August 8th caused the dry stream to rise to a level that triggered sampling by the automatic water sampler, but the streambed was dry within four hours.

As estimated from periodic sampling, sediment and nutrient exports from Onion Creek to Squaw Creek from March 2012 to April 2013 were 435 +/- 12 kg dissolved phosphate, 574 +/- 14 kg total phosphorus, 42 +/- 0.5 Mg $NO_3^{-}N$, 46 +/- .05 Mg total nitrogen, and 80 +/- 30 Mg suspended sediment (95% confidence intervals given for these and all subsequent statistics). Adding storm samples, loads for this same period were 465 +/- 50 kg dissolved phosphate, 810 +/- 30 kg total phosphorus, 66 +/- 2 Mg $NO_3^{-}N$, 73+/- 4 Mg total nitrogen, and 480 +/- 115 Mg suspended sediment. The totals with and without storm samples are significantly different for all nutrients and sediment. Especially for sediment, much of the annual loads moved during major storm events, particularly the storm flow which peaked on April 15, 2012 (Figures 1, 3, and 6). In comparing flux estimates using grab sampling versus event sampling, Kronvang and Bruhn (1996) found that the sampling method which would give the most accurate and time-efficient measure of total phosphorus and total nitrogen loads was periodic samples every two weeks, supplemented with more frequent sampling during high flow periods, as this method better captures the high variability seen during storm flow compared to simple periodic sampling. Lawler and Dolan (1992) and Zaimes et al. (2006) found similar results for sediment loads. Therefore, the data set that includes both storm and periodic samples was deemed to best represent total flux from Onion Creek.

Observed nutrient concentrations on Onion Creek exceeded proposed USEPA ecoregional criteria (2002) on most sampling dates. Total phosphorus in periodic samples exceeded the USEPA's recommended concentration limit of 76 µg/L on eight out of the twelve periodic sampling dates, and frequently rose to levels above 1000 µg/L during storm flows. Nitrate-nitrogen levels were above 2.2 mg/L (USEPA 2002 recommended parameter) from March 1, 2012 to July 5^{th}, 2012, reaching a peak of 19.5 ppm nitrate-N on June 7, 2012. The spring of 2013, when flows returned, the nitrate concentrations again returned to levels above the USEPA's recommended parameters. Suspended sediment concentrations were high at times, with a maximum of 2000 mg/L on April 15, 2012. As a comparison, Zaimes and Schultz (2011) measured a maximum of 81 mg/L on a similar central Iowa stream. However, these samples were intentionally collected during base flow. High suspended sediment concentrations on Onion Creek were noted for just a brief period during one storm flow and the average suspended sediment levels for all water samples was 82 mg/L, quite similar to that reported by Zaimes and Schultz.

Annual sediment loads are relatively small for the 5700 ha Onion Creek watershed. Looking at a ten year study of two ~5000 ha watersheds, in central Iowa, Schilling et al. (2011) calculated an average sediment export of 1.6 Mg/ha*year for a watershed dominated by row crops and 1.4 Mg/ha*year for a watershed with some prairie restoration. In contrast, Onion Creek's export was 0.08 Mg sediment/ha*year, about 5% of the export seen by Schilling et al. Results similar to those observed for Onion Creek were reported in the 1160 ha Galbæk Stream watershed, which saw 0.08 Mg sediment exported/ha*year, though the exported phosphorus was 0.034 kg P/ha*year (Kronvang et al. 1997), roughly three times the 0.09 kg/ha*year observed on Onion Creek. The Galbæk Stream watershed was intensively farmed and drained like Onion Creek, but was in Denmark, which averages 72 cm annual precipitation, similar to the 68 cm of precipitation seen in the Onion Creek watershed in 2012 (Data from a weather station two km south of the Onion Creek watershed was obtained from the National Climatic DataCenter: NOAA <www.ncdc.noaa.gov/>).

Relation of Sediment and Nutrient Concentrations

Observed patterns in the concentration of nitrate and total nitrogen were not significantly related to total phosphorus, dissolved phosphate, or sediment concentrations. However, both total phosphorus and dissolved phosphate concentration was correlated with suspended sediment concentration. This correlation was stronger for total phosphorus, with 65% of the variation in total phosphorus concentrations explained by the concentration of suspended sediment ($p<0.001$). This relationship of sediment to total phosphorus follows a pattern documented in many other studies (e.g.

Laubel et al. 2003, Kronvang et al. 2012). In contrast, only 18% of the variation of the concentration of dissolved phosphate was explained by sediment concentration ($p<0.001$). As dissolved phosphate is not attached to sediment, this relationship may indicate that desorption of phosphate from sediment occurs within Onion Creek. Jin et al. (2006) showed that phosphate desorption from sediments occurred rapidly in the first 20 minutes after sediment suspension and sorption and desorption reached equilibrium within 10 hours. Similarly, Kronvang et al. (2012) found that phosphorus attached to sediment became bioavailable while being transported in surface water and Wildman and Hering (2011) noted dissolved phosphate levels rising subsequent to sediment re-suspension (2011). The correlation noted between sediment and dissolved phosphate concentrations in Onion Creek samples also suggests a rapid conversion between dissolved and sediment-adsorbed phosphate.

Relation of Bank Erosion to Discharge and Sediment Loads

The survey of eroding streambanks identified 20.1 km of severely eroding streambanks with an average height of 2.05 m within Onion Creek. Using NRCS (1998) guidelines, we estimate these soils have an average annual recession rate of 12.2 cm, a bulk density of 1.36 Mg/m^3, and an 80% sediment delivery rate, which results in an estimated annual average of 5500 Mg of sediment delivered to the outlet of Onion Creek. Wendt (2007) estimated the average annual surface runoff adds another 677 Mg of sediment to the Onion Creek stream outlet. These estimates of sediment loads were both higher than the observed flux from March 2012 to February 2013: 440+/-100 Mg, even though they do not include sediment from gully erosion. However, the Onion

Creek watershed experienced drought conditions for much of the year, so it is not surprising that measured suspended sediment loads were much lower than that predicted for an average year.

Because we directly measured streambank erosion rates over the water sampling period, we are able to compare measured bank erosion with measured suspended sediment export. The majority of the suspended sediment delivery occurred during one storm event (Figures 3, 6). Storm flow peaked early April 15th, 2012, as a result of a 5.8 cm rainfall occurring over a four hour period on April 14th, 2012 (data from the National Climatic Data Center: NOAA <www.ncdc.noaa.gov/>). This was the first and most rapid storm event of 2012 (Figure 1) and was responsible for the majority of sediment loss from streambanks. From April 12-17, 1.15 cm +/- 0.55 cm of erosion was measured using pin plots on a subsample of severely eroding streambanks on Onion Creek. With a total length of 20.1 km severely eroding streambank, an average severely eroding bank height of 2.05 m, and an estimated bulk density of 1.36 Mg/m^3, this translates to 340-950 Mg of sediment lost from severely eroding streambanks. During that same period, a flux of 360-590 Mg of suspended sediment was estimated using samples collected with the automatic water sampler (95% confidence interval given for both statistics). There is no significant difference between sediment eroded and sediment exported during this storm flow. However, because of the high variance of the erosion pin data, it is unclear if this is a validation of the erosion pin data.

Beyond this one particular storm, severely eroding streambanks eroded 4.1 cm from March 2012 to April 2013, producing an estimated 2320+/-650 Mg of sediment. During that same period, 480 +/- 115 Mg of suspended sediment left Onion Creek, or 21% of the total sediment lost from severely eroding streambanks. However, additional sediment likely entered the channel from surface runoff and gully erosion from March 2012 to April 2013. Because of this, less than 21% of the sediment eroded from severely eroding streambanks left the Onion Creek watershed.

Although bank soils erode directly into the stream, that sediment does not immediately reach the outlet. The NRCS sediment delivery calculator (1998) estimates that 80 to 100% of sediment eroded from streambank will reach a channel outlet, but in fact, sediment removed from a streambank by fluvial entrainment may be stored in the floodplain, bed, and point bars of a channel (Walling 2005, Trimble 1983, 1999, Walling 2005, Kronvang et al. 2012). Particularly in dry years, vegetation which grows along the bed can catch and store fine-grained sediment for several years (Walling et al. 2002). Although there was water flowing in Onion Creek when streambanks eroded, the banks and bed were largely dry from fall of 2011 to early spring of 2012. Anecdotally, July-September 2012, we noted areas where about 2 cm of sand and silt covered the crowns of grasses growing along the bed, indicating channel storage of sediment (Figure 7).

Although at least 79% of the sediment eroded from Onion Creek streambanks over this observation period has not reached the outlet, the eroded sediment is now detached and structureless and is quite likely to move downstream. Despite noting significant channel storage, Walling et al. (2002) found that 57-86% of eroded sediment left their study watershed within a year. Though the storm flow of April 12-17, 2012 has been treated as a major event, Onion Creek has had and will have larger storm events.

The bank and channel dynamics which will occur in a larger storm may cause a higher proportion of eroded bank sediment to be delivered to the outlet, as found by Bull (1997). The Onion Creek channel is still evolving and is currently largely in a widening phase, in which most of the sediment eroded from banks will eventually be exported from the channel (Schumm et al. 1984 and Chapter 3 of this thesis). Future channel adjustments will also reflect any changes in watershed hydrology and climate patterns. The high degree of variability in these driving factors, even within a relatively small watershed, emphasizes the necessity of detailed, long-term records of sediment and nutrient flux to be able to link changes in management to watershed exports.

Summary and Conclusions

The primary objective of the described monitoring was to estimate total sediment and nutrient flux from the Onion Creek Watershed and compare values with measured sediment loss from severely eroding stream banks. This chapter merely provides a foundation for this work, as it reports results for just one atypically dry year. As such, results likely provide an estimate of annual sediment and nutrient export at the lower end of possible ranges and are lower than values reported from similar watersheds in the region. Nitrogen concentrations were higher in the spring and exhibited significant seasonal variability. Sediment, and to a lesser extent phosphorus, was largely transported during storm flows. 65% of the variation in total phosphorus concentrations was explained by variation in the suspended sediment concentration, indicating much of the phosphorus is transported adsorbed to sediment. Finally, 79% of the sediment estimated to have been eroded from stream banks was not delivered to the outlet of Onion Creek, suggesting significant channel storage. This work provides estimates of nutrient and sediment dynamics during a significant regional drought, useful for comparison with a range of future stream flow levels.

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Figures

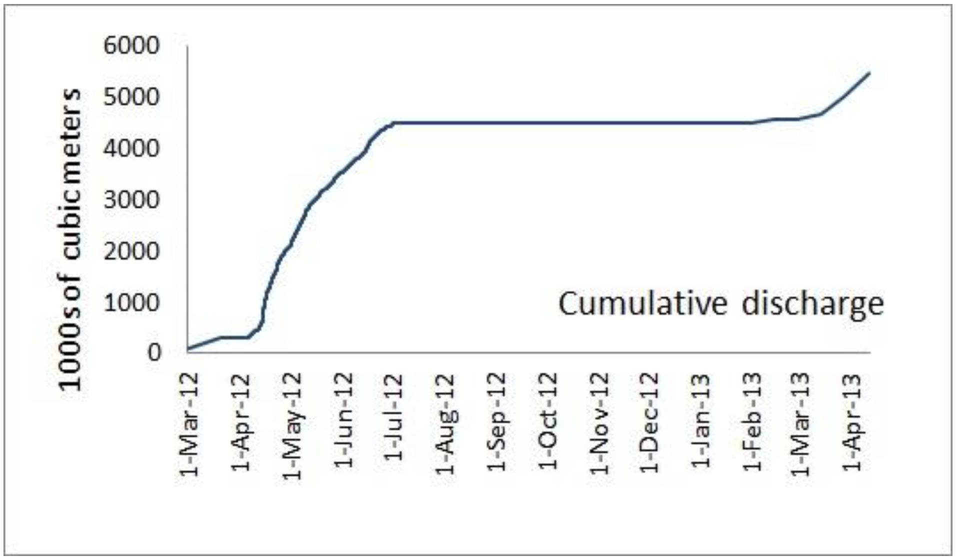

Figure 1: Cumulative water discharge from Onion Creek. Most water movement occurred in the spring of 2012, followed by a long period of very little discharge from Onion Creek. February-April 2013, water flow returned as result of snow melt and late winter rain.

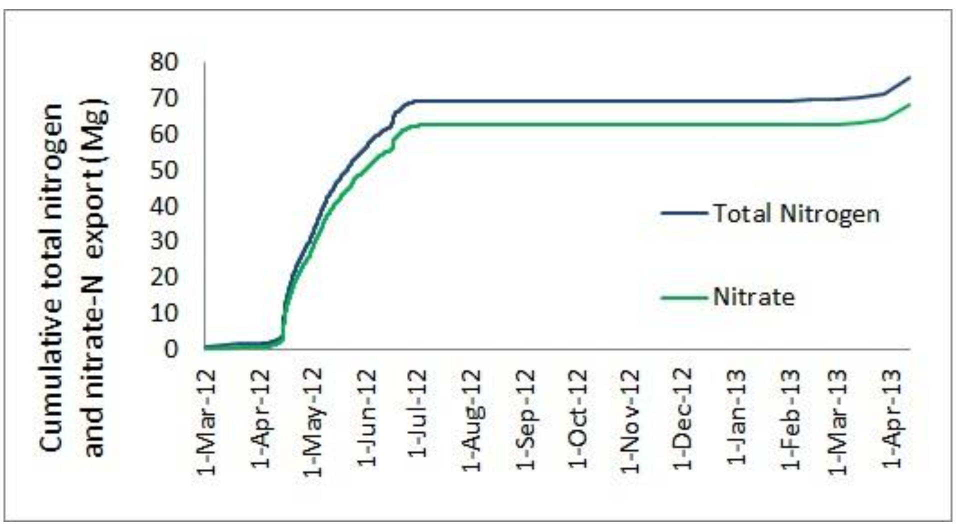

Figure 2: Cumulative nitrogen loading from Onion Creek. Both total nitrogen and nitrate roughly follow the water discharge.

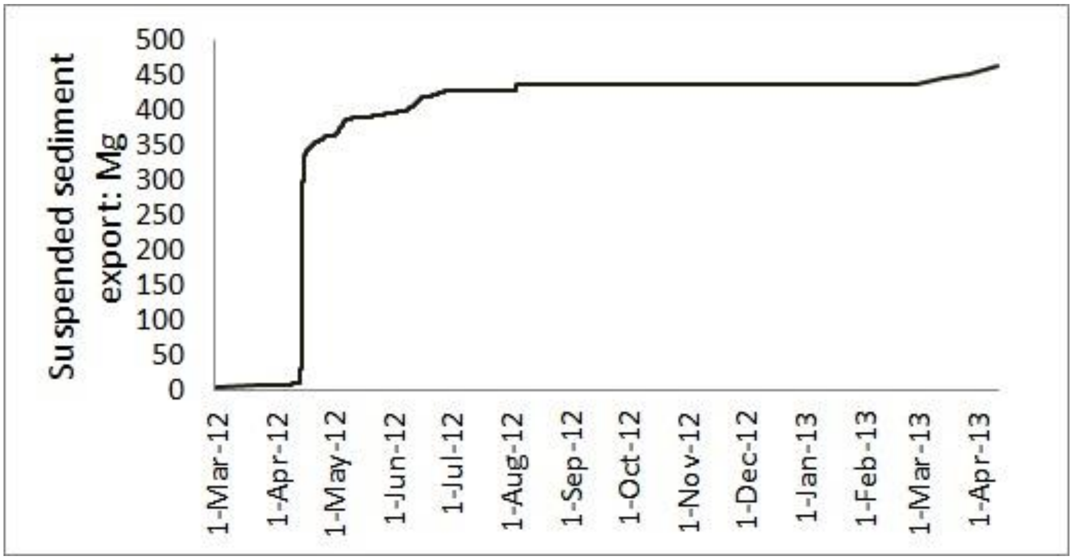

Figure 3: Cumulative sediment loading from Onion Creek. The bulk of sediment exported happened on a single day, April 15, 2012, after a storm event which delivered 5.8 cm of rain in 4 hours on April 14, 2012 (Data from the NOAA) (Figure 6).

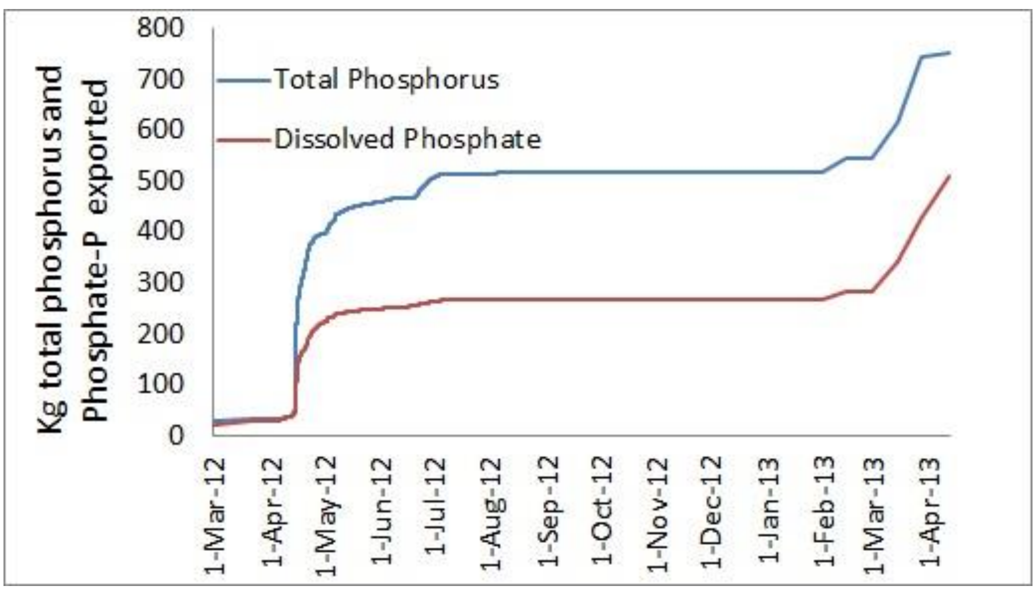

Figure 4: Cumulative phosphorus and dissolved phosphate export from Onion Creek. A substantial portion of the total phosphorus is not in the form of dissolved phosphate.

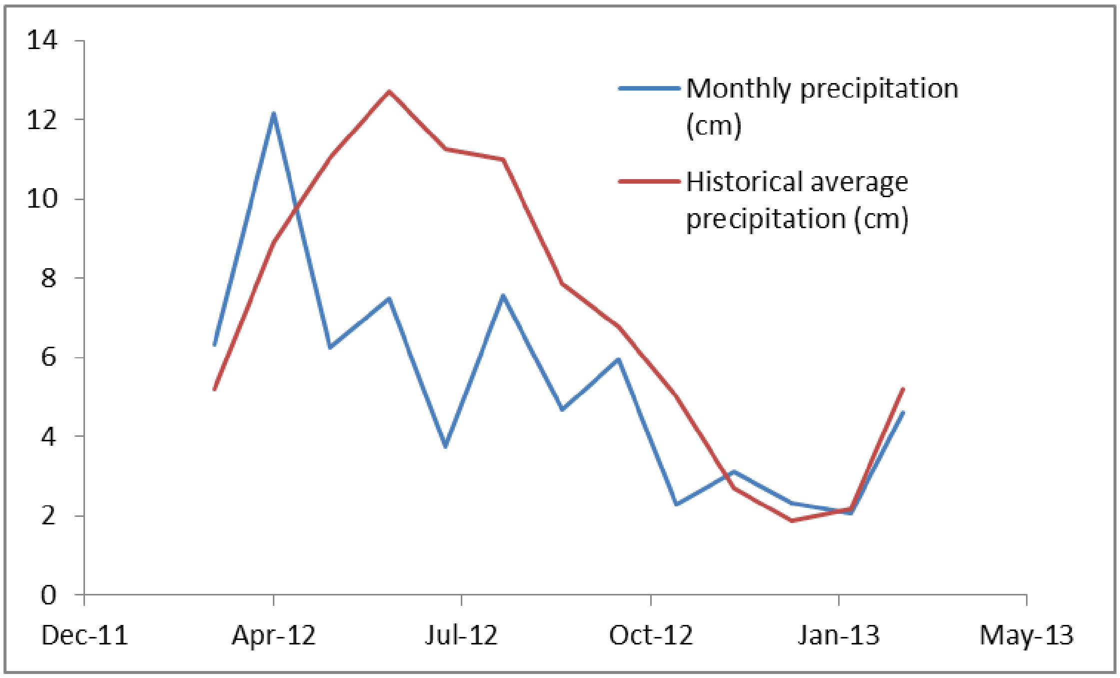

Figure 5: Monthly precipitation March 2012 to March 2013 plotted with historical averages. Historical averages and precipitation records for March to November 2012 are from a weather station two km south of the Onion Creek watershed and were obtained from the National Climatic DataCenter: NOAA <www.ncdc.noaa.gov/>. Data from this site were not available December 2012 to March 2013, so data from a weather station six km southeast of the Onion Creek watershed were obtained from the Iowa Environmental Mesonet: <http://mesonet.agron.iastate.edu/>).

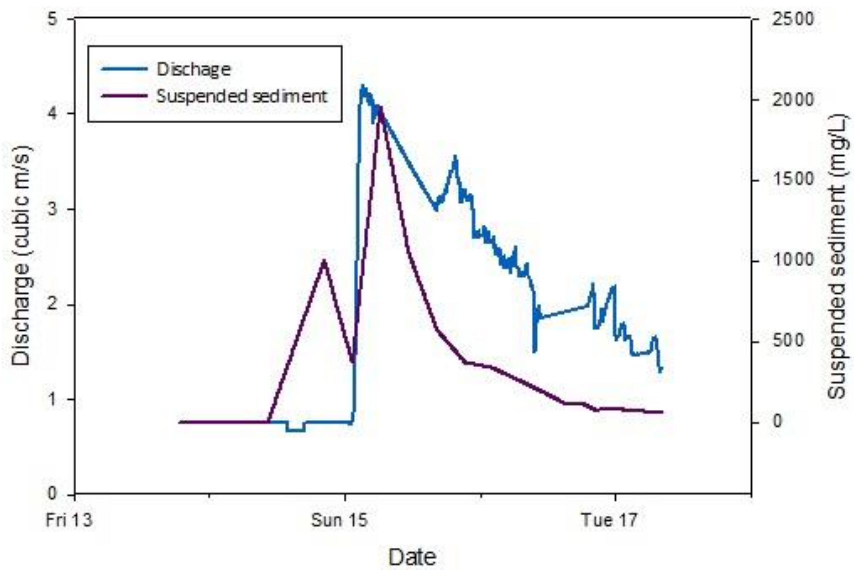

Figure 6: Discharge and suspended sediment concentration near the outlet of Onion Creek, April 13, 2012 to April 17, 2012.

Figure 7: Vegetation growing on the bed of Onion Creek, August 2012. Vegetation on the bed had been present for several months.

CHAPTER 6: GENERAL CONCLUSIONS

Streambank erosion involves numerous factors. Despite extensive research there is still considerable uncertainty about how these factors affect bank stability and under what conditions those factors are more or less important. A better understanding of the causes, processes and effects of bank erosion is needed in order to make recommendations for practices to protect riparian areas, aquatic ecosystems and water quality in agricultural landscapes. This thesis has attempted to add to that understanding.

The first part of this study examined current conditions along Onion Creek, a second order Iowa watershed located on the Des Moines Lobe landform region. This consisted of a Rapid Assessment of Stream Conditions Along Length (RASCAL), in which the riparian land use, points of interest for sediment and water movement, and severely eroding streambanks were mapped throughout the length of Onion Creek. In this assessment, 115 tile outlets, 764 sediment bars, and 164 gullies were found. 24.5% of the total bank length was characterized as severely eroding, defined as having very low vegetative cover, severe vegetative overhang, and fallen trees and slumps. This is not a particularly high incidence of bank erosion, but the stream still serves as a case study to examine which factors cause increased bank erosion, especially as certain stream sections were more unstable, with up to 50% severely eroding streambank length. In examining factors which contributed to higher amounts of severely eroding streambanks, greater amounts of erosion were seen in areas with narrower perennial buffers, in meandering sections downstream of channelized reaches, and more downstream stream reaches. We also found that a lower percentage of streambanks were severely eroding on channelized reaches and upstream of human-made flow restrictions such as bridges, culverts, and drop structures. We did not find a relationship between the type of riparian land use and bank erosion.

The second part of our study examined historical movement of the Onion Creek channel. Over 70 years, natural meandering was extending and increasing the sinuosity of the channel, though this increase in sinuosity and stream length was counteracted by anthropogenic stream straightening. Meander migration was more prominent in reaches with a higher starting sinuosity, wider floodplains, and in the upper parts of the watershed. The lack of overall change gives an appearance of stability, as a stream system in equilibrium will generally maintain its length and sinuosity. However, this average obscures instability which is apparent when looking at specific sections of the stream. In areas where stream straightening had not occurred, the stream system was increasing in length and sinuosity, which is characteristic of a stream which has not reached equilibrium with the energy of the water flowing through it. This conclusion of instability is supported by an analysis of the channel evolution phase of Onion Creek and the results of the first part of our study. Again, on average, 24.5% of streambanks were severely eroding, which is a sign of a stream near stability. However, some reaches had up to 50% severely eroding streambanks, which is not a sign of a stream in equilibrium with its hydrology. Reaches with high amounts of severe erosion were also found to have some of the most rapidly increasing stream length in the historical analysis.

The third part of our study examined erosion and deposition on Onion Creek streambanks from October 2011 to April 2013, using erosion pin plots. A drought during much of this period resulted in a relatively low amount of erosion, so we were not able to examine the effect of the factors used in analyzing the RASCAL assessment. We did observe substantial freeze-thaw destabilization of streambanks during each winter period. In early spring flows caused by rain and snow melt, much of this destabilized soil was removed by fluvial entrainment, contributing 2320 Mg of sediment to the stream.

The final part of this study examined sediment and nutrient loads exported from Onion Creek. Nutrient concentrations regularly exceeded ecologically healthy limits. Total phosphorus levels were usually above the USEPA's recommended concentration of 76 ppb, and rose above 1000 ppb during storm flows, and nitrate levels were above the USEPA's recommended concentration of 2.2 ppm the majority of the time water was flowing. However, because of drought conditions, transport of nutrients and suspended sediment was relatively low. For example, Onion Creek sediment flux was 5% of the annual suspended sediment loads reported for similar watersheds in the region. Of the 2320 Mg sediment contributed by streambank erosion, at least 79% did not reach the channel outlet, indicating that erosion from Onion Creek streambanks has at least a year-long residence time.

In contrast to many other studies, research presented in this thesis did not show a dramatic effect of riparian vegetation type on the rate of streambank erosion. This should not be interpreted to mean that the type of vegetation along a streambank is unimportant. A structurally diverse perennial buffer provides numerous benefits, including interception of sediment and nutrients from surface runoff, recreation, alternative revenues, and aquatic and terrestrial habitat. This study did not examine these riparian functions or how they were affected by different management strategies. However, they should be kept in mind when planning riparian management to mitigate streambank erosion. Ideally, management strategies will be implemented which improve all of these functions.

This thesis is a small part of a project dedicated to improving water quality by decreasing sediment and nutrient loads exported from Onion Creek. Water quality measurements from Onion Creek show high concentrations of nutrients and sediment, warranting conservation measures. Conservation measures such as riparian buffers strips, grassed waterways, and managed wetlands should reduce the input of sediment and nutrients from field and gully sources. However, the factors which affected the incidence of severely eroding streambanks in our study were largely hydrological, involving channelization and watershed position. Further, large-scale conversion of the landscape to row crops has intensified storm flows and nutrient and sediment loads, as has the pervasive altering of drainage, which can be seen with the 115 tile outlets found on Onion Creek in our RASCAL survey. These changes to the landscape are extensive and their negative effects are difficult to surmount. As we move forward with this project, we will continue to look for ways to reduce the damaging effects of excessive streambank erosion and improve water quality, but the solution likely requires more than just a change in riparian management.