Alteration of Sediment in a Ravine during Storage and Transport

By

Rachel Mohr

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By
Rachel Mohr
Under the supervision of Laura Triplett and Julie Bartley

ABSTRACT

As a result of increasing rates of erosion in the Minnesota River Basin over the past 200 years, the Minnesota River has become polluted with elevated levels of suspended sediment, which reduce water clarity and pose a threat to aquatic ecosystems. Successful erosion management could reduce the amount of sediment reaching the river, but first, the sources of erosion must be identified and the processes of erosion understood.

Of the many potential sources of eroding sediment in the Minnesota River Basin, ravines are unique because they can store eroded sediment for a time before transporting it to the main river channel. During this period of storage or during transportation, ravine sediment may be altered by chemical or physical weathering. These alterations can provide the evidence needed to determine the relative importance of transportation or storage as ravine processes.

This study quantifies the physical and chemical alteration of sediment eroded and stored within a ravine. Samples of a ravine wall and ravine floor were taken from a ravine feeding Seven Mile Creek, a tributary of the Minnesota River. Physical alteration of sediments was assessed via analysis of grain morphology and grain size distribution, measured using laser diffractometry. Chemical alteration was evaluated via an analysis of sediment mineralogy, measured using x-ray diffraction and optical microscopy. Sediment transportation was found to be the more dominant ravine process; evidence for sediment storage was distinct but more subtle.
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INTRODUCTION

The Minnesota River watershed is experiencing unprecedented levels of erosion. The natural erosion that started as a response to the drop in base level of the Minnesota River Valley by the Glacial River Warren has been amplified by anthropogenic alterations to the land, namely the conversion of wetlands to row-crop agriculture and the installation of artificial drain tile (Gran et al., 2009). The landscape is still in transition as a response to these changes, and tributaries continue to incise and cut headwards. The rapid incision and erosion of the landscape has led to increased amounts of sediments reaching the river, and increased levels of suspended sediments in the river.

Elevated levels of suspended sediment increase the turbidity, or murkiness, of water. High levels of turbidity pose a threat to aquatic ecosystems and diminish the quality of water for consumption or recreational uses (Lee et al., 1985; Neves et al., 1997). Turbidity is considered the most harmful of aquatic pollutants for fish and their habitats, as excess sediment can bury spawning grounds and reduce the populations of food sources like algae and insects (Charlton, 2008; Ogg and Perez, 2012). Currently, several reaches of the Minnesota River are classified as impaired under the Clean Water Act due to high levels of turbidity (Gran et al., 2011).

Efforts to reduce the level of turbidity in the Minnesota River will require an understanding of the sources of eroded sediment and the processes of erosion within the watershed. There have been many studies recently aimed at identifying the sources of eroded sediment using fingerprinting (Wilcock, 2009), gauging (Gran et al., 2011), LiDAR imagery (Azmera et al., 2016), and other methods. The most significant potential sources of sediment are ravines and bluffs (Wilcock, 2009). Recent studies have suggested that other potential sources, such as bedrock and upland soils, are not significant contributors of sediment (Triplett and Leaf, 2009).
Figure 1. Potential sources of sediment in the Minnesota River watershed, including ravines and bluffs. (Image from Gran et al., 2009)

The incision of the Minnesota River has resulted in the creation of bluffs and ravines, both erosional features. Bluffs are steep cliffs along the river channel, and typically form alongside river meanders, where the relatively fast current on the outside of the river’s curve erodes the adjacent bank. Bluff erosion supplies 50-60% of the Minnesota River’s suspended sediment (Gran et al., 2011).

Ravines are the result of streamcutting erosion, in which a stream acting as a tributary to the river will cut through the surrounding till and form a narrow valley that opens up into the river. Ravines typically contribute 2-20% of the eroded sediment in the Minnesota River watershed (Gran et al., 2011). Though they are net erosional features, ravines can store as well as erode sediments (Wilcock, 2009), and ravine floors often possess fluvial features such as small channels, sand bars, and floodplains. These fluvial deposits are candidates for a unique mineralogical and physical signature because of the reworking of the sediments by stream processes (Triplett and Leaf, 2009).
Although ravines are not the most significant source of sediment in this watershed, ravines are the focus of this study for several reasons. Firstly, little is known about the erosion processes within ravines. Past studies have disagreed on the dominant processes of erosion within ravines; Azmera et al. (2016) found that ravine walls are the major source of eroded sediment within ravines, but Gran et al. (2009) and Charlton (2008) have emphasized headcutting as a significant source of erosion within ravines. Also, while ravines are known to store sediment, little is known about how long sediments are stored within the ravine or whether the sediments are altered as a result of this storage (Gran et al., 2011).

Secondly, of the many potential mitigation strategies for controlling erosion in this watershed, the strategies targeting ravines are often cheaper, more feasible, and easier to implement (Braun and Magner, 2011; Gran et al., 2011). For example, installing woody debris on the floors of ravines would be a less labor-intensive strategy than restoring lakes or wetlands or stabilizing high bluffs along the Minnesota River (Braun and Magner, 2011). If ravines are providing a significant amount of sediment to the Minnesota River, even if they are not the single largest producers, cheap erosion control strategies might be cost effective while still making a significant impact on the turbidity problem.

Finally, forecasts for a wetter climate with an increasing frequency and intensity of precipitation events could disproportionately affect ravines and increase the relative importance of ravines as sources of sediment in the Minnesota River watershed (Wilcock, 2009; Garbrecht et al., 2014). The primary control on ravine erosion is fluvial discharge, and ravines respond nonlinearly in sediment production with increasing amounts of rainfall (Gran et al., 2011). It is important that we try to understand ravines now, before they become a bigger problem.

This study examines the physical and chemical alteration of sediments in a ravine to determine the relative amounts of transportation and storage of sediment within the ravine. Besides reducing erosion at its source, management strategies seeking to reduce the amount of sediment exiting ravines will aim to either reduce the amount of transportation or increase the amounts of storage within ravines. Understanding the processes of transportation and storage within ravines and their effects on ravine sediments are crucial for a successful application of management efforts.

**GEOLOGIC SETTING**

During the Wisconsin glaciation 75,000 years b.p., the Des Moines Lobe of the Laurentide ice sheet advanced from the northwest and covered the current extent of the Minnesota River Valley (Matsch, 1972). The Des Moines Lobe reached its maximum extent in central Iowa 14,000 radiocarbon years b.p. and then began to retreat, depositing thick layers of glacial sediments across southern Minnesota (Matsch, 1972; Belmont, 2011). These deposits are known as the New Ulm Formation, which is present at the surface in most of southern Minnesota (Lusardi, 1998; Jennings et al., 2012). The New Ulm Formation is
a Pleistocene-aged, vaguely bedded, pebbly sandy loam to pebbly clay loam, with a clasts composed of crystalline rock, carbonates, and shales characteristic of the Riding Mountain provenance (Jennings et al., 2012; Johnson et al., 2016). The New Ulm Formation is underlain by glacial tills from previous glaciations, the most recent being the Granite Falls Till (Matsch, 1972). These glacial tills remain un lithified and unconsolidated. The glacial tills in the Minnesota River watershed are underlain by Cretaceous and Paleozoic bedrock, such as the Upper Cretaceous Dakota Formation, the Lower Ordovician Oneota Dolomite, and the Upper Cambrian Jordan Sandstone, which are exposed in several places along the Minnesota River (Mossler and Chandler, 2012).

Figure 2. Location of the Des Moines lobe and Riding Mountain Provenance sediments in relation to Minnesota and Nicollet County (from Meyer et al., 2012).

Following the end of the last glaciation, the landscape was relatively flat (Belmont, 2011) and poorly drained (Jennings et al., 2012), with low-gradient streams of glacial meltwater origin (Wilcock, 2009; Belmont, 2011; Gran et al., 2011). In some locations, temporary ponding of meltwater produced deposits of fine-grained lacustrine sediments (Matsch, 1972). Most of the meltwater from the retreat of the Des Moines Lobe was confined to a large proglacial lake, called Lake Agassiz, which covered an area
of about 200,000 square miles in western Minnesota, eastern North Dakota, and parts of Manitoba and Ontario (Matsch, 1972; Gran et al., 2009).

Glacial Lake Agassiz was bordered to the south by several low moraine dams (Grant et al., 2009; Belmont, 2011). These damming moraines were breached around 11,500 radiocarbon years b.p. (13,400 calendar years before present), and Glacial River Warren formed as the spillway, creating a southern outlet for Lake Agassiz (Matsch, 1983; Belmont, 2011). The Glacial River Warren discharged southward, following a channel previously occupied by a glacial meltwater stream (Matsch, 1972), and cut through the landscape, incising and widening the ancestral Minnesota River Valley (Gran et al., 2011). The initial incision of the Minnesota River Valley 11,500 radiocarbon years b.p. (13,400 calendar years b.p.) dropped base level by nearly 70 m (Matsch, 1983; Belmont, 2011), and the River Warren occupied this valley until 10,900 radiocarbon years b.p. (Gran et al., 2011).

![Figure 3. Glacial Lake Agassiz and its southern outlet, Glacial River Warren (adapted from Johnson et al., 1998).](image)

The dramatic reduction in base level of the Minnesota River Valley left tributary streams stranded above the master stream (Gran et al., 2009; Wilcock, 2009). These tributaries incised rapidly and extended headward in response to this reduction in base level (Gran et al., 2009; Wilcock, 2009; Belmont, 2011; Gran et al., 2011; Jennings et al., 2012). In response to tributary stream incision, a drainage network of headward-migrating ravines now connects the steep stream gradients to the relatively flat uplands (Gran et al., 2012). These ravines act as pathways that transport runoff and sediment and increase connectivity within the watershed (Gran et al., 2011; Azmera et al., 2016).
The rapid incision of tributaries and ravines through the readily-erodible glacial deposits of this region has increased the supply of sediment to the Minnesota River. These natural rates of erosion have been further magnified by the introduction of row-crop agriculture in the last 170 years (Kelley and Nater, 2000b), which would ultimately modify as much as 92% of the land in the Minnesota River watershed (Kelley & Nater, 2000a). Artificial drainage was first introduced as early as the 1880s (Payne, 1994), and nearly all farms in the area today have some combination of drain tile or drainage ditches in order to improve crop yields (Gran et al., 2009). This extensive drainage network increased the hydraulic connectivity of the landscape (Azmera et al., 2016); precipitation that would once have infiltrated wetlands and slowly evaporated is now drained rapidly into the tributaries and the main channel of the Minnesota River (Payne, 1994). Increased runoff and erosion as a result of agricultural modifications have resulted in a 12-fold increase in the suspended sediment load of the Minnesota River (Kelley & Nater, 2000a).

In addition to the natural erosion occurring as a response to the drop in base level, and the increased erosion caused by the recent introduction of agriculture and artificial drainage, erosion in the Minnesota River watershed could be further exacerbated by an increasingly wetter climate. Climate change projections suggest that the frequency and intensity of rainfall events in this region will increase (Gran et al., 2011; Garbrecht et al., 2014). These predicted precipitation trends would result in increased erosion and movement of sediment to the Minnesota River (Gran et al., 2011).

Study Area

Seven Mile Creek is a steep, sediment-impaired tributary to the Minnesota River in Nicollet County, south-central Minnesota. It has a small, agricultural watershed of just under 80 km², and is fed by a network of ravines (Belmont, 2011; Hammer-Lester et al., 2015). Seven Mile Creek is rapidly incising and has two major headward-migrating knickpoints. One knickpoint is located 7 km upstream from the mouth, and is a response to the base level fall of the Minnesota River Valley; the other knickpoint is located 2 km upstream from the mouth, and is a result of the exposure of the Cambrian Jordan Sandstone (Belmont 2011; Mossler and Chandler, 2012).
Figure 4. Seven Mile Creek Watershed in relation to the Minnesota River Basin and the Middle Minnesota Major Watershed (adapted from Kuehner, 2001).

Much of Nicollet County, including the Seven Mile Creek watershed, has the Heiberg Member of the New Ulm Till present near the surface (Jennings et al., 2012). The Heiberg Member is a pebbly loam to clay loam with a matrix comprising 38% sand, 37% silt, and 25% clay. It is mostly unsorted glacial till, but also contains associated fine-grained lacustrine sediments and sand and gravel from meltwater streams. The very coarse sand fraction is 36% crystalline, 23% carbonate, and 41% shale, all from the Riding Mountain provenance (Jennings et al., 2012; Johnson et al., 2016). The Upper Cambrian Jordan Sandstone underlies the glacial till at Seven Mile Creek, and crops out in several bluffs in the lower reaches of the stream.
A ravine feeding Seven Mile Creek was chosen as the sampling location for this study. The ravine is known as ‘Ravine Z’ and is crossed near its mouth by a footpath that follows the creek along the length of Seven Mile Creek Park. Ravine Z is about 220 m long and contains a variety of fluvial features such as terraces, bars, knickpoints, and plunge pools. The ravine walls are primarily colluvium, with visible slumping of the original Heiberg Member Till (Jennings et al., 2012). Ravine Z is higher than the top of the Jordan Sandstone in Seven Mile Creek; thus, there is no exposed bedrock within the ravine.

METHODS

Field Methods

A ravine in Seven Mile Creek Park, known as “Ravine Z,” was selected as the study area for this project. A total of 50 sediment samples were collected along the length of the ravine. 22 of these samples were “till” samples taken from the walls of the ravine. These till samples were mostly taken from fresh, unweathered surfaces. The other 28 samples were “ravine channel” samples collected from a variety of fluvial features on the ravine floor, including terraces, sandbars, channels, and plunge pools. For each sample, 100-200 g of sediment were collected in a labeled plastic sample cup and field descriptions were logged in a field notebook. At each sample site, a photo was taken and a GPS location was recorded.
Figure 6. GPS locations of channel and till sediment samples collected in Ravine Z, and the relative location of Ravine Z within Seven Mile Creek Park. The head of the ravine is to the southwest, and the mouth of the ravine is to the northeast. Contour interval is 10 ft.
Figure 7. An example of a collection site for ravine channel sediments. Left image was taken on Sept. 24, 2015, when water was flowing through the ravine. Right image was taken on Oct. 4, 2015, when the ravine was dry. Ravine channel samples were taken from this location as a transect from the main channel (cup on the far left) to the highest point on a gravely bar (cup to the far right).

Figure 8. An example of a knickpoint in the ravine channel. Left image was taken on Sept. 24, 2015, when water was flowing through the ravine. Right image was taken on Oct. 4, 2015, when the ravine was dry. In both images, the arrows indicate the level of the channel above the knickpoint, and a plunge pool is visible in the lower left corner. The channel level drops 110 cm at this knickpoint.
Figure 9. Examples of ravine walls and till sediments. In some locations, such as in the top photo, the till had lenses of coarse, red-orange sand.
Linear distance into the ravine was measured approximately using a measuring tape. The distance was measured from the mouth of the ravine to the head of the ravine. The distance into the ravine as indicated by the measuring tape was noted for each sample site and was also recorded for significant ravine features such as knickpoints or plunge pools. As measured using the tape measure, the length of the ravine was 221 m. When measured using GIS and the sample GPS points, the length of the ravine was 194-210 m.

Samples were collected on October 4, 2015. On the day of sample collection, the ravine was not flowing and was completely dry. The ravine was also visited earlier that week, on September 24. At this time the ravine had a very low level of flow, but the ravine floor was completely saturated, and the walls were damp. In some places, the mud in the ravine channel was ankle-deep.

**Lab Methods**

Sample cups were brought back to the lab and weighed. Each sample was thoroughly stirred and homogenized, and for each sample, a representative 10 g subsample was set aside. The rest of the sample was dried in an oven at 100°C for several days and then weighed again. The dried samples were sieved using a 2.00 mm sieve to separate the gravel fraction (>2.00 mm) and the <2.00 mm fractions. The mass of each fraction was recorded.

The 10 g subsamples removed previously were wet-sieved to remove the gravel (>2.00 mm) fraction, which was discarded. 5 g of the <2.00 mm fraction was dried and powdered in preparation for the lithium metaborate fusion and loss on ignition (LOI) procedures. The rest of the <2.00 mm fraction was used for laser diffraction analysis.

**Figure 10.** Flowchart of sediment preparation
Analysis of Grain Size and Morphology

The grain size distributions and grain morphologies of the sediment samples were analyzed using a Microtrac S3500 Laser Diffractometer and in-line Imager. A detailed procedure for this method is outlined in Appendix 1. Each sediment sample was prepared and run on the Laser Diffractometer three times in order to meet accepted standards and test reproducibility (Horiba, 2014).

Analysis of Major Element Ratios

The concentrations of major elements (Al, Ca, K, Na) in the sediment samples were measured using an Agilent 7700x Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Sediment samples were prepared for ICP-MS analysis using a lithium metaborate fusion (Knurr, 2014). A detailed procedure for the lithium metaborate fusion is outlined in Appendix 2. Due to time constraints, only 18 of the 50 sediment samples were prepared for and run on the ICP-MS, but these 18 samples were selected to be representative of the different types of sediment samples collected.

For all of the samples prepped for ICP-MS analysis, the amount of carbonate in each sample was determined using a loss-on-ignition procedure (Myrbo, 2013). Clean, dry crucibles were weighed, and a small amount of the powdered sediment was placed into each crucible. The mass of the crucibles and sediment was recorded before the crucibles were placed in a furnace at 550°C for four hours to burn off the organic matter. The crucibles were allowed to cool before their masses were again recorded. The crucibles were then placed in a 1000°C furnace for 2 hours to burn off the carbonate material. After the crucibles cooled, their masses were recorded.

RESULTS

Chemical Alteration

Chemical Index of Alteration (CIA) values were calculated for 11 ravine floor and 8 till samples, and these CIA values were plotted against the locations of the samples within the ravine (Figure 1). CIA values indicate the relative amount of chemical alteration of silicate minerals, on a scale from 1 to 100, with higher values indicating a greater degree of chemical alteration. Typical CIA values for fresh granites and feldspars range between 45 and 55, and typical values for secondary clay minerals range between 75 and 100 (Table 1). Ravine floor samples had measured CIA values ranging between 60.9 and 71.6; till samples had CIA values between 62.0 and 75.4 (Table 2). Triplicate measurements on one of the ravine floor samples produced CIA values with a 0.72% relative standard deviation, with repeat measurements deviating a maximum of ±0.58 units from the mean measured value.
A Mann-Whitney U-test showed no statistical difference between CIA values for ravine floor and till samples (Table 3), but Figure 11 shows that ravine floor samples tend to have CIA values higher than those of nearby till samples. Spearman correlation tests showed no statistically significant correlations between ravine floor or till samples and their locations within the ravine (Table 4).

<table>
<thead>
<tr>
<th>Rock/Clay</th>
<th>CIA Value</th>
<th>Intensity of Weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite</td>
<td>~100</td>
<td>High</td>
</tr>
<tr>
<td>Illite</td>
<td>~75-90</td>
<td>Moderate</td>
</tr>
<tr>
<td>Muscovite</td>
<td>~75</td>
<td>Moderate</td>
</tr>
<tr>
<td>Shale</td>
<td>~65-70</td>
<td>Low</td>
</tr>
<tr>
<td>Feldspar</td>
<td>~50</td>
<td>Low</td>
</tr>
<tr>
<td>Fresh Granite/Granodiorite</td>
<td>~45-55</td>
<td>None</td>
</tr>
<tr>
<td>Average Upper Crust</td>
<td>~47</td>
<td>None</td>
</tr>
<tr>
<td>Fresh Basalt</td>
<td>~30-45</td>
<td>None</td>
</tr>
</tbody>
</table>

Table 1. Approximate range of typical CIA values in various rock and clay mineral sources (adapted from McLennan, 1993; Hofer et al., 2012; Adolphi, 2014).

Chemical Proxy of Alteration (CPA) values were also calculated for 11 ravine floor and 8 till samples, and these CPA values were plotted against the locations of the samples within the ravine (Figure 12). Like the CIA, CPA values indicate the relative amount of chemical alteration of silicate minerals, on a scale from 1 to 100, with higher values indicating a greater degree of chemical alteration. Ravine floor samples had measured CPA values between 82.4 and 88.1; till samples had CPA values between 81.4 and 87.5 (Table 2). Triplicate measurements on one of the ravine floor samples produced CPA values with a 0.094% relative standard deviation, with repeat measurements deviating a maximum of ±0.09 units from the mean measured value.

A Mann-Whitney U-test showed no statistical difference between CPA values for ravine floor and till samples (Table 3), but Figure 12 shows that ravine floor samples tend to have CPA values higher than those of nearby till samples. Spearman correlation tests showed no significant correlations between ravine floor or till samples and their locations within the ravine (Table 4).
The amount of carbonate and organic matter in the sediments as a weight/weight percentage was determined for the same 11 ravine floor and 8 till samples that were analyzed for chemical weathering using the CIA and CPA. The % (w/w) organic matter (OM) in the sediments was plotted against the samples’ locations within the ravine (Figure 13). Till samples had an average of 2.47% (w/w) OM, with a total range from 1.13 to 5.02%, and ravine floor samples had an average of 2.41% (w/w) OM, with a total range from 0.95 to 4.90% (Table 2). A Mann-Whitney U-test showed no statistical difference between %OM for ravine floor and till samples (Table 3). The highest values for %OM in ravine floor samples
occurred within 80 m of the mouth of the ravine, or within 26 m of the head of the ravine. The only statistically significant correlation between location and %OM was found for till samples, which decrease in %OM towards the mouth of the ravine (Table 4).

Figure 13. Organic matter present in ravine floor and till sediments in Ravine Z, expressed as a weight/weight percentage of the total amount of sediment.

The % (w/w) carbonate in the sediments was also plotted against the samples’ locations within the ravine (Figure 14). Till samples had an average of 4.19% (w/w) carbonate, with a total range from 2.22 to 6.91%, and ravine floor samples had an average of 3.74% (w/w) carbonate, with a total range from 2.78 to 4.90% (Table 2). A Mann-Whitney U-test showed no statistical difference between carbonate content for ravine floor and till samples (Table 3). In general, the carbonate content of ravine floor samples remains fairly consistent throughout the ravine, with less variation than the till samples. The carbonate content of till samples varies the most within 47 m of the head of the ravine. A lack of till samples near the mouth of the ravine makes it unclear whether or not the variation in till carbonate content actually decreases towards the mouth of the ravine, as it appears to do. There is no statistically significant correlation between location within the ravine and carbonate content for either ravine floor or till samples (Table 4).

A second 4-hour burn at 1000°C was conducted for two of the till samples (T-10 and T-14) to determine the accuracy of the first carbonate burn. For T-10, the second burn only increased the carbonate content by 0.03% (w/w), for a new total carbonate content of 6.94% (w/w). For T-14, the second burn only increased the carbonate content by 0.04% (w/w), for a new total carbonate content of 2.68% (w/w). The CIA values for these two samples were recalculated with these new, increased values for carbonate content, but the CIA value did not change in either case.
**Figure 14.** Carbonate present in ravine floor and till sediments in Ravine Z, expressed as a weight/weight percentage of the total amount of sediment.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>% (w/w) organic matter</th>
<th>% (w/w) carbonate</th>
<th>CIA</th>
<th>CPA</th>
<th>Site Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-02</td>
<td>1.83</td>
<td>3.32</td>
<td>66.75</td>
<td>84.03</td>
<td>channel</td>
</tr>
<tr>
<td>C-03</td>
<td>1.28</td>
<td>3.31</td>
<td>65.86</td>
<td>82.42</td>
<td>main channel</td>
</tr>
<tr>
<td>C-07</td>
<td>0.95</td>
<td>3.28</td>
<td>68.03</td>
<td>83.81</td>
<td>channel, reddish color</td>
</tr>
<tr>
<td>C-09</td>
<td>4.90</td>
<td>3.75</td>
<td>70.14</td>
<td>87.27</td>
<td>channel under woody debris</td>
</tr>
<tr>
<td>C-12</td>
<td>3.25</td>
<td>3.97</td>
<td>68.51</td>
<td>85.60</td>
<td>small terrace, 20 cm high</td>
</tr>
<tr>
<td>C-15</td>
<td>3.85</td>
<td>3.17</td>
<td>69.27</td>
<td>85.59</td>
<td>large terrace, 60-70 cm high</td>
</tr>
<tr>
<td>C-19</td>
<td>1.38</td>
<td>2.78</td>
<td>67.48</td>
<td>83.20</td>
<td>main channel</td>
</tr>
<tr>
<td>C-20</td>
<td>1.21</td>
<td>4.90</td>
<td>60.93</td>
<td>83.17</td>
<td>channel, reddish sand</td>
</tr>
<tr>
<td>C-24</td>
<td>1.52</td>
<td>4.62</td>
<td>65.61</td>
<td>82.78</td>
<td>main channel, incised 30-40 cm</td>
</tr>
<tr>
<td>C-27</td>
<td>3.85</td>
<td>3.69</td>
<td>71.58</td>
<td>88.06</td>
<td>channel</td>
</tr>
<tr>
<td>C-28</td>
<td>2.49</td>
<td>4.29</td>
<td>68.13</td>
<td>85.61</td>
<td>plunge pool</td>
</tr>
<tr>
<td>T-02</td>
<td>1.95</td>
<td>3.87</td>
<td>66.83</td>
<td>82.68</td>
<td>till</td>
</tr>
<tr>
<td>T-05</td>
<td>1.13</td>
<td>4.59</td>
<td>62.31</td>
<td>82.49</td>
<td>till, reddish sand</td>
</tr>
<tr>
<td>T-10</td>
<td>1.51</td>
<td>6.91</td>
<td>62.00</td>
<td>81.40</td>
<td>till, graded beds</td>
</tr>
<tr>
<td>T-11</td>
<td>2.14</td>
<td>2.22</td>
<td>75.40</td>
<td>86.40</td>
<td>till and weathered, crumbling rock</td>
</tr>
<tr>
<td>T-13</td>
<td>2.35</td>
<td>5.37</td>
<td>65.15</td>
<td>83.29</td>
<td>till, graded beds</td>
</tr>
<tr>
<td>T-14</td>
<td>5.02</td>
<td>2.64</td>
<td>71.50</td>
<td>87.47</td>
<td>till, unweathered surface</td>
</tr>
<tr>
<td>T-18</td>
<td>3.13</td>
<td>4.66</td>
<td>69.23</td>
<td>86.56</td>
<td>fresh slump surface</td>
</tr>
<tr>
<td>T-20</td>
<td>2.53</td>
<td>3.22</td>
<td>70.51</td>
<td>86.17</td>
<td>head of ravine</td>
</tr>
</tbody>
</table>

**Table 2.** Site descriptions and chemical weathering data, including organic and carbonate content and chemical index of alteration (CIA) and chemical proxy of weathering (CPA) values, for ravine floor (C) and till (T) samples from Ravine Z.
Table 3. P-values for Mann-Whitney U-tests comparing the means of chemical variables for ravine floor and till samples from Ravine Z. P-values less than 0.050 (highlighted) indicated statistically significant differences between ravine floor and till samples. For each chemical variable listed, the 95% confidence interval for each sample type is listed.

<table>
<thead>
<tr>
<th></th>
<th>Ravine Floor</th>
<th>Till C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIA</td>
<td>0.901</td>
<td>67.481 ± 1.881</td>
</tr>
<tr>
<td>CPA</td>
<td>0.967</td>
<td>84.685 ± 1.258</td>
</tr>
<tr>
<td>% Organic Matter</td>
<td>0.773</td>
<td>2.410 ± 0.904</td>
</tr>
<tr>
<td>% Carbonate</td>
<td>0.650</td>
<td>3.737 ± 0.440</td>
</tr>
</tbody>
</table>

Table 4. P-values (P) and correlation coefficients ($R_s$) for Spearman Correlation tests measuring the strength of association between chemical variables of ravine floor or till samples and the samples’ locations within Ravine Z. P-values less than 0.050 (highlighted) indicate statistically significant correlations, and $R_s$ values range between -1 and +1, with positive values indicating a positive relationship between the chemical variable and the distance from the ravine mouth.

<table>
<thead>
<tr>
<th></th>
<th>Ravine Floor</th>
<th>Till</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIA</td>
<td>0.633</td>
<td>0.260</td>
</tr>
<tr>
<td>CPA</td>
<td>0.384</td>
<td>0.072</td>
</tr>
<tr>
<td>% Organic Matter</td>
<td>0.538</td>
<td>0.196</td>
</tr>
<tr>
<td>% Carbonate</td>
<td>0.188</td>
<td>0.416</td>
</tr>
</tbody>
</table>

Physical Alteration

Average values for grain roundness and sphericity for each sample measurement were obtained from the imager on the Microtrac laser diffractometer. For both roundness and sphericity, the possible scale of values ranges from 0 to 1, with 1 being the most rounded or most spherical. The 95% confidence interval for the average roundness was 0.588 ± 0.002 for ravine floor sediments and 0.575 ± 0.005 for till sediments (Figure 15). The 95% confidence interval for the average sphericity was 0.863 ± 0.001 for ravine floor sediments and 0.858 ± 0.002 for till sediments (Figure 16). A Mann-Whitney U-test showed a statistical difference between ravine floor and till sediments for both roundness and sphericity values (Table 5).
Figure 15. Average roundness values for ravine floor and till sediments in Ravine Z. Error bars indicate the extent of the 95% confidence interval for each set of samples.

Figure 16. Average sphericity values for ravine floor and till sediments in Ravine Z. Error bars indicate the extent of the 95% confidence interval for each set of samples.

Roundness and sphericity values for ravine floor and till sediments were plotted against the samples’ locations within the ravine (Figures 17 and 18). The only statistically significant correlation between location and morphology is the negative correlation between the roundness of ravine floor sediments and the distance from the mouth of Ravine Z (Table 6).
**Figure 17.** Average roundness values for ravine floor and till samples in Ravine Z. Error bars indicate the actual range of roundness values measured for each sample.

**Figure 18.** Average sphericity values for ravine floor and till samples in Ravine Z. Error bars indicate the actual range of sphericity values measured for each sample.
Table 5. P-values for Mann-Whitney U-tests comparing the means of physical variables for ravine floor and till samples from Ravine Z. P-values less than 0.050 (highlighted) indicated statistically significant differences between ravine floor and till samples. For each physical variable listed, the 95% confidence interval for each sample type is listed.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ravine Floor C.I.</th>
<th>Till C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundness</td>
<td>&lt;0.001</td>
<td>0.588 ± 0.003</td>
</tr>
<tr>
<td>Sphericity</td>
<td>0.002</td>
<td>0.863 ± 0.001</td>
</tr>
<tr>
<td>Sorting (phi)</td>
<td>0.009</td>
<td>2.388 ± 0.162</td>
</tr>
<tr>
<td>% Gravel</td>
<td>0.087</td>
<td>21.632 ± 7.686</td>
</tr>
<tr>
<td>Matrix % Sand</td>
<td>0.005</td>
<td>73.460 ± 4.112</td>
</tr>
<tr>
<td>Matrix % Silt</td>
<td>0.018</td>
<td>22.813 ± 3.319</td>
</tr>
<tr>
<td>Matrix % Clay</td>
<td>&lt;0.001</td>
<td>3.727 ± 0.939</td>
</tr>
</tbody>
</table>

Table 6. P-values (P) and correlation coefficients (R_s) for Spearman Correlation tests measuring the strength of association between physical variables of ravine floor or till samples and the samples’ locations within Ravine Z. P-values less than 0.050 (highlighted) indicate statistically significant correlations, and R_s values range between -1 and +1, with positive values indicating a positive relationship between the physical variable and the distance from the ravine mouth.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ravine Floor</th>
<th>Till</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundness</td>
<td>0.0133</td>
<td>0.709</td>
</tr>
<tr>
<td>Sphericity</td>
<td>0.245</td>
<td>0.848</td>
</tr>
<tr>
<td>Sorting (phi)</td>
<td>0.0502</td>
<td>0.653</td>
</tr>
<tr>
<td>% Gravel</td>
<td>0.344</td>
<td>0.119</td>
</tr>
<tr>
<td>Matrix % Sand</td>
<td>0.0003</td>
<td>0.257</td>
</tr>
<tr>
<td>Matrix % Silt</td>
<td>0.0012</td>
<td>0.326</td>
</tr>
<tr>
<td>Matrix % Clay</td>
<td>0.0000</td>
<td>0.337</td>
</tr>
</tbody>
</table>

The percentage of gravel (>2mm) in each sediment sample was determined and plotted against the samples’ locations within the ravine (Figure 19). The percentages of sand, silt, and clay were also determined for each sediment sample and reported as percentages of the <2 mm fraction. Grain size data for each sample are listed in Table 7. In general till samples had larger percentages of gravel than ravine floor samples, but this difference is not statistically significant (Table 5). Additionally, no statistically significant correlation was found between the amount of gravel in till or ravine floor sediments and those samples’ locations within the ravine (Table 6).
Figure 19. Percent gravel in ravine floor and till sediment samples in Ravine Z.
Table 7. Site descriptions, locations, and grain size distribution data, including percentage of gravel and percentages of sand, silt, and clay in the <2mm sediment fractions, for ravine floor (C) and till (T) samples from Ravine Z.

The proportions of sand, silt, and clay present in the till and ravine floor sediments were plotted on a ternary diagram (Figure 20). The majority of the measured samples have compositions corresponding to ‘sandy loam,’ although the ravine floors samples have a wider spread, extending further into the ‘loamy sand’ and ‘sand’ categories. The ravine floor samples were plotted separately on another ternary diagram, with the samples further categorized as either “channel,” “bar/terrace,” or “plunge pool” locations (Figure 21). In this diagram, it is clear that most of the ravine floor samples taken from a bar, terrace, or plunge pool location have a sandy loam grain size distribution, whereas channel samples have sandier compositions.
Figure 20. Ternary diagram of the grain size distributions of the <2 mm fraction of ravine floor and till sediments from Ravine Z. Each sample was measured three times and each of these measurements is represented by a single point on the diagram.
Figure 21. Ternary diagram of the grain size distributions of the <2 mm fraction of ravine floor sediments from Ravine Z further distinguished as specific features, including channel, bar/terrace, and plunge pool samples. Each sample was measured three times and each of these measurements is represented by a single point on the diagram.

The percentages of sand, silt, and clay in the ravine floor and till samples were plotted against their locations within the ravine (Figures 22-24). Ravine floor and till sediments have statistically significant differences in mean percentages of sand, silt, and clay (Table 5). No correlations between grain size and location were found for any till samples, but ravine samples had statistically significant correlations between location and all three grain size categories (Table 6). The percentage of sand in ravine floor sediment has a negative correlation with the distance from the mouth of the ravine, and the percentages of silt and clay both have positive correlations with the distance from the mouth of the ravine.
Figure 22. Percent sand in the <2mm fraction for ravine floor and till sediment samples in Ravine Z. Error bars indicate the actual range of measurements recorded for each sample.

Figure 23. Percent silt in the <2mm fraction for ravine floor and till sediment samples in Ravine Z. Error bars indicate the actual range of measurements recorded for each sample.
Figure 24. Percent clay in the <2mm fraction for ravine floor and till sediment samples in Ravine Z. Error bars indicate the actual range of measurements recorded for each sample.

The degree of sorting of each sediments’ grain size distribution was also determined using the Microtrac Laser Diffractometer, with values corresponding to the phi scale in Table 8. Ravine floor sediments had an average phi value of 2.388 and till sediments had an average phi value of 2.724. Both of these indicate a very poorly sorted sediment on the phi scale, but the Mann-Whitney U-test indicates that there is a statically significant difference between the two populations (Table 5), meaning that till sediments are significantly less sorted than ravine floor sediments. There is no correlation between location and the sorting of either ravine floor or till sediments (Table 6).

<table>
<thead>
<tr>
<th>Degree of Sorting</th>
<th>Phi Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>very well sorted</td>
<td>under 0.35 phi</td>
</tr>
<tr>
<td>well sorted</td>
<td>0.35 to 0.50 phi</td>
</tr>
<tr>
<td>moderately well sorted</td>
<td>0.50 to 0.71 phi</td>
</tr>
<tr>
<td>moderately sorted</td>
<td>0.71 to 1.0 phi</td>
</tr>
<tr>
<td>poorly sorted</td>
<td>1.0 to 2.0 phi</td>
</tr>
<tr>
<td>very poorly sorted</td>
<td>2.0 to 4.0 phi</td>
</tr>
<tr>
<td>extremely poorly sorted</td>
<td>over 4.0 phi</td>
</tr>
</tbody>
</table>

Table 8. Phi scale indicating the degree of sorting of a sediment’s grain size distribution. Phi values are obtained from the inclusive graphic standard deviation. (Adapted from Microtrac, 2012).
DISCUSSION

An understanding the processes involved in ravine erosion is vital in order to successfully implement erosion mitigation strategies within ravines. As erosion of sediment occurs within a ravine, the sediment will either be stored within the ravine or transported through the ravine (Gran et al., 2011). Evidence of physical and chemical weathering can help determine whether sediments have been influenced more by storage or by transportation. Sediment in storage generally experiences chemical weathering, since chemical weathering requires prolonged exposure to atmospheric conditions, and sediment in transport generally experiences physical weathering, often as a result of fluvial processes that sort or rework the sediment (Adolphi, 2014). In combination, these factors can provide a wealth of information about the processes involved in ravine erosion, and may be able to assist in the selection of erosion mitigation strategies.

Physical Weathering

Fluvial processes can cause physical weathering in sediments as a result of hydrodynamic sorting, which can alter the grain size distributions of sediments; or as a result of turbulence which causes suspended grains to crash into each other or into grains at rest, which can alter the grain size or grain morphology of sediments. The sediments in Ravine Z are undergoing an observable amount of physical weathering, as evidenced by statistically significant differences between several physical characteristics of ravine floor and till sediments, including roundness, sphericity, sorting, and grain size distributions.

Grain Morphology

Ravine floor samples had higher values for roundness and sphericity than till sediments, indicating that sediments transported through the ravine were reworked and physically altered by fluvial processes (Bahlburg and Dobrzinski, 2009). These slight, but statistically significant increases in roundness in sphericity were surprising, as the fluvial processes that cause these morphological changes are generally thought to be gradual, occurring as a result of significant amounts of processing (Payne, 1994), yet the fluvial system in Ravine Z is relatively short – only about 221 m long. These observable morphological changes in the sediments despite the short length of the ravine—and therefore a low amount of potential processing—may indicate that much of the sediment in the ravine channel was sourced at the head of the ravine and traveled most of the length of the ravine. The farther that sediment travels through the ravine, the more it maximizes its potential to be morphologically altered.

However, it is also likely that the apparent morphological alterations to the ravine floor sediments are due partly to the increase in the proportion of sand along the length of the ravine. Smaller particles
like silts and clays tend to be less rounded and spherical than sand, so the proportions of sand can artificially affect measurements for the roundness and sphericity of whole sediments. Values for roundness, sphericity, and the proportion of sand in ravine floor sediments all increase towards the mouth of Ravine Z, and there is a statistically significant positive correlation between roundness and the proportion of sand in the ravine floor sediments ($P=0.0003$). Measuring the morphological characteristics of consistent size fractions of ravine sediments in a future study could help determine whether or not the morphology trends for ravine sediments in Ravine Z are significantly influenced by the grain size distributions.

The idea that a large portion of the ravine channel sediment is eroding from the head of the ravine is at odds with recent studies which have suggested that the ravine walls are the more important source of eroded materials within ravines (Gran et al., 2011; Azmera et al., 2016). For example, Azmera et al. (2016) found that ravine walls were a more important source of eroded sediment than headcuts for certain ravines in the Le Sueur River watershed. It is important to note, however, that the ravines used in that study were nearly 17 times longer than Ravine Z. It is possible that the relative importance of erosion sources within a ravine depend on the length of the ravine in question; with a shorter overall length and therefore relatively less wall area to erode, Ravine Z may have a higher proportion of eroding sediment sourced from its headcut than the ravine studied by Azmera et al.

Knowing which part of a ravine has a higher relative contribution of eroded sediment can provide valuable information for the implementation of erosion mitigation strategies. If a significant amount of Ravine Z’s transported sediment is sourced at its head rather than from along the ravine walls, then mitigation strategies focused on slowing headward erosion might be more effective than strategies focused on stabilizing the ravine walls. For longer ravines where wall erosion is a greater supplier of sediment, like the ones studied by Azmera et al. (2016), the opposite might be true, and stabilizing the ravine walls might be more effective. Future studies intending to compare potential erosion mitigation strategies for ravines should take the length of the target ravines into account, as different management strategies may be more effective in different lengths of ravines.

**Grain Size Distributions**

In fluvial systems, hydrodynamic sorting will cause sediment to become depleted in finer particles, because the smaller particles of silt and clay are more easily carried away in the suspended load (Bahlburg and Dobrzinski, 2009; Gran et al., 2009). This transportation and depletion of the suspended load leaves behind more well-sorted sediments enriched in sands and gravels, depending on the velocity and turbulence of the discharge (Payne, 1994). The trends in grain size distributions of the sediments along the ravine floor in Ravine Z are evidence of this hydrodynamic sorting; from the head of Ravine Z...
to the mouth, ravine floor sediments have decreasing proportions of silt and clay, and increasing proportions of sand. This depletion of fine-grained sediments results in ravine floor sediments that are significantly more well sorted than the original till sediments ($P=0.009$). For till sediments in Ravine Z, grain size distributions do not change systematically along the length of the ravine, which indicates that the trends in grain size for ravine floor sediments are not simply a reflection of spatial differences in till composition, but are actually a result of fluvial processes reworking sediment within the ravine.

Channel sediments are notably sandier than nearby bar or terrace sediments throughout the length of the ravine (Figure 22). Similarly, in Figures 23 and 24, the opposite trend is true, with channel sediments generally having lower proportions of silt or clay than nearby bar or terrace sediments. These differences between channel and bar or terrace sediments indicate that some physical process is reworking sediment on the floor of the ravine to give these two populations distinct grain size distributions. Additionally, the greater similarity of the grain size distributions of bar and terrace sediments to those of till sediments than to those of channel sediments (as shown in Figures 20 and 21), indicates that most of the alteration of sediment grain size distributions within the ravine is occurring within the ravine channel, as a result of fluvial processes, since the fluvial channel has sediments most different from the original till material.

**Chemical Weathering**

Sediments exposed to atmospheric surface conditions experience chemical weathering, which modifies the major element ratios of the sediment and results in the production of secondary clay or hydrous minerals (Adolphi, 2014). Chemical weathering is a process that takes time, and significant alterations due to chemical weathering cannot occur in a rapidly eroding environment (McLennan, 1993). This means that the relative degree of chemical weathering in ravine floor sediments can be used to determine the relative length of storage of those sediments; sediments that have been in storage for a long time will have higher degrees of chemical weathering than sediments frequently in transport will have.

**CIA and CPA**

The CIA and the CPA are quantitative indicators of the relative degree of chemical weathering in sediments (Burke et al., 2008; Shao and Yang, 2012). In Ravine Z, there were no statistically significant differences for CIA or CPA between till and ravine floor sediments, which would initially suggest that there is not a significant amount of chemical weathering occurring within the ravine. However, a closer look at ravine floor sediments reveals subtle, but distinct evidence of chemical weathering.
For ravine floor sediments, the highest CIA and CPA values were calculated for samples located either on terraces or in channels dammed by woody debris (Figures 25 and 26); sediments in active channels had the lowest values for CIA and CPA. The higher CIA and CPA values for terrace sediments indicate that these sediments were not part of the active fluvial channel and had a longer period of storage, allowing increased chemical weathering to occur. The even higher CIA and CPA values for dammed channel sediments indicate that these sediments were also stored longer than the typical ravine channel sediments – likely as a result of the woody debris blocking the flow of the channel in these locations, causing sediment to build up as a result. Although the sample size in this instance is small, the measurable increase in chemical weathering as a result of woody debris suggests that the artificial addition of woody debris to the ravine channel could be an effective mitigation strategy for reducing the amount of sediment leaving the ravine. The measurably higher CIA and CPA values for terraces and dammed channels indicates that for these sediments, the chemical weathering signal was able to overpower the physical weathering signal, suggesting that storage rather than transportation is the dominant process at these sites.

**Figure 25.** Annotated chart of Chemical Index of Alteration (CIA) values for ravine floor and till sediments in Ravine Z. Ravine floor sediments from terraces or blocked channels are labeled and grouped roughly within the pink circle. The lower green circle roughly encompasses the CIA values of the unblocked channel sediments. The ravine floor sample farthest to the left is a plunge pool site.
Figure 26. Annotated chart of Chemical Proxy of Alteration (CPA) values for ravine floor and till sediments in Ravine Z. Ravine floor sediments from terraces or blocked channels are labeled and grouped roughly within the pink circle. The lower green circle roughly encompasses the CPA values of the unblocked channel sediments. The ravine floor sample farthest to the left is a plunge pool site.

The low CIA and CPA values for ravine sediments in unblocked channels indicate that these sediments are not stored long enough to experience significant chemical weathering. This means that transportation, rather than storage, is the dominant process in this part of the ravine. However, it is also possible that fluctuations between storage and transportation, and therefore the relative amount of chemical weathering (and the magnitude of CIA and CPA values), are seasonal phenomena. Ravines have ephemeral flows, flowing heavily in the spring and early summer, and running dry in the fall and winter (Gran et al., 2011). It is possible that significant chemical weathering occurs in the ravine channel during the fall and winter, when the ravine is dry. This would make CIA and CPA values high for ravine sediments in the late winter, before the ravine begins to flow again. Similarly, CIA and CPA values would then be seasonally low at the end of summer, after the more chemically weathered sediment in the ravine has been thoroughly flushed out by spring melts and summer storms. The low CIA and CPA values measured for ravine channel sediments in this study may be due to the timing of the collection of data. It is possible that sample collection in the same location at a different time of year could produce significantly different results for these values.

Several studies have shown that CIA or CPA values may also be artificially affected by hydrodynamic sorting. Since chemical weathering produces clay minerals, fluvial sediments depleted or enriched with clay-sized particles as a result of sorting will present artificially low or high CIA or CPA values, respectively (Bahlburg and Dobrzinski, 2009; Shao and Yang, 2012; Adolphi, 2014). It is possible that our ravine channel samples had artificially low CIA and CPA values due to a depletion of
clay-sized particles that were carried away as a result of fluvial processes. However, there were no significant correlations found between the proportion of clay in ravine channel samples and their CIA or CPA values (P=0.450 and 0.116). To test the possibility of hydrodynamic sorting affecting the measurements of chemical weathering, future studies should use a consistent grain size fraction to measure CIA and CPA values.

It is possible that the wide variation in CIA and CPA values for the till in Ravine Z may be obscuring trends in chemical weathering of the ravine floor sediments that might otherwise be apparent. The variations in the tills’ chemical weathering could be due to the presence of two slightly different till units within Ravine Z, since there are two spatially distinct populations of CIA or CPA values for till sediments, with higher values occurring near the head of the ravine, and lower values occurring near the mouth of the ravine. More samples and detailed descriptions of till sediments would be required to confirm or refute the possibility of two distinct till units within Ravine Z.

In a typical fluvial system, CIA and CPA values are known to increase from the upper to lower reaches (Bahlburg and Dobrzinski, 2009; Shao and Yang, 2012). However, no significant correlations were found between CIA or CPA values and location within the ravine for ravine floor samples. It is likely that Ravine Z is not a long enough system for this trend to emerge.

**Carbonate and Organic Matter**

Other indicators of chemical alteration in sediments include their relative proportions of carbonate and organic matter. The percentage of organic material present in ravine floor and till sediments was positively correlated with the CPA values of those sediments (P=0.00285 and 0.0000002), indicating that sediments with higher degrees of chemical weathering also had higher amounts of organic matter. The amount of organic matter is not a direct result of increased chemical weathering, but it is likely that the same sites that experience enhanced chemical weathering also collect greater amounts of organic matter due to their longer period in storage. Sediments that sit undisturbed for longer periods of time, such as terrace sediments or sediments in dammed channels, will have more time to chemically weather and more time to collect and incorporate organic material such as seasonal leaf litter. Channel sediments that are frequently flushed through the ravine are in transit more frequently than in storage, so they have less time to chemically weather or accumulate organic material.

Unlike the organic matter, the percentage of carbonate in ravine sediments was negatively correlated with chemical weathering. The negative correlation between CIA values and percentage of carbonate is statistically significant for till sediments (P=0.0000002). These negative correlations indicate that sediments with a higher degree of chemical weathering have relatively lower amounts of
carbonate. This trend can be explained by the fact that carbonate minerals are unstable under atmospheric conditions and readily break down or dissolve (Adolphi, 2014).

Pollutants

Physical and chemical weathering are not independent processes within ravines. Sediments that are in storage longer—whether because they on bars or terraces outside of the active fluvial channel, or because they consist of the larger sands and gravels left behind after hydrodynamic sorting—have more time to be affected by chemical weathering. Not only does the chemical weathering alter the chemistry of the sediment, but it also breaks up larger grains into smaller grains, in part through the formation of secondary clay minerals. This means that sediments in storage long enough to be significantly chemically weathered will have increased amounts of fine-grained particles that can be carried in the suspended load when the sediment is ultimately carried out of the ravine. The cycles of transportation, storage, weathering, and remobilization of sediments within ravines may be resulting in more fine-grained particles exiting the ravine and joining the suspended sediment load than were present in the original eroded source material. In a sense, ravines are capable of manufacturing fine-grained particles.

An increased amount of fine-grained particles passing through the ravine is not only a concern because it increases the load of total suspended solids and enhances turbidity, but also because smaller particles can increase the mobility of pollutants, such as nutrients or pathogens, through the ravine (Kelley and Nater, 2000a; Azmera et al., 2016). Smaller grain sizes of suspended sediments have higher adsorptive capacities, meaning that more pollutants can cling to them (Knighton, 1998). Since ravines in the highly agricultural Minnesota River watershed are often draining agricultural fields, and in many cases, directly fed by drain tile, they likely receive a significant amount of agricultural runoff including contaminants such as nutrients or pathogens (Kuehner, 2001; Mulla et al., 2008; Hammer-Lester et al., 2015). The combination of direct agricultural runoff and the large amount of fine particles onto which contaminants can be adsorbed may mean that ravines like Ravine Z are relatively larger contributors of pollutants to the Minnesota River than other sources of eroding sediment are.

Mitigation Strategies

The goals of any erosion mitigation strategies in ravines in the Minnesota River watershed—besides reducing erosion at its source—are essentially to minimize or slow the transportation of sediments through the ravine, and to increase the length of storage of sediments within the ravine. In general, the evidence of physical weathering in Ravine Z was much more significant than evidence of chemical weathering, indicating that transportation rather than storage is the dominant process within the ravine.
This information, combined with the knowledge that the sediment output of ravines increases nonlinearly with increased levels of discharge (Gran et al., 2011), suggests that management strategies aimed at reducing the amount of flow through the ravine may be the most effective way to initially reduce the amount of sediment exiting the ravine. Reduced flow to ravines can be implemented by installing buffer zones in between highly drained agricultural fields and the heads of nearby ravines.

The most effective natural storage of sediments within Ravine Z occurred in channels blocked by woody debris, which is indicated by high levels of chemical weathering in those locations. Management strategies aimed at reducing the amount of sediment exiting the ravine by increasing its length of storage within the ravine may therefore meet the greatest success when they imitate the natural blockage of the ravine channel. The application of woody debris along the ravine channel could therefore be an effective way to reduce the amount of sediment transported through the ravine. This strategy has the added benefit of being relatively cheap to implement and not very labor-intensive (Braun and Magner, 2011).

Erosion mitigation strategies that seek to prevent further erosion within the ravine can be divided into two categories: stabilization of ravine walls or stabilization of the head of the ravine. The part of the ravine that contributes relatively more eroded sediment should be the focus of these stabilization strategies. As discussed previously, the relative importance of the ravine head or ravine walls may depend on the length of the ravine, and so stabilization strategies should be selected with each specific ravine’s characteristics in mind.

Finally, since the relative amounts of storage and transportation within the ravine channel may depend on the time of year, with transportation dominating in the spring and summer, and storage dominating the rest of the year, erosion mitigation efforts should consider these seasonal trends. For example, management efforts aimed at reducing the flow through the ravine should be prioritized during the spring and summer, when flows are generally the highest due to snow melt and storms.

**CONCLUSIONS**

This study produced a detailed snapshot of Ravine Z as it existed on October 4, 2015 by describing the nature of the till and sediments, and quantifying the physical and chemical weathering processes occurring within the ravine. We found that the fluvial transportation of sediment was the dominant process within Ravine Z; evidence for sediment storage and chemical weathering was much more subtle. Any management attempts to reduce the amount of sediments exiting this ravine should focus on reducing the amount of water flowing through the ravine.

The data collected in this study serves as a baseline for Ravine Z. Future samples collected from Ravine Z could be compared to the data produced in this study to measure any changes in the ravine or to
test the effectiveness of any applied erosion management strategies, such as application of woody debris to the ravine channel.

As this study only meaningfully describes a single ravine at a single point in time, its findings cannot be generally applied to all ravines in all seasons. More work will be needed before we will be able to determine how representative this data is of the actual processes and seasonal cycles within the ravine, and how representative this ravine is of all the ravines in Seven Mile Creek Park, or in the wider Minnesota River watershed. Future studies could sample the ravine at multiple times throughout the year to determine whether seasonality is an important component of ravine processes, or alternatively, they could sample several different ravines and find out how comparable their sediments and processes are.
REFERENCES


Appendix 1

Preparation of Sediment for Analysis on the Laser Diffractometer

MATERIALS

Chemicals
- Sodium Hexametaphosphate ((NaPO$_3$)$_6$, or “Na-HMP”)
- Milli-Q Water

Lab Supplies
- 50 mL centrifuge tubes
- 1000 mL volumetric flask
- Spatula
- Manual transfer pipet
- Kimwipes
- Wet Sieve (2.00 mm)
- Dry Sieve (2.00 mm)

Lab Equipment/Instrumentation
- VWR Drying Oven
- VWR Fixed-Speed Mini-Vortexer
- Microtrac S3500 Laser Diffractometer and in-line Imager

Safety Equipment
- Ear protection (optional, for operating the ultrasonic feature of the laser diffractometer)
- Disposable Nitrile Gloves
- Oven tongs or mitts, to remove cups from oven

PROCEDURE

Whole-Sample Sediment Preparation

Use a clean spatula to stir and thoroughly homogenize the sediment in each plastic sample cup. Transfer a representative sub-sample of 10 g of each sediment sample into labeled test tubes. Record the mass of sediment removed, and set the test tubes aside.

Record the mass of the open plastic sample cups and remaining sediment before placing the lidless cups into the drying oven at about 100°C for at least 48 hours. Only place the plastic sample cups on the oven shelves; do not place any cups on the bottom of the oven – this location is too hot for the sample cups and they may melt. Once the sediments are completely dry, remove them from the oven, let cool, and then record the mass of the sample cups again.

Gently disaggregate the dried sediment with a mortar and pestle to break up any fine sediments that have clumped together. Dry-sieve the sediment through a 2.00 mm sieve to separate the gravel fraction. Record the mass of the gravel fraction (>2.00 mm), and record the mass of the <2.00 mm fraction.
Sediment Preparation for Laser Diffractometry

Set the dry sediments aside and return to the fresh sub-samples placed into test tubes earlier. Wet-sieve these sediment samples with a 2.00 mm sieve and remove the gravel fraction (particles larger than 2.00 mm cannot be run through the Laser Diffractometer). Discard the gravel fraction and use a clean spatula to stir and thoroughly homogenize the <2.00 mm fraction. Transfer 0.07-0.33 g of each homogenized sample into labeled 50 mL centrifuge tubes. The amount of sample required varies—for sandier samples, about 0.33 g of sediment should be used, and for siltier samples, about 0.07 g of sediment should be used. Record the mass of sediment used in each trial.

Prepare a solution of 5% Na-HMP by adding water and 50.0 g solid Na-HMP pellets to a 1000 mL volumetric flask. Na-HMP will act as a surfactant that keeps the sediment grains from sticking to each other in solution. Transfer 5 mL of 5% Na-HMP to each centrifuge tube and thoroughly mix the sediment and surfactant by placing each centrifuge tube on the mini-vortexer for 30 seconds. Let the samples sit overnight. Directly before being run on the Laser Diffractometer, each sample is mixed on the vortexer again for 30 seconds.

Running the samples on the Laser Diffractometer and Imager

The Laser Diffractometer and In-Line Imager and associated software are operated according the manufacturer manual (Microtrac, 2011 & 2012), and more specifically, the student use manual (Mohr and Van Orsdel, 2013), with the exception that carboys of Milli-Q water were used as the water source instead of the water filter. The “Platte Sand Test” standard operating procedure was used.

Obtaining Data from the Laser Diffractometer and Imager

Grain size distribution data can be obtained from the Laser Diffractometer using the “Sediments” tool available on the Microtrac FLEX software. This method is outlined in another student use manual, called “Sediment Analysis using Laser Diffraction” available on the lab computer (Krueger, 2016). For this method, the mass of the >2.00 mm fraction and the mass of the <2.00 mm fraction of the sample must be known. In this procedure, these masses were previously obtained from the dry-sieving of the sediment samples.

Grain morphology data is obtained from the Imager software, “AnaTec SI.” When viewing a recalled measurement, click on “Scatter Diagram” and change the axes of the scatter diagram to Sphericity and Roundness. The tables on the right side of the screen will list a mean value for each of these two parameters.

REFERENCES (APPENDIX 1)


Microtrac, 2011, SI Analyzer Operation and Maintenance Manual, Rev. B.

Appendix 2
Preparation of Sediment for ICP-MS Major Element Analysis
Using Lithium Metaborate Fusion

MATERIALS

Chemicals
- Lithium Metaborate (LiBO₂), 98.0-102.0%
- Nitric Acid (HNO₃), 67-70%, trace metal grade (~15.25 M)
- Standard “7A-1” (10 ppm each: Ag, Al, As, B, Ba, Be, Ca, Cd, Ce, Co, Cr₃⁺, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ho, K, La, Lu, Mg, Mn, Na, Nd, Ni, P, Pb, Pr, Rb, S, Se, Sm, Sr, Th, Tl, Tm, U)
- Standard “GAC-1” (10 ppm each: Be, Bi, Ga, In, Sc, Tb)

Lab Supplies
- Graphite fusion crucibles, 7.5 cc
- 125 mL polyethylene (HDPE) bottles
- 15 mL test tubes
- 50 mL centrifuge tubes
- 1000 mL volumetric flask
- Spatula
- Kimwipes
- 150 mL beakers

Lab Equipment/Instrumentation
- 1200°C Box Furnace
- VWR Drying Oven
- SPEX Mixer/Mill
  - Alumina ceramic grinding vials with ½ inch ceramic ball
- Agilent 7700x ICP-MS

Heat Safety Equipment
- Extra-long metal tongs
- Lab coat
- Heat resistant gloves
- Safety goggles
- Face-shield Visor
- Heat-resistant shelves (to protect countertop)

PROCEDURE

Sediment Preparation

Place about 5 g of each sediment sample into a labeled glass beaker and dry in the oven at 100°C for 12-24 hours. Remove beakers from the oven and let cool completely. Transfer the sample to the
mixer/mill alumina vial and grind the sample in the mixer/mill for 8 minutes, or until finely powdered. Transfer the powdered sample to a labeled 10 mL test tube.

**Fusion Preparation**

Wipe a graphite crucible with a Kimwipe. Mass 0.150 g of powdered sample and 0.750 g LiBO$_2$ into the crucible, and gently stir with a clean spatula. One crucible should be prepared as a blank, and should not contain any sample—only 0.750 g LiBO$_2$. Record the mass of sample and LiBO$_2$ added to each crucible, and keep the crucibles in order, since they cannot be easily labeled.

Prepare 1 M HNO$_3$ by combining Milli-Q water and 65.57 mL of 67-70% stock nitric acid in a 1000 mL volumetric flask. For each sample, mass 61.50 g of 1 M HNO$_3$ into a labeled 125 mL polyethylene bottle. Record the mass of acid added to each bottle, and record the mass of the capped, filled bottle.

**Fusion**

Turn on the box furnace and set the temperature to 1020°C (acceptable temperature range is 1000-1050°C). The furnace takes about 1 hour to reach the desired temperature. Once the furnace is hot enough, up to 4 crucibles are placed inside. The furnace temperature will drop after the crucibles have been added, but once the temperature re-stabilizes, start a timer for 10-12 minutes. After the time has passed and the samples have become molten, remove the crucibles one by one from furnace, pouring each into the corresponding prepared bottle of 1 M HNO$_3$. Cap the bottle and shake vigorously until the glassy solid is mostly dissolved. If not all of the molten material transfers from the graphite crucible, let the crucible cool and then use a spatula to scrape off the remaining sample and transfer it to the bottle of acid. Let bottles sit overnight to allow for complete dissolution. Record the final mass of each bottle.

**SAFETY NOTES** Operating the furnace at high temperatures requires 2 people; one who will open and close the furnace door, and one who will insert and remove the crucibles. Both participants should wear lab coats, safety goggles, and heat-resistant gloves; whoever transfers the crucibles should also wear a face-shield visor. Extra-long metal tongs should be used to insert or remove crucibles from the furnace. To minimize heat escaping from the furnace, the furnace door should be closed in between each addition or removal of a crucible. Heat-resistant oven shelves should be placed on the countertop and used as a work surface for pouring the molten material into the bottles of acid.

**Preparing Samples for ICP-MS**

Prepare a 0.1 M HNO$_3$ solution by combining Milli-Q water and 6.56 mL of 67-70% stock nitric acid in a 1000 mL volumetric flask. This 0.1 M HNO$_3$ will be used to dilute the fusion solutions (molten material dissolved in 1 M HNO$_3$) and prepare calibrations standards for the ICP-MS. The fusion solutions were diluted 100 times in preparation for running them on the ICP-MS. Every sample, blank, and calibration standard run on the ICP-MS should have the same concentration of internal standard GAC-1. The desired concentration is 100 ppb, which is equivalent to 100 μL GAC-1 in every 10 mL of total solution prepared. Calibration standards were prepared at concentrations of 0, 0.2, 0.4, 0.8, and 2.0 ppm, with 7A-1 serving as the stock calibration standard.
Recipes for preparing samples and calibration standards:

<table>
<thead>
<tr>
<th></th>
<th>ICP-MS Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume 0.1 M NHO₃</td>
<td>9.801 mL</td>
</tr>
<tr>
<td>Volume fusion solution</td>
<td>0.099 mL (99 μL)</td>
</tr>
<tr>
<td>Volume GAC-1 (internal standard)</td>
<td>0.100 mL (100 μL)</td>
</tr>
<tr>
<td></td>
<td>Makes: 10 mL total volume</td>
</tr>
</tbody>
</table>

ICP-MS samples are prepared in 15 mL test tubes. This recipe produces a 100x dilution of the original fusion solution.

<table>
<thead>
<tr>
<th></th>
<th>0 ppm standard</th>
<th>0.2 ppm standard</th>
<th>0.4 ppm standard</th>
<th>0.8 ppm standard</th>
<th>2.0 ppm standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume 0.1 M NHO₃</td>
<td>9.900 mL</td>
<td>9.702 mL</td>
<td>9.504 mL</td>
<td>9.108 mL</td>
<td>7.920 mL</td>
</tr>
<tr>
<td>Volume 7A-1 (calibration standard)</td>
<td>0.000 mL</td>
<td>0.198 mL</td>
<td>0.396 mL</td>
<td>0.792 mL</td>
<td>1.980 mL</td>
</tr>
<tr>
<td>Volume GAC-1 (internal standard)</td>
<td>0.100 mL (100 μL)</td>
<td>0.100 mL (100 μL)</td>
<td>0.100 mL (100 μL)</td>
<td>0.100 mL (100 μL)</td>
<td>0.100 mL (100 μL)</td>
</tr>
<tr>
<td></td>
<td>Makes: 10 mL total volume</td>
<td>Makes: 10 mL total volume</td>
<td>Makes: 10 mL total volume</td>
<td>Makes: 10 mL total volume</td>
<td>Makes: 10 mL total volume</td>
</tr>
</tbody>
</table>

Calibration standards are prepared in 50 mL centrifuge tubes and the recipes are scaled up by three to produce 30 mL total volume for each standard.

REFERENCES (APPENDIX 2)