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Annual Erosion of a Small Watershed in the North Dakota Badlands; USA

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B.S. in Geology

Senior Thesis

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Abstract

Understanding the process of erosion is important and necessary to guide not only land management today, but serve as a basis for future practices. The seasonal rate of sediment transport was monitored in a small drainage basin near the North Unit of Theodore Roosevelt National Park in western North Dakota. Soil traps, erosion pins, painted pebble lines, and aluminum markers were placed throughout the valley to monitor seasonal sediment transport. Once the observation period ended, the amount of sediment leaving the drainage basin was calculated to be 81.4 m^3. It is not certain that all of this sediment traveled directly to the Little Missouri River but we can say the sediment left the drainage basin. Monitoring erosion is important for manmade structures such as the Lake Sakakawea reservoir. Water exiting the badlands complex watersheds contains sediment that has been eroded from the valley walls. The Little Missouri River carries this sediment to Lake Sakakawea, where it is deposited. Knowing the amount of sediment escaping the badlands and entering the lake will provide a better estimate of the life span for the reservoir.

Introduction

The badlands of North Dakota have been extensively eroded by intense fluvial dissection which has produced steep hillslopes and high local relief (Dick et. al, 1997). Hillslope erosion rates in badlands have been found to be on the order of millimeters/year and are among the highest measured in any landscape (Schumm, 1956). Because the rates of landscape evolution in badlands are so high, we are able to observe the changes in a relatively short period of time. Observing erosion is important for manmade structures such as the Lake

Sakakawea Reservoir. Sediment that has been eroded from valley walls of the badlands is carried through streams and rivers that lead to Lake Sakakawea, where it is deposited. Knowing the amount of sediment escaping the badlands and entering the lake will provide a better estimate of the life span of the reservoir.

In 2013 the seasonal rate of sediment transport was monitored in a small drainage basin near the North Unit of Theodore Roosevelt National Park in western North Dakota. The methods include soil traps, erosion pins, painted pebble lines, and aluminum markers. Using data from these instruments, the amount of sediment leaving the drainage basin was calculated.

Previous Research

The field area of this study has been sparsely examined by other scientists. Information from research studies in another area of the Little Missouri badlands was used to gain an understanding of the topic.

Tinker (1970) studied the rates of hillslope lowering in the badlands of North Dakota from July 1967-1969. Tinker (1970) observed the factors that control the hillslope processes on a drainage basin in the South Unit of Theodore Roosevelt National Park; 70 miles south of this project's study area. Tinker (1970) measured the lowering of hillslope from slopewash by observing the amount of exposure of 15.24 cm long erosion pins. His results showed 20.6 ± 7.9 mm of erosion over the two year study. From the erosion rates and area of the hillslopes, he calculated the total sediment yield of the study basin. In this study, 30 cm long erosion pins were used to find the amount of sediment leaving the study basin.

Persico et. al. (2005) were involved in a research project to find short-term rates of sediment movement on four Mojave Desert Piedmont surfaces. 1600 painted and numbered pebbles were laid out in straight lines across an area and their locations recorded. The pebbles were revisited five times in two years to track and record movement. This method gives a clear indication of the regolith movement on the soil surface. The pebbles are to be large enough to see and similar in size and shape to naturally occurring pebbles (Perisco et. al., 2005). By painting and numbering them, they become more visible and are easier to track and record. The painted pebble method was used in this study by placing 2 cm in diameter pebbles across a slope.

Study Area

The study area of this project is in the Little Missouri Badlands approximately one mile south of the North Unit of Theodore Roosevelt National Park in western North Dakota (Figure 1). The study area is a small drainage basin with a creek that runs down the center which leads to the Little Missouri River. In this area of the badlands, only the Sentinel Butte formation is exposed. It is composed of approximately 43% siltstones, 30% mudstones, 11% sandstones, 9% claystones, and 3% lignites (Forsman, 1985). The valley has steep hillslopes and high local relief. The bottom of the valley is relatively flat with a slight dip towards the creek that runs down the middle. During times of no precipitation, the creek will dry up and stop the transport of sediment out of the valley. The drainage basin is approximately 128,114 m^2 with 82% being vegetated and 18% non-vegetated (Figure 2). Only the non-vegetated slopes contribute to the short term loss of sediment because the vegetated soils are relatively stable, although landslides do occur in the area. Long term studies should incorporate the erosion rates of the vegetated soils.

Figure 1. Image showing location of study area south of the North Unit of Theodore Roosevelt National Park

Figure 2. Google Earth image showing the whole drainage basin study area. The red is the outline, green marks non-vegetated slopes, and blue marks the creek.

Climate

The Little Missouri River is a semi-arid, desert-like environment with long, cold winters and short, hot summers. The annual amount of rainfall averages approximately 390 mm a year (Figure 3). Three quarters of this amount falls between mid-May and mid-September (Godfread, 1994). Daytime temperatures of over 38 degrees Celsius are common in the summer and winter lows can drop below -40 degrees Celsius.

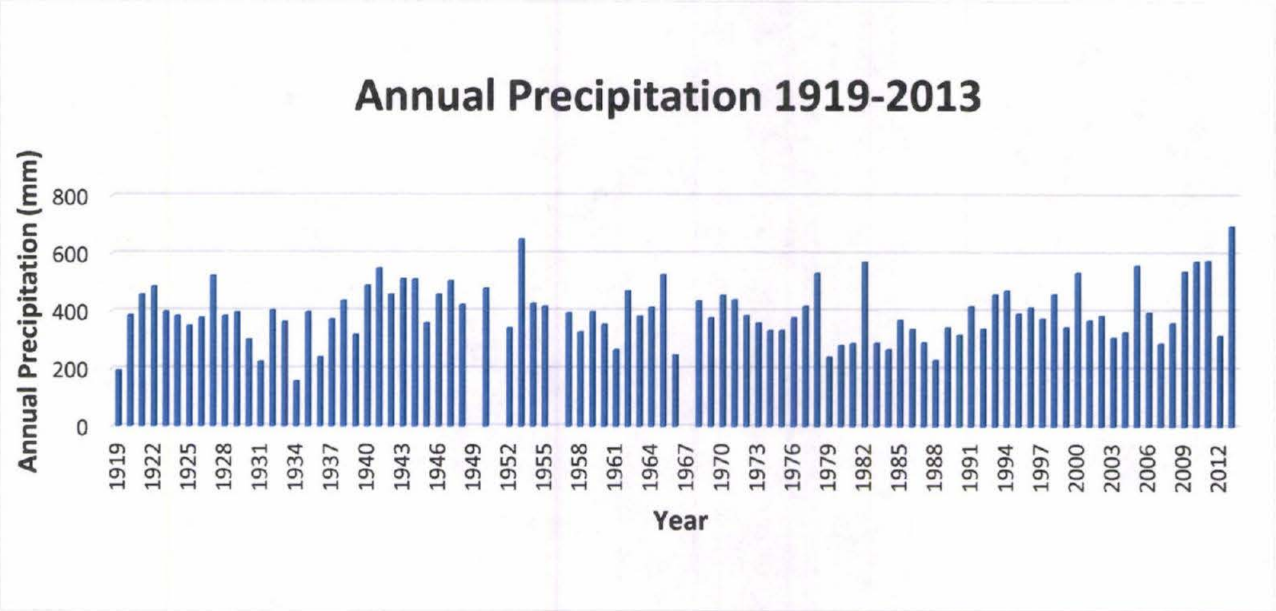

Figure 3. Annual precipitation measured at the North Unit of Theodore Roosevelt National Park. (National Climatic Data Center)

Methods

Four methods where used to monitor the current sediment transport rates of a small drainage basin in the Little Missouri Badlands. These methods include erosion pins, soil traps, painted pebble lines, and aluminum pieces.

Erosion pins are metal pins that are hammered into the ground that show changes in the level of the soil surface caused by deposition and erosion. 30 cm long pieces of rebar were used for the pins in this study (Figure 4). At the beginning of the research period the distance from the top of the pin to the soil surface was measured. At the end of the research period the distance was measured again. Changes in the previously measured distance shows net erosion or deposition. If more pin is exposed, then overall erosion has occurred. If less pin is exposed, overall deposition has occurred. A total of 55 erosion pins were placed throughout the study area.

Figure 4. 30 cm long rebar erosion pins.

Soil traps are small wooden boxes with an open top that are buried with the top flush with the slope surface (Putkonen et. al., 2007). As sediment moves down slope it falls into the box. When collected, the topographic diffusivity κ (m^2/month) can be calculated, which describes the amount of regolith that travels along the soil surface in a given time period and on a given slope angle (Putkonen, et. al., 2007). A total of 14 soil traps were placed throughout the study area.

Painted pebbles are pebbles that are placed in a line between two fixed rebars. The pebbles are to be large enough to see and similar in size and shape to naturally occurring pebbles (Perisco et. al., 2005). By painting and numbering them, they become more visible and are easier to track and record. The locations of the pebbles are recorded at the beginning and end of the research period. This method gives a clear indication of pebble sized particle movement on the soil surface. Using the initial and final position the distance traveled downslope can be calculated. One pebble line composed of 1.5 cm in diameter pebbles was placed in the valley.

The aluminum pieces method is similar to the painted pebbles method except 0.5 cm in diameter pieces of aluminum where placed near a stationary metal pin on a slope. When revisited, a metal detector is used to find the pieces. A measuring tape is then used to get the distance traveled down slope. Due to the small size, labeling the pieces is difficult and means that if the pieces had different initial positions, we would not know which pebble came from where once they moved. To alleviate this problem one stationary pin was placed on the slope with ten of the 0.5 cm in diameter aluminum markers placed within a 10 cm radius of the pin. This may lead to a small error in distance traveled by +/- 10 cm, but we can generally refer the initial position of each aluminum piece to be the location of the fixed pin. When found by the metal detector, the distance downslope is measured from each piece to the stationary pin. In the study area, two pins were placed with ten, 0.5 cm in diameter aluminum pieces at each pin (Figure 5).

Figure 5. Aluminum pieces set near stationary pin. The arrows point to the aluminum markers at their initial position.

Results

The field research period began May 18th of 2013 when five soil traps and one painted pebble line were installed in the valley. On June 28th the rest of the instruments were installed. During this time it was noticed that only four of the five soil traps were visible. Over the month that the first traps were in the field, 215 mm of rain fell. This led to a large amount of sediment transport which buried one of the soil traps (Figure 6 and 7).

Once installed on June 28th, the instruments were left until September 2013. On September 15th, sediment from the soil traps was collected, erosion pins were measured, and the final positions for the painted pebbles and aluminum pieces were recorded.

Figure 6. Soil trap 13-BB-ST-03 installed in May.

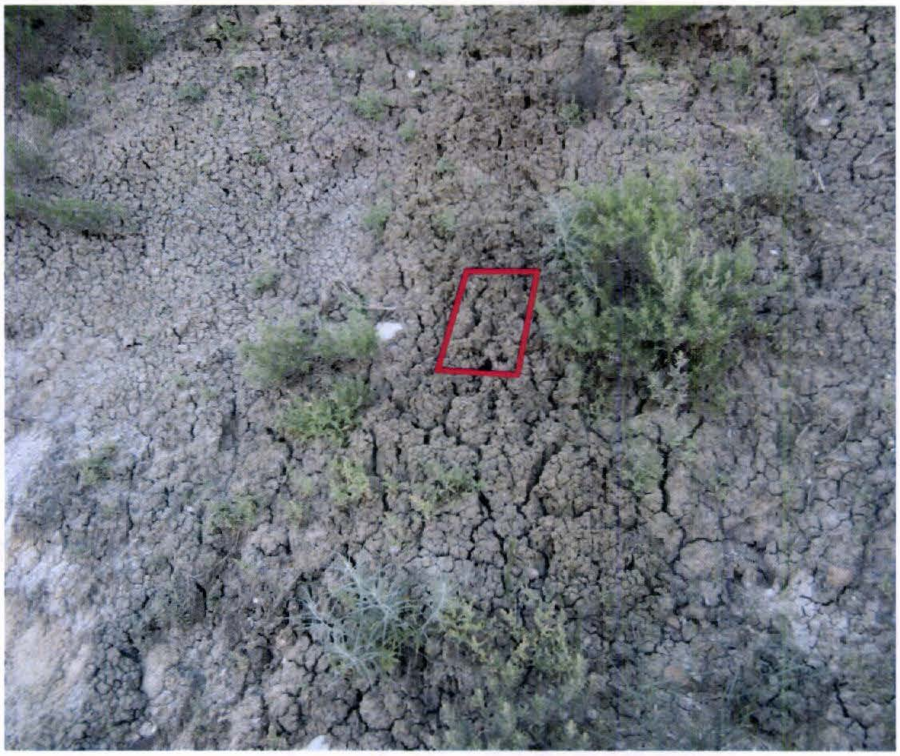

Figure 7. Soil trap 13-BB-ST-03 buried by heavy erosion (June 28th 2013). The red line indicates the approximate location of the buried soil trap.

In order to determine the amount of sediment that travels along the soil surface in a given time period and on a given slope angle, the topographic diffusivity κ (m^2/yr) was calculated using the soil trap data (Putkonen, et. al. 2007). The equation for the Greek letter kappa is $q_{vol,x}=\kappa*dy/dx$ where q is the sediment transport down the slope and dy/dx is the tangent slope (Putkonen, et. al. 2007). Topographic diffusivity is normally used to show long term mean annual values but instead of using the unit of m^2/year, kappa was measured using m^2/month to show the high seasonal rates. Using the amount of sediment in the soil traps, $q_{vol,x}$ was calculated and was put into the equation along with the tangent slope. The results in figure 8 shows that the most sediment moves during the early summer months. The topographic diffusivity values can be compared to the monthly precipitation shown in figure 9. May and June have both the highest precipitation and k value (m^2/month).

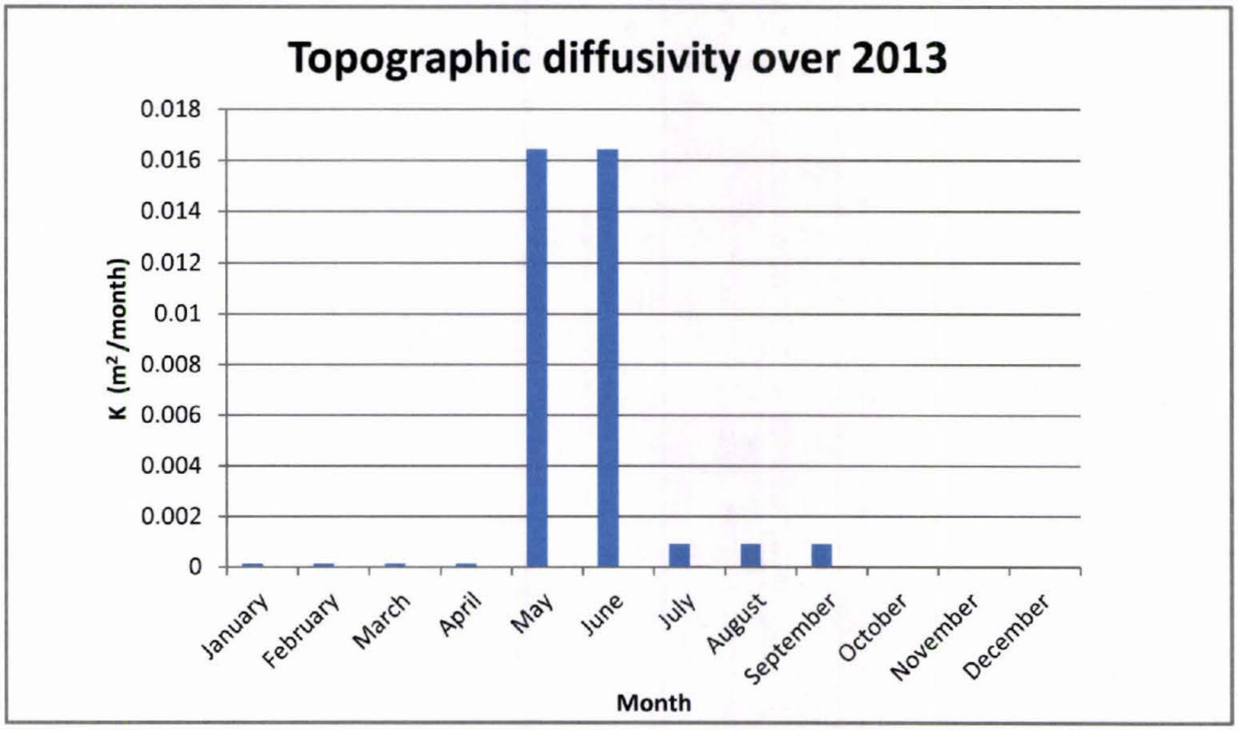

Figure 8. Topographic Diffusivity of soil traps. Very low erosion occurs in the winter months and very high erosion occurs in the summer months. The very small red bars in July, August, and September are the transport rates of the vegetated areas.

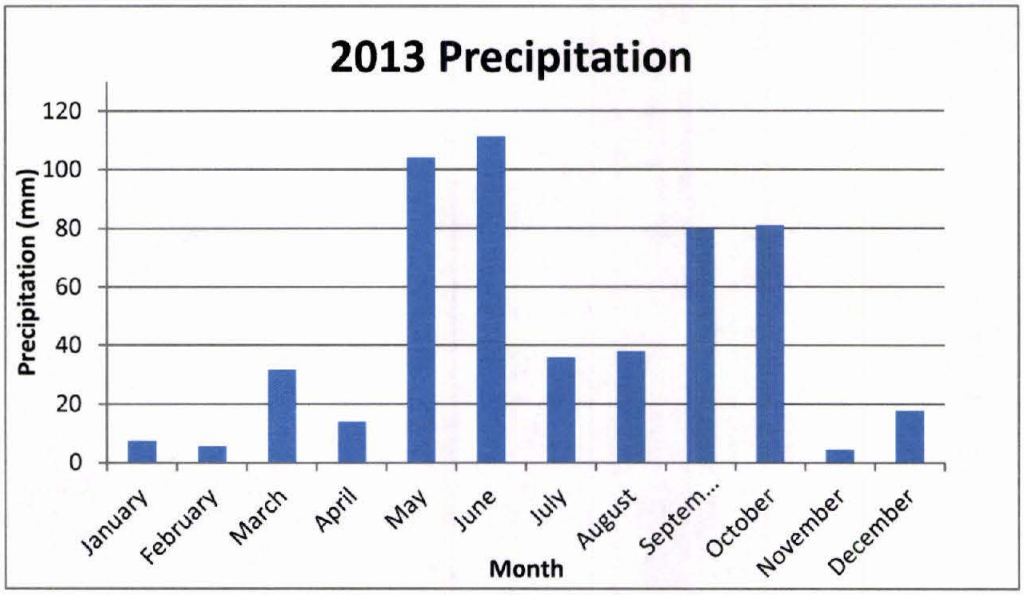

Figure 9. Monthly precipitation during 2013 (National Climatic Data Center).

The final locations of the painted pebbles were recorded on September 15th of 2013 which was one year from when it was installed in September of 2012. The pebble line was on a slope of 37 degrees and was located on a mound below a channel that has been cut from high precipitation runoff. The average distance the 1.5 cm in diameter pebbles moved was 111 cm. Figure 10 shows that some pebbles stayed at their original position while some traveled relatively long distances.

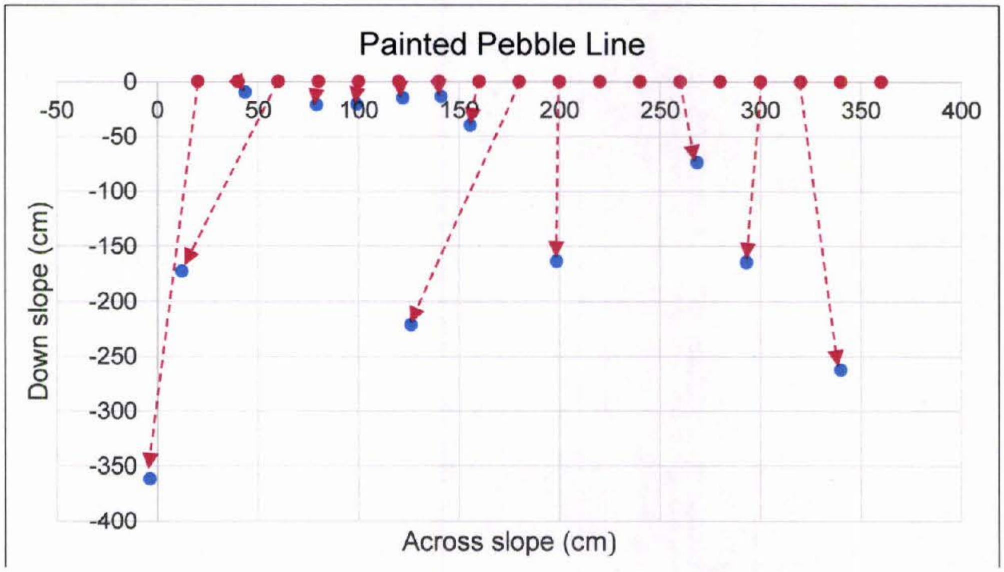

Figure 10. Movement of 1.5 cm in diameter painted pebbles. Average distance moved was 111 cm.

The aluminum markers showed similar results to the painted pebbles. Some aluminum markers moved very little while some moved long distances (Figure 11 and 12). The 0.5 cm in diameter aluminum markers were found using a metal detector. At Pin#1 (Figure 11), seven of the original ten aluminum markers were found. The missing markers where either buried too deep or carried more than a few meters away from the zone scanned by the metal detector. At Pin#2 (Figure 12) six of the original ten markers were found. The average distance moved of the located markers was 89.7 cm. This is assumed to be the minimum estimate as the lost markers likely traveled furthest.

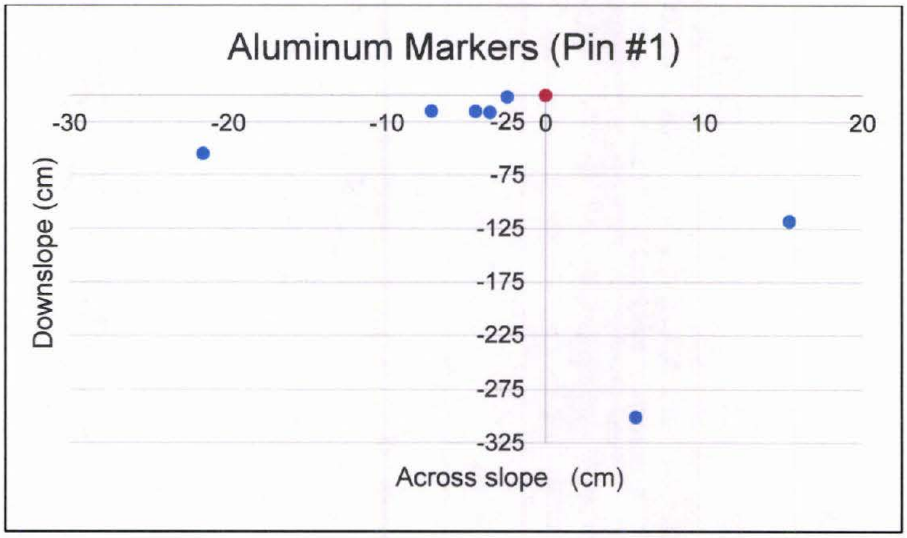

Figure 11. Aluminum marker movement from Pin#1. Red dot indicates the initial position at the pin.

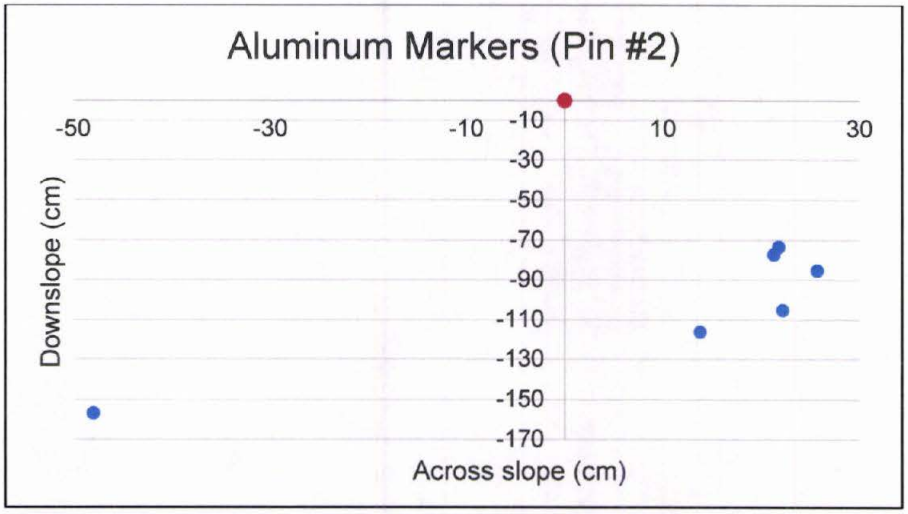

Figure 12. Aluminum marker movement from Pin#2. Red dot indicates the initial position at the pin.

After measuring the 55 erosion pins, 14 had shown net deposition and 39 showed net erosion. Two of the pins had fallen out of the slope face. The goal of the project is to find how much sediment was leaving the valley. The process was similar to finding the topographic diffusivity using the soil trap data. The equation $\varepsilon = P * dy/dx$ was derived from the original $q_{vol,x} = \kappa * dy/dx$. Here ε is the change in surface elevation and dy/dx is the tangent of slope. P was found by plotting the net change in surface elevation against the dy/dx of the slope. This gave a trend line equation of y = -0.0246x - 0.3419 where x equals the dy/dx of the slope, and y equals erosion (Figure 13). The slopes and area of all the non-vegetated surfaces in the valley was found using Google Earth Pro. The known dy/dx was then plugged into the trend line equation to get the amount of erosion for the given slope. This was repeated for every known slope in the valley. The studied drainage basin had approximately 23,062 m^2 of non-vegetated surface area. Vegetated slopes are relatively stable and contribute less than error estimates to the overall short term erosion. The total volume of sediment that left the study area was approximately 81.4 m^3.

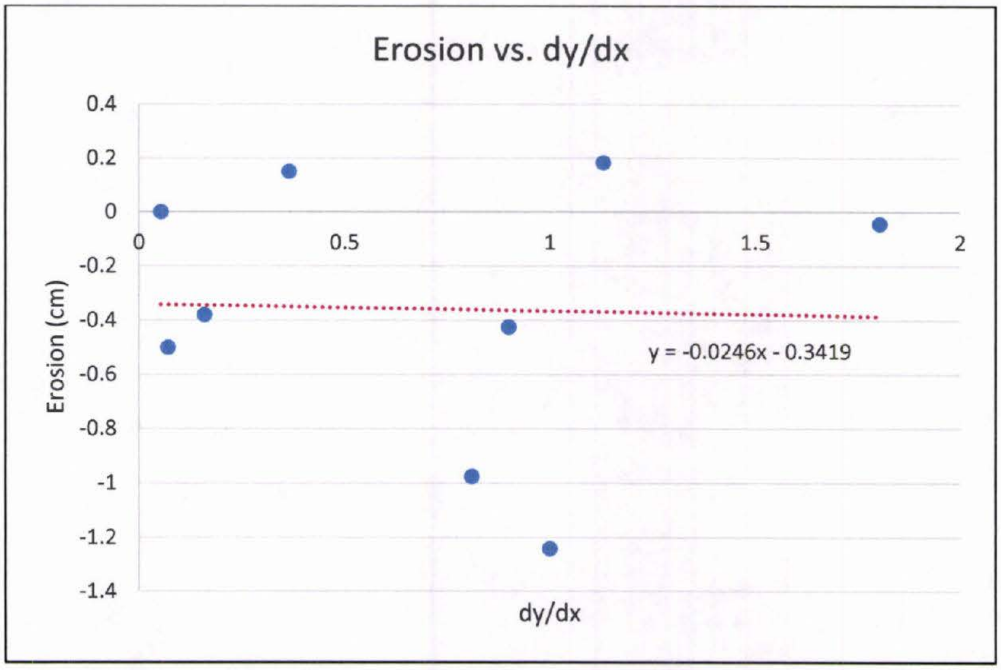

Figure 13. Erosion plotted against dy/dx. The trendline equation y=-0.0246x-0.3419.

Discussion

The results from the painted pebble line and aluminum markers were not able to be compared as planned. The goal was to see what type of sediment is moving further, smaller or larger particle. The smaller particles were hypothesized to move further than the larger ones. Difficulties arose when there were too many variables between the two sets. Both the aluminum markers and painted pebbles were located in areas with different slopes. The painted pebbles were placed in an area where high water flow carved a small channel into the slope face while the aluminum markers were placed on a more even slope. In an ideal situation, the aluminum pieces and painted pebbles should be place at the same location with the same environment and slope angle.

We cannot for certain say that all of the eroded sediment traveled directly to the Little Missouri River, but it can be assumed that the sediment left the drainage basin. The creek leading out of the drainage basin is not being filled in so we can infer that the sediment eventually reaches the Little Missouri River and later, Lake Sakakawea where it is deposited.

One thing to take into consideration is the large amount of rainfall during the observation period. Over 500 mm of rain fell during 2013 with 40% of it falling in the first month of the observation period. Sediment transport in the badlands is dependent on rainfall which means that 2013 had above average sediment transport rates. Further monitoring of the drainage basin will improve the accuracy and give us a better understanding of the correlation between precipitation and erosion.

One of the goals of this project was to compare its' results with the results of Tinker's (1970) study. His results showed 20.6 ± 7.9 mm of erosion over the two year study from 1967-1969. These were only the results of the Sentinel Butte Formation portion of his study. The Tongue River Formation (now defined as Bullion Creek Formation) was focused on more in his study but that formation has lower erosion rates than the Sentinel Butte Formation. The 20.6 ± 7.9 mm of erosion over the two year study is much higher than this studies average erosion of 3.5 mm/year. In the authors opinion, Tinker (1970) used too short of erosion pins in his study. He used 15.24cm long erosion pins which could have been easily affected by frost heave during winter months or could have fallen out due to gravity on the slope. This could have resulted in above actual measurements leading to an over estimate average erosion rate. It would be beneficial to duplicate Tinker's (1980) research using longer erosion pins.

Conclusion

The badlands of North Dakota have been extensively eroded by intense fluvial dissection which has produced steep hillslopes and high local relief (Dick et. al, 1997). Because the rates of landscape evolution in badlands are so high, we are able to observe the changes in a relatively short period of time. In this study the seasonal rate of sediment transport was monitored in a small drainage basin in western North Dakota using soil traps, erosion pins, and painted pebble lines, and aluminum pieces. 2013 was a record year with over 500 mm of rain. 40% of the rain occurred during the first month of the observation period and caused large amounts of sediment transport. The sediment transport completely buried one of the soil traps. At the end of the observation period, the amount of sediment leaving the drainage basin was calculated to be 81.4 m^3. We cannot for certain say that all of this sediment goes directly to the Little Missouri River but the creek leading out of the drainage basin is not being filled in so we can infer that the sediment eventually reaches the Little Missouri River and later, Lake Sakakawea where it is deposited.

Resources

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Precipitation records obtained from the National Climate Data Center website.

All photos taken by Erin Hoeft.

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