Mitigation of Ravine Hillslope Erosion in Southern Minnesota Using Infiltration Basins and Hydrologic Models

By

Patrick Day

A thesis submitted in partial fulfillment of the requirements of the degree of Bachelor of Arts

(Geology)

at

Gustavus Adolphus College

[2017]

Mitigation of Ravine Hillslope Erosion in Southern Minnesota Using Infiltration Basins and Hydrologic Models

By

Patrick Day

Under the Supervision of Laura Triplett

Abstract

The ravine networks in southern Minnesota are facing significant hillslope erosion because of large volumes of water draining from agricultural fields. The fields capture water from rain storms which then drain into drainage tile. Many drain tile systems outlet at the top of ravines, leading to fluvial erosion in concentrated areas. The hillslopes are made of loosely consolidated glacial till that had been deposited by the Des Moines lobe of the Laurentide ice sheet. So, the sediment that is being eroded from the slopes ranges from clay to sand and gravel. When the sediment becomes saturated it may become unstable, resulting in landslides.

To mitigate the problem, I designed an infiltration basin for a typical farm that would reduce surface water draining into ravines. I used Quaternary Stratigraphy maps to analyze the till matrix and determined the hydraulic conductivity to determine whether it would be feasible to create an infiltration basin further away from the ravines. The basin can collect and infiltrate the rain water from a 200-acre plot of land because of the till's moderate hydraulic conductivity. Drainage tile would drain water into the infiltration basin rather than into the ravines. In this study, I calculated that an infiltration basin with dimensions of 590ft x 590ft x 7.5ft would have a discharge rate (to the groundwater) of 789,000 cubic feet/day. The size of the infiltration basin would hold a 3.6-inch rain storm over a 200-acre plot of land and it would empty in 3.5 days. The infiltration basin would take the large amounts of extra water out of the eroding ravines and send it into the groundwater, where it may other recharge deeper aquifers or eventually flow into the Minnesota River.

Acknowledgements

I would like to thank Laura Triplett for her guidance and helping me come up with this idea for my project and revising it throughout the whole project. I would like to thank the Fredricks family for letting me have access to their property, and Charlotte Cowdrey for helping with the background research. I would also like to thank James Welsh for the help in revising my final paper.

Table of Contents

Figures and Tables

Introduction

Southern Minnesota is an area with abundant farming. The farming mainly takes place on soil that developed from glacial till. That till was deposited by the Des Moines lobe, a late lobe that extended south of the Laurentide Ice Sheet (Jennings, et al 2012). By studying one farm that is typical of those in the region, we may learn more about how the geologic material affects farming and landscape. The farm chosen for this study, owned by the Fredricks family is a few miles south of Seven Mile Creek Park, on a peninsula that is underlain by the Heiberg Member Till. (Figure 1) The Heiberg Member Till consists of loam and clay loam with some spots of sand and gravel. The peninsula is edged by ravines that cut through that poorly consolidated till, which is very easy to erode away (Meyer, et al 2012).

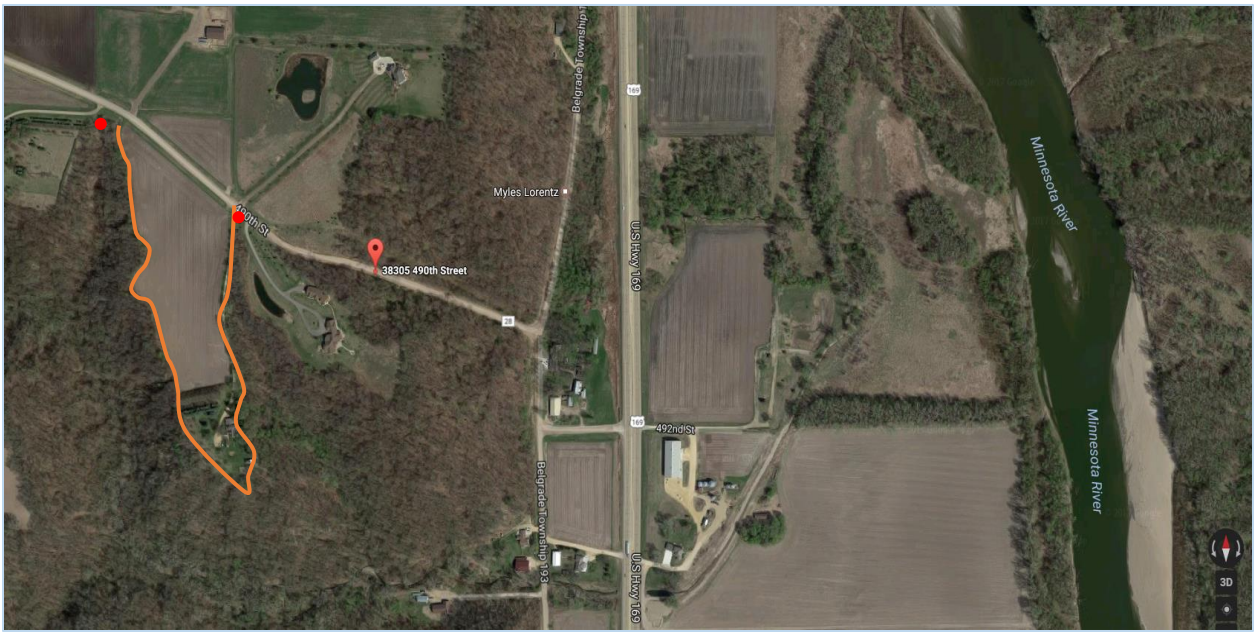

Figure 1: The Fredrick's property to the West of the Minnesota River. The property on the peninsula is outlined by orange and the red dots indicate the drainage outlet pipes.

A study done by Wang showed that with higher kinetic energy of rainfall greater amounts of larger sized particles were carried and eroded away. Conversely, with lower kinetic energy the breakdown of aggregates is not as great, but the overland flow is increased (Wang, 2014). Depending on the size of the rainfall event, there may be enough kinetic energy to erode the material that is on the steep slopes of the ravine.

The farm that I studied is situated on a small peninsula that is surrounded by the ravine. The farm land collects the rain water in drainage tile and discharges it in specific locations down in to the ravines through several drainage pipes. The excess rain water erodes the ravines headward towards the farm land. The amount of erosion on the ravine has caused the Fredricks to consider different options to try and mitigate the issue. The Fredricks reported that in past years they could jump over the stream because it was approximately two feet wide and one foot deep. Now, after ten years of erosion, it is 12 feet by 12 feet and the knickpoint has migrated back 100 feet. A former student at Gustavus, Michael Dickens, did research on the knickpoint migration in the ravine systems in Seven Mile Creek Park. Dickens found after a year of study that one of the main causes for the knickpoints migrating further up the ravines were the concentration of the drainage tiles discharging down the steep slopes (2015).

The landowners haven taken various actions to try and reduce the amount of degradation that is occurring. Their primary solution is putting in filter fabric on the ground surface underneath where the water discharges from the draintile outlet (Figure 2). Underneath the filter fabric they placed boulders to slow down the water so that it is not cutting down through the ground right below the discharge pipe. The filter fabric and boulders work right next to the drainage pipe, but it is not solving the problem further down slope. The ground becomes more and more saturated which makes it more likely for the land to erode away with the knickpoint

migrating further up the ravine. The landowner indicated that he used to have his farm drain through a six inch diameter discharge pipe that saturated a thirty foot wide section of the slope. There was a storm in 1993 that caused it to finally give way, creating a land slide down in to the ravine. At the bottom of the ravine, the trees are growing back at a slight angle. The slight angle growth shows that since 1993 the hillslope has slumped a few centimeters.

Figure 2: Filter fabric on top of large cobbles/boulders to reduce the amount of erosion directly under the outlet point of the drainage tile

The purpose of this study is to determine whether there is an alternative system for the drainage of the excess water from farm land, in such a manner that it does not harm the integrity of the ravines.

Geologic Setting

Nicollet County is located in south-central Minnesota and the southern part of the county is bordered by the Minnesota River (Figure 3). The river travels south east through the state and then turns north-east. The Fredricks' farm is situated in the south eastern part of the county where the Minnesota River is flowing north east. The farm is positioned on a peninsula above a large ravine and is 1300 meters west of the Minnesota River and 750 meters from U.S. 169.

Figure 3: The red indicates Nicollet County and the southwest and eastern borders are where the Minnesota River runs

The most recent glaciation that covered Minnesota had four lobes that were an extension from the Laurentide Ice sheet. The glaciers retreated about 10,000 years ago in this area which led to the drainage of Glacial Lake Agassiz, an immense glacial lake that was in the northern part of North America. The retreat of the Des Moines Lobe in this region opened up the spillway for Glacial Lake Agassiz, which cut through the glacial till in this region creating a large valley (Jennings., et al 2012). The large valley, where the Minnesota River is located, was created when Glacial River Warren dropped the base level, so the existing tributaries had to adjust their

gradients to reach the newly formed deep valley. This caused the streams that drain into the Minnesota River to have a steep gradient, such as the ravine near the Fredricks' farm.

The glacier deposited till in this region that was carried from Canada. The ice crossed through this area in Minnesota multiple times depositing many layers of the sediment. The till consists of sand, silt, clay, and gravel. (Jennings, et al 2012). The till is heterogeneous as described by Myer et al (2012).

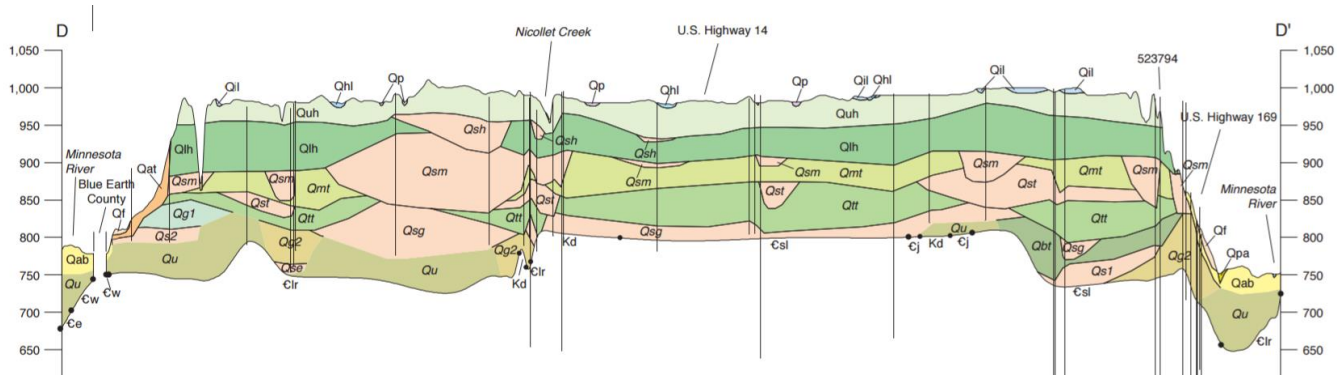

Figure 4: This figure shows the till layers that were deposited during the last glaciation. The top two layers in light and dark green are the Heiberg Member till, Quh and Qlh. (Meyer, et al 2012)

The surficial geology at the farm's location is interpreted to be "aligned hills" with diamicton, which is associated with the Des Moines Lobe (Jennings, et al 2012). The diamicton associated with the Des Moines lobe consists of a loam matrix with gravel, scattered cobbles, and rare boulders which are unsorted sediments. The farm itself is sitting on 50 feet of the upper Heiberg Member Till followed by another 50 feet of the Lower Heiberg Member Till. The Heiberg Member Till has a matrix texture of 5% of total sample weight of gravel, 37% sand, 39% silt, and 24% clay (Meyer, et al 2012). This is described as a loam to a clay loam diamicton.

The land in this area is predominantly used for farming purposes. Typically corn and soy beans are rotated.

The glacial strata in this region is underlain by the bedrock of the Jordan sandstone which is from the Upper Cambrian in the Paleozoic. The Jordan sandstone is a medium- to coarse-grained, quartz sandstone as well as a very fine-grained, feldspathic sandstone. The sandstone is generally bioturbated or has hummocky cross stratification (Mossler, John H., et al.). The Jordan is 201-250 ft. in depth from the surface of the land.

Research Methods

The Nicollet County Geologic atlas and in-person observations were used to characterize the subsurface geology, the hydraulic conductivity of materials, and the locations of draintile outlets.

The hydraulic conductivity for the loam was set for the upper limit of the hydraulic conductivity meaning the fastest discharge and fastest recharge of the infiltration basin. The hydraulic conductivity for the clay loam was set for the lowest limit of the hydraulic conductivity which is the slowest rate of the discharge and the recharge of the basin.

A 200-acre plot of farm land was used to estimate the amount of precipitation that was being captured by the drainage tile. Weather data ("Weather Underground", 2016) was analyzed to determine the amount of precipitation that fell in the year 2016 with the highest and lowest amounts and consecutive days that rain had occurred. The highest rainfall was used to calculate the amount of rain that a 200 acre farm would discharge from its drainage tile without taking into account the water taken in by the crops, soil, or from evapotranspiration. That calculation was

used to determine the total amount of rain that a hypothetical infiltration basin should hold. Using the volume of water, size of the infiltration basin and the hypothesized hydraulic conductivity, rate of discharge out of the infiltration basin was determined using Darcy's Law. The hydraulic gradient was found by an equation that uses the depth of the infiltration basin (7.5ft) plus the length of the wetting front (50ft) which is the Heiberg member till divided by the length of the wetting front (50ft).

$$Q = (K)(dh/dl)(A)$$

Stella models were designed to show the discharge rates for the infiltration basin that was modeled along with the rates for consecutive rainfall dates. The Stella Model in Figure 6 has the equations that are described above to come up with the Stella Model graph shown in Figure 7.

Topo Drive was used to model groundwater flow underneath the farm land. The multiple layers below the farm were assigned with three different hydraulic conductivities. The Heiberg Member Till has a hydraulic conductivity of 7.19×10^{-6} m/s, which is a hydraulic conductivity between loam and clay loam. There is a lens of silty sand where the Moland Member till is and the hydraulic conductivity for that is 3.17×10^{-5} m/s. The third hydraulic conductivity was calculated from sand and gravel which is 3.17×10^{-3} m/s. The domain length of the model is set to 1500 meters, even though the house is only 1300 meters from the river. The domain length is 1500 meters to see whether it would be more feasible to put an infiltration basin 200 meters away from the edge of the ravine. The vertical exaggeration is 17x.

Results

The total amount of rain that fell in 2016 was 31.93 inches. No rain fell in January or February. Most rainfall fell in May through September. There were three distinct peaks in June, July and August. June had the largest rainfall event of the year at 3.6 inches. August had the largest amount of prolonged rain at a total of 6.35 inches over 12 days. In the past 10 years, only a handful were larger than the 3.6 inches that fell in June of 2016. On August 10th, 2006 10.10 inches of rain fell, August 1st, 2007 4.19 inches fell, July 24th, 2008 10 inches fell, June 24th, 2010 10.16 inches fell, and on August 4th, 2011 8.11 inches fell. There are also consecutive days of rainfall in 2016 that would have accumulated in the infiltration basin. On the 5th through the 7th of September a total amount of 1.84 fell.

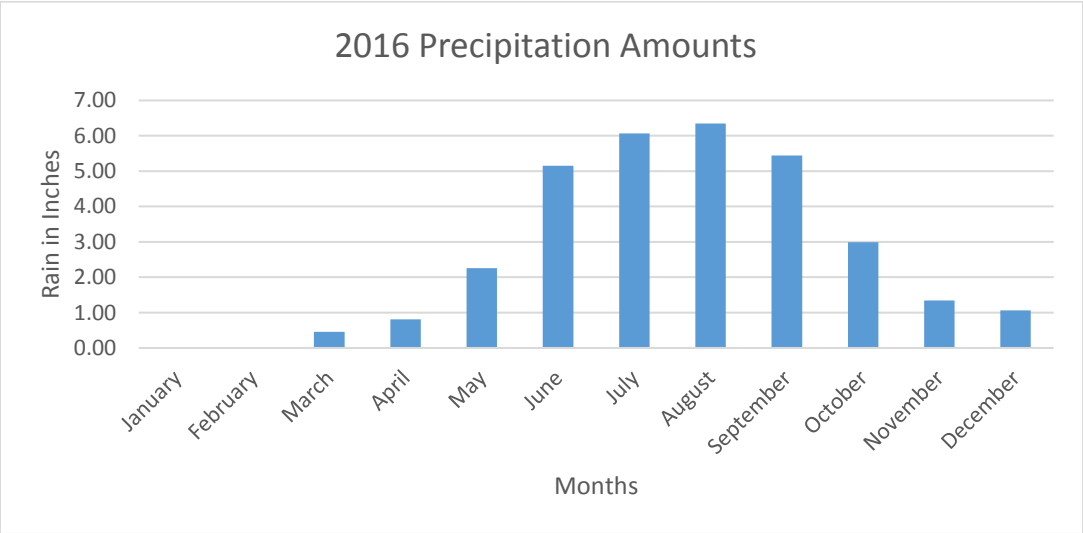

Figure 5: The 2016 Precipitation Amounts Graph shows how the amount of rain progressed through the year.

The most rain at one time was 3.6 inches according to Weather Underground ("Weather Underground",2016). For the 200 acre area the 3.6 inches accumulates a volume of 2,613,600ft^3. The amount of rain that would fall directly on the basin would be 104,544ft^3. From this it was calculated that an infiltration basin with dimensions of 590ft x 590ft x 7.5ft.

would be sufficient to hold this volume. Loam was chosen to model the hydraulic conductivity for this model because it was the closest matrix to what the composition is for the Heiberg Member Till which is 1.97 feet/day. The hydraulic gradient was found to be 1.15.

$$Q = (K_s)(^{dh}/_{ds})(A)$$

$$Q = (1.97ft/day)(1.15)(348{,}480ft^2)$$

$$Q = 789{,}000\ ft^3/day$$

The infiltration basin will take one day to drain 789,000ft^3 in to the Heiberg member till and through the 50 foot section of it. After that the water will flow faster because the till units below Heiberg member till, which are the Lower Heiberg and the Moland Member till have higher hydraulic conductivities. For the largest rainfall in 2016 it would take 3.44 days to drain the whole infiltration basin.

For the year of 2016, the infiltration basin that was proposed would capture and discharge about 90% of the rain that fell.

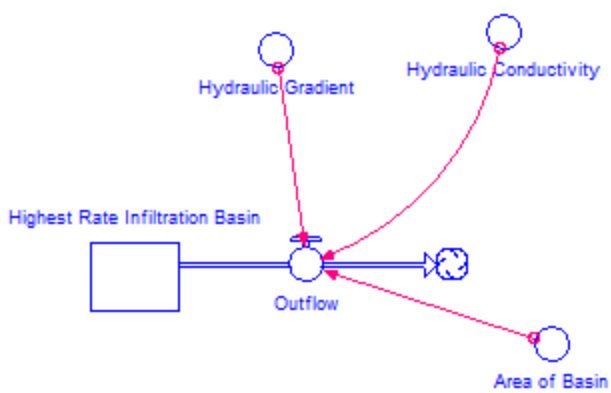

Figure 6: This Stella Model shows the infiltration basin with the different out flows coming out of the infiltration basin

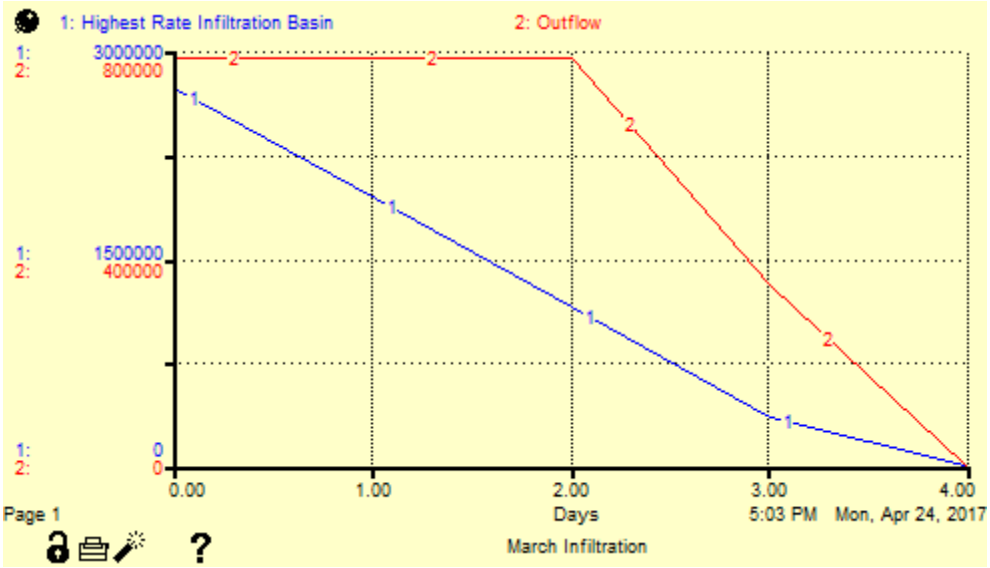

Figure 7: This Stella Model Graph shows the rate of discharge for the infiltration in a rain storm in March. The Red shows the outflows of the infiltration basin and the blue shows the volume of water in the infiltration basin.

The Topo Drive model shows that if the infiltration basin is located nearer to the ravine edge, then water will discharge out of the ravine wall rather than to the river. It also shows that the infiltration basin 200 meters inland would discharge right in to the river (Figure 8).

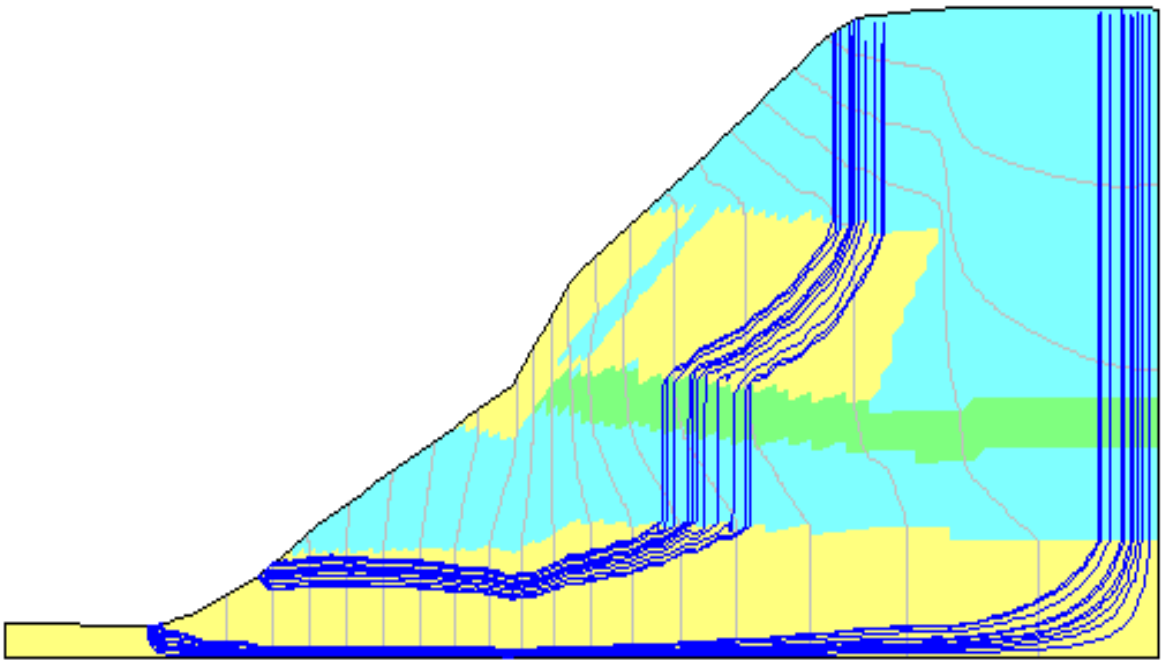

Figure 8: The Blue represents the loam to clay loam with a hydraulic conductivity of 7.19×10^{-6} m/s. The green is a silty sand with hydraulic conductivity of 3.17×10^{-5} m/s. The yellow is a sand and gravel with a hydraulic conductivity of 3.17×10^{-3} m/s. The bottom most yellow is representative of the Jordan Sandstone. The blue lines on the left show the water flow from the property next to the ravine and the right blue lines show the water flow from 200 meters inland from the ravine. The total domain length is 1500 meters with a vertical exaggeration of 17x.

Discussion

The size of the infiltration basin will affect the rate at which the water is infiltrated into the ground below it. Over the year there have also been rain storms that occur for 3 days straight, dumping a few inches of rain on the farms. The infiltration basin would be able to drain 1.08 inches of rain that has fallen on the 200 acres in one day, equaling a water collection rate of 789,000ft^3/day, which is the rate of discharge. So if in those three days there are storms that are over 1.08 inches, then it is going to take longer to drain, which could lead to overflow of water in the basin.

The Topo Drive model (Figure 8) shows the direction of flow if the basin is located next to the ravine and 200 meters inland from the ravine. The model has a no-flow boundary at the base. No-flow means that none of the water is being introduced as groundwater in to the aquifers further down in the layers. In reality, some water will reach deeper aquifers.

The water being infiltrated near the edge of the ravine does not make it all the way to the river. The water is also running too close to the ravine, so it will make that section of the land saturated, leading to instability. With the land being unstable, the land owners could see another landslide like they did in 1993, but at a much larger scale that would take out most of their property. Locating the basin 200 meters away from the ravine edge is a better option, because it would not cause the ravine slopes to become unstable.

The problem with building an infiltration basin further inland is that all of the drainage tile that is already in place for all of these farms are sloping downhill towards the ravines and the Minnesota River. So in order for this to work there would need to be a lot more money spent either changing the way that the drainage tile is laid or putting in more piping from where the drainage tile discharges in order to drain back to the infiltration basin. The area of discharge would have a pumping system that would pump the water back to the infiltration basin.

The evaporation rates will help decrease the volume of water in the infiltration basin, so a larger footprint was designed to increase the rate at which the water is evaporated. The surface area also helps with the total amount of water being infiltrated. One problem with having the infiltration basin at such a large surface area is that for every 200 acres of farm land that there is, there would need to be an additional 8 acres just for the infiltration basin of the farm. The Department of Natural Resources has pan evaporation amounts for the months of April through October going all the way back to 1972. The averages are lowest in April and October and the highest in July. The evaporation amounts are taken from a pan at the University of Minnesota, St. Paul Campus. That is only about 60 miles north so the amounts would not differ very much from those in St. Peter.

There are some factors that help mitigate the problem of excess water. When the rain first falls on the land a certain amount of the water will be soaked up by the plants and then go through transpiration with the corn or whichever crop is grown that year. This reduces the amount of water that is going through to the drainage tile and being discharged.

When large storms occur in June through September when the crops are in season, evapotranspiration can significantly decrease the amount of water that is being sent to the drainage tile.

The size of this infiltration basin is based on the largest storm in 2016 and it does not take into account the larger rain storms that have taken place in the past 10 years. For the 200 acres that are being taken into account the infiltration basin would need another 7.5 acres of land to accommodate this amount of rainfall. The Heiberg Member Till would prove affective at discharging this amount of rain through its more sand-filled stratigraphic layers and back in to the saturated zone and the Minnesota River without running over the surface.

Conclusion

Ravines and farmland in southern Minnesota are in danger of erosion from draintile outlets. The hillslopes of the ravines are predominantly made up of clay and sand and gravel. That sediment on the hillslopes is very prone to erosion and the concentrated amounts of water running down the ravines is speeding up the process of knickpoint migration. The current draintile outlets are being managed with boulders and filter fabric to preserve the sediment nearest to the top of the ravines. This thesis work shows that there are alternative ways to drain the excess water from the farm fields without disrupting the integrity of the ravine systems. The Heiberg Member till underlying the farmlands south of St. Peter has great hydraulic conductivity to be able to discharge water from the farms through the stratigraphic layers below it and not over the surface.

References

Agronomy, M.A.-K.D. Crop water use or evapotranspiration | Integrated Crop Management: Crop water use or evapotranspiration | Integrated Crop Management, http://www.ipm.iastate.edu/ipm/icm/2000/5-29-2000/wateruse.html (accessed April 2017).

Arnáez, J., 2015, Effects of farming terraces on hydrological and geomorphological processes. A review: Catena, v. 128, p.122-134

Chen, Shih-Kai., 2012, Assessing soil erosion in a terraced paddy field using experimental measurements and universal soil loss equation: Catena, v. 95, p. 131-141.

Dickens, M., 2015, Measuring Knickpoint Migration in Ravine Z, Seven Mile Creek Park, Nicollet County, MN

Fitts, Charles R., 2013, Groundwater Science: Second Edition

Jennings, CarrieE., Lusardi, Barbara A., Gowan, Angela S., Adams, Roberta S., Meyer, Gary N., Kneable, Alan R., Mossler, John H., Steenberg, Julia R., Chandler, V.W., Minnesota Geologic Survey, 2012, Nicollet County Geologic Atlas:

Monthly Pan Evaporation - U. of M. St. Paul Campus Monthly Pan Evaporation - St. Paul Campus: Minnesota DNR, http://www.dnr.state.mn.us/climate/wxsta/pan-evaporation.html (accessed April 2017).

Wang, L., 2014, Rainfallkineticenergycontrollingerosionprocessesandsedimentsortingonsteep hillslopes: A case study of clay loam soil from the Loess Plateau, China: vo. 512, no. 6, p.168-176

Weather Underground History, 2016

Zhang, J.H., 2014, Effect of terrace forms on water ad tillage erosion on a hilly landscape in the Yangtze River Basin, China: Geomorphology, v. 216, p.114-124