Utilizing a High Resolution Digital Elevation Model (DEM) to Develop a Stream Power Index (SPI) for the Gilmore Creek Watershed in Winona County, Minnesota

Tyler Danielson
Department of Resource Analysis, Saint Mary's University of Minnesota, Winona, MN 55987

Keywords: GIS, Winona County, Agriculture, Erosion, ArcGIS, Slope, Aspect, Flow Direction, Flow Accumulation, Stream Point Index, SPI, Critical Threshold, Digital Elevation Model, DEM, LiDAR, Gully Erosion

Abstract

Erosion on the landscape usually happens in small increments and over thousands of years. With the advent of the agricultural and industrial revolutions many areas within the United States have witnessed increased top soil erosion. Much of this erosion has originated on agricultural lands, usually being attributed to the lack of adequate ground cover and not taking advantage of "best management practices." These "best management practices" include: terracing, conservation dams and/or grass flow ways. The objective of this project was to utilize a high resolution digital elevation model developed using LiDAR (Light detection and ranging) paired with the SPI model of erosion prediction to test the model's applicability to an entire watershed as a way to quickly identify areas at risk of gully erosion.

Introduction

Topography defines the pathways of surface water movement across a watershed and is a major factor watershed hydrologic response to rainfall inputs. Raster-based digital elevation models (DEMs) have been widely applied to efficiently derive topographic attributes used in hydrologic modeling such as slope and upslope contributing area (Wu, Li, and Huang, 2008). Numerous soil erosion models have been developed during the last fifty years to estimate rates of soil erosion under different land use systems (Wilson and Lorang, 2000).

Erosion analysis models such as USLE (Universal Soil Loss Equation) and RUSLE (Revised Universal Soil Loss Equation) developed and used by the United States Department of Agriculture (USDA) can be very cumbersome in practice.

USLE is a multiplicative model that was empirically derived from over 10,000 plot years of data (Wischmeier and Smith, 1965; Wischmeier, 1976). The equation consists of the following formula:

$$A = R\,K\,L\,S\,C\,P$$

Where A is the mean soil loss in tons per hectare over the entire slope length, R is the rainfall-runoff erosivity factor, K is the soil erodibility factor, C is a cover management factor, P is a supporting practices factor, L is a slope length factor and S is a slope steepness factor. R is the product of the storm total kinetic energy and the maximum 30 minute intensity for qualifying storms (Meyer, 1984; USDA 2013).

Danielson, Tyler. 2013. Utilizing a High Resolution Digital Elevation Model (DEM) to Apply Stream Power Index (SPI) to the Gilmore Creek Watershed in Winona County, Minnesota. Volume 15, Papers in Resource Analysis. 11 pp. Saint Mary's University of Minnesota University Central Services Press. Winona, MN. Retrieved (date) http://www.gis.smumn.edu

The model is used to compare soil erosion from individual farm fields to that expected from a ‘standard’ soil-loss plot. The USLE defines soil loss as the amount of eroded soil and how far it has moved down slope (Yoder and Lown, 1995). RUSLE retains the basic structure of the original model but incorporated new factor values that were based on the analysis of thousands of new erosion measurements (Renard, Foster, Weesies, and Porter, 1991; Renard, Foster, Weesies, McCool, and Yoder, 1993; Renard, Foster, Yoder, and McCool, 1994).

In general, the improvements to the USLE model included; revising the *R* factor values, allowing the ability to adjust *K* and *C* factor values and to improve the *LS* factor equations.

These models calculate the mass of soil eroded by a rain event. This can be helpful in many instances. However in other instances, it may not be important to know exactly how many tons of soil were moved during an event but rather knowing the spatial location of where gully erosion is occurring on the landscape thus allowing a land manager to more quickly and effectively mitigate the erosion issue.

In contrast, to the efforts during the last decades to investigate sheet and rill soil erosion processes, relatively few studies have been focused on quantifying and/or predicting gully erosion. The expansion of the use of modern spatial information technologies such as geographical information systems (GIS), digital elevation modeling (DEM) and remote sensing have created new possibilities for research in this field (Martinez-Casasnovas, 2003).

Terrain Analysis

LiDAR based DEM data allows the cell resolution to be as small as 1 meter, this brings a dataset with 900 times more detail than a 30 meter resolution DEM (Nelson, 2010).

High resolution data allows predictions of erosion without the need of lengthy volume calculations. Digital Terrain Analysis (DTA or TA) can be used as a way to interpret LiDAR elevation data. DTA is a remote sensing methodology that combines DEM-based topographic data analysis in GIS with imagery, field-based observation and the study of landscape processes. The purpose of Digital Terrain Analysis is to predict landscape processes reliably while minimizing the time and effort invested in field work and modeling procedures (Dogwiler, Dockter, and Omoth, 2010).

Primary attributes are calculated directly from elevation data. These include aspect, slope, and flow accumulation as well many others. Stream Power Index (SPI) is a secondary attribute calculated from several primary attributes. Secondary or compound attributes involve the combinations of primary attributes; these are indices (Nelson, 2010). Indices describe the spatial variability of specific landscape processes, such as the potential for sheet erosion (Moore, Grayson, and Ladson, 1991).

According to Wilson and Lorang (2000) SPI is the measure of erosive power associated with flowing water based on the assumption that discharge is proportional to the specific catchment area and it predicts net erosion in areas of profile convexity and tangential concavity (flow acceleration and convergence zones) as well as the net deposition in areas of profile concavity (zones of decreasing flow velocity).

Study Area

The study area for this project was the

Gilmore Creek, Minnesota, USA watershed, which is 6216 acres. Gilmore Creek starts in the hills and bluffs and flows downstream through the towns of Goodview and Winona, Minnesota before draining into the Mississippi River. Large bluffs dominate the areas between the farming uplands and the suburban style subdivision housing developments in the lower elevations. Nearing the northern (downstream) portion of the watershed, Gilmore Creek passes through the Saint Mary's University of Minnesota's Winona campus (Figures 1 and 2).

Figure 1. General location of the Gilmore Creek Watershed.

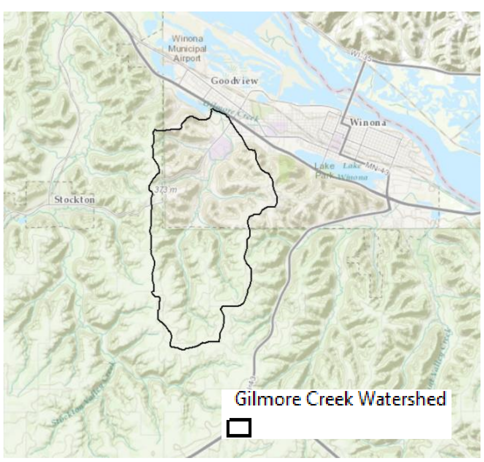

Figure 2. General outline of the Gilmore Creek Watershed.

Methods/Analysis

Software Used

GIS software used to perform the SPI analysis were the ESRI ArcGIS v10.1 with the ESRI Spatial Analyst extension.

GIS Data

For SPI to be a useful model, high resolution DEM data are required (Nelson, 2010). High resolution refers to the cell size of a DEM, the smaller the cell size the higher the resolution of the DEM. Generally, high resolution is considered to be less than a 6 meters cell size. For the purpose of this study 1 meter resolution data were used. Figure 3 is an example of a raster dataset.

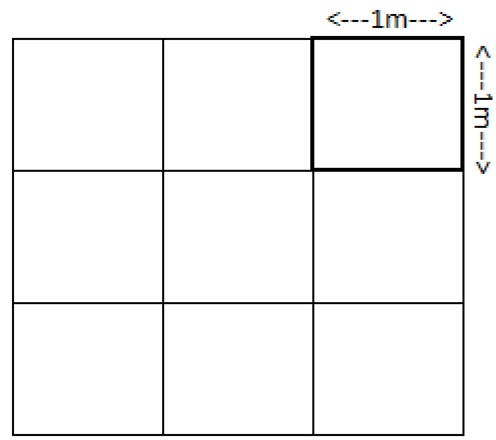

Figure 3. Cell size.

High resolution DEM datasets were until recently prohibitively expensive to produce, however recent advances in LiDAR techniques and detectors have allowed a more cost effective way to produce such datasets.

Pre-Processing of GIS Data

GIS data were processed to ensure proper care had been taken in the development of the data. Accuracy and precision were scrutinized. During this step data were clipped, merged, and joined to provide seamless GIS data for the study area. In addition to these steps, pit filling and filtering of the DEM data were performed on the entire extent of the Gilmore Creek watershed (Figure 4).

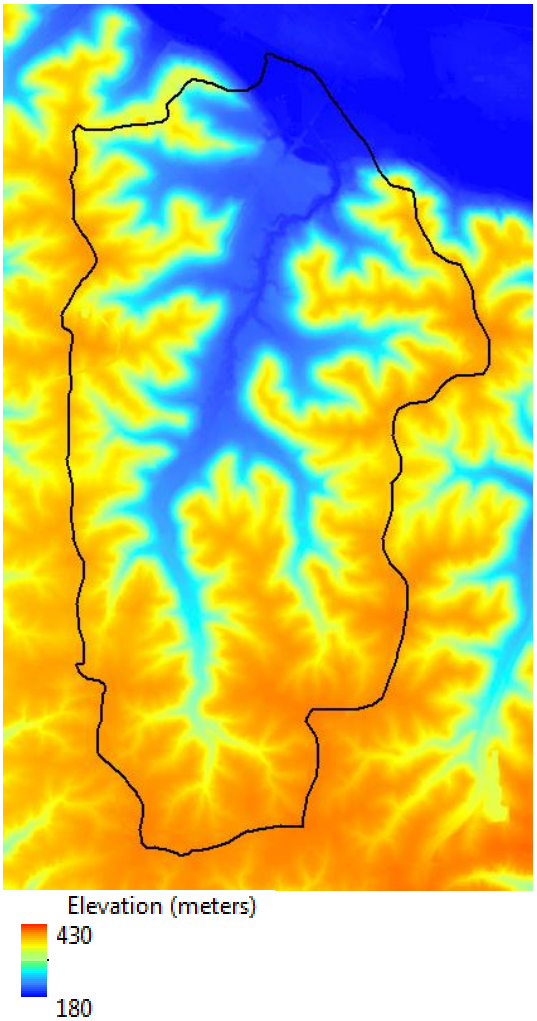

Figure 4. LiDAR DEM of the Gilmore Creek Watershed.

Pit filling fills any sink or pit in the DEM. A pit is a depression in the DEM where all slopes are positive surrounding an area (ESRI, 2013a). For the purpose of this study, this was performed so areas where pooling occurs would 'force' the flow downstream.

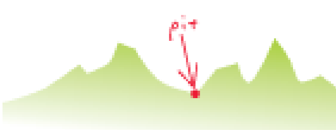

Figure 5. Example of a pit (ESRI, 2013a).

A low level filter (3x3, mean) was also performed on the DEM. This process smoothed the data to create elevation averages for better interpretation. LiDAR data expressed in file-resolution DEMs can contain either errors or spurious features which can impede flow analysis (Nelson, 2010). When a low level filter (3x3, mean) is performed on a raster dataset, a 3x3 cell window moves systematically across the dataset (Figure 6) changing the middle cell's value to the mean of the nine window cells (ESRI, 2013a).

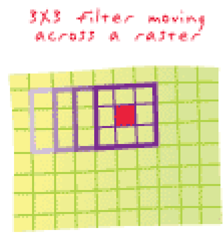

Figure 6. Depiction of a 3x3 filter (ESRI , 2013a).

It should be noted that pit filling by filter use can change the nature of the DEM data in a way that may not fully represent the landscape.

ArcGIS Analysis Methods

The pre-processed DEM was then used to develop several intermediate raster datasets. These intermediates datasets were referred to as primary attributes because they were calculated directly from the elevation dataset, these included: slope, flow direction, and flow accumulation.

Slope calculates the maximum rate of change in elevation from one cell to its neighbors. For the purposes of this study, percent based slope was calculated. Percent based slope, also referred to as 'percent rise' was calculated by rise divided by run multiplied by 100 (Figure 7). Slope is used directly in the calculation of SPI.

$$\frac{rise}{run} * 100 = Percent\ of\ Slope$$

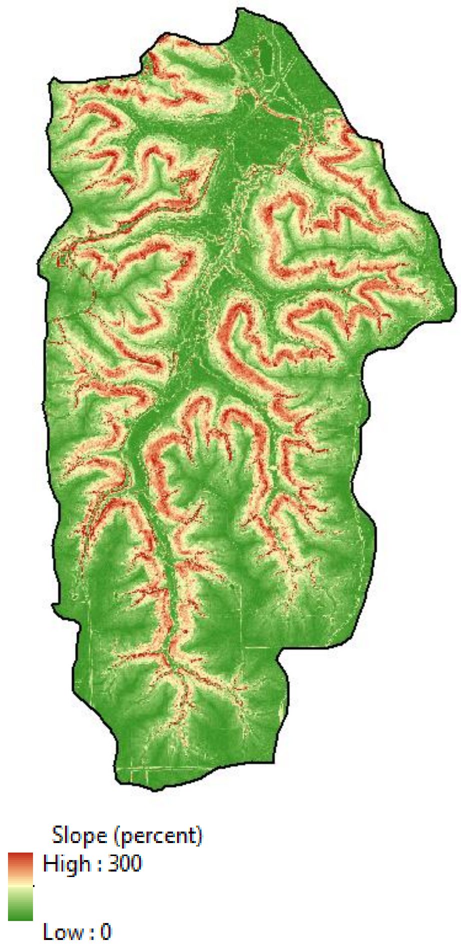

Figure 7. Slope Analysis output of the Gilmore Creek watershed.

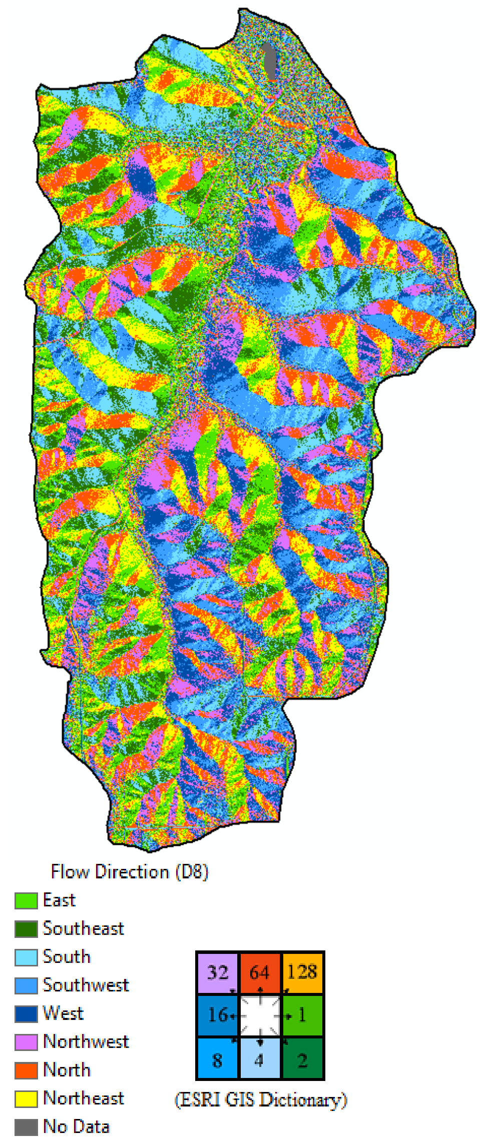

Figure 8. Flow direction analysis output for the Gilmore Creek watershed (secondary legend provided by ESRI's, 2013a). *Note: No data on a flow direction analysis implies an area does not drain to an adjacent cell (i.e. an area with no slope).

Flow direction calculates the direction of flow from every cell in the raster. For purposes of this study, an eight direction (D8) flow was used. The D8 flow direction model had eight valid output directions relating to the eight adjacent cells into which flow could travel, this follows the approach presented in Jenson and Domingue, 1988 (ESRI, 2013a). Figure 8 shows the output of the D8 Flow direction analysis performed on the Gilmore Creek watershed.

The resulting flow direction was the input for the flow accumulation analysis. Flow accumulation calculates accumulated flow as cells flow downslope. Figure 9 illustrates how a flow direction analysis translates to flow accumulation and Figure 10 shows the output of the flow accumulation model using the Gilmore Creek flow direction data.

Finally, with the use of the raster calculator SPI was calculated with the

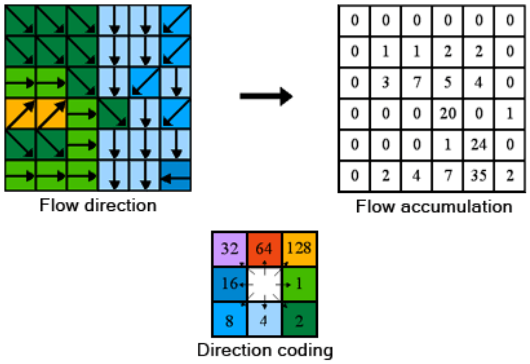

Figure 9. Example Flow accumulation raster calculation (ESRI, 2013b).

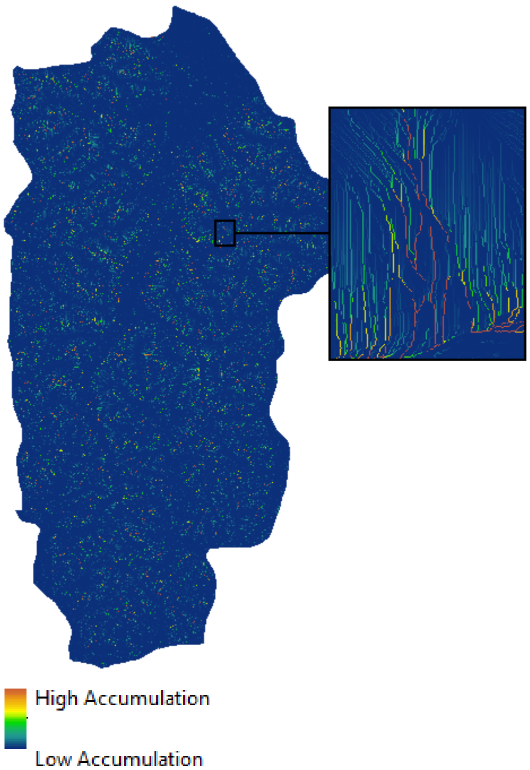

Figure 10. Flow accumulation analysis output for the Gilmore Creek watershed.

following equation:

SPI = LN(([FlowAccum_Raster] + 0.001) * ((Slope_Raster]/100) + 0.001))

The above equation for SPI refers to the FlowAccum_Raster which is the output from the flow accumulation analysis (Figure 9) and Slope_Raster which is the output from the slope analysis (Figure 7). Figure 11 illustrates the resulting SPI raster dataset. The inset map shows the same location as the flow accumulation raster (Figure 10) for comparison. A higher SPI value should correspond to a higher likelihood of erosion on the landscape.

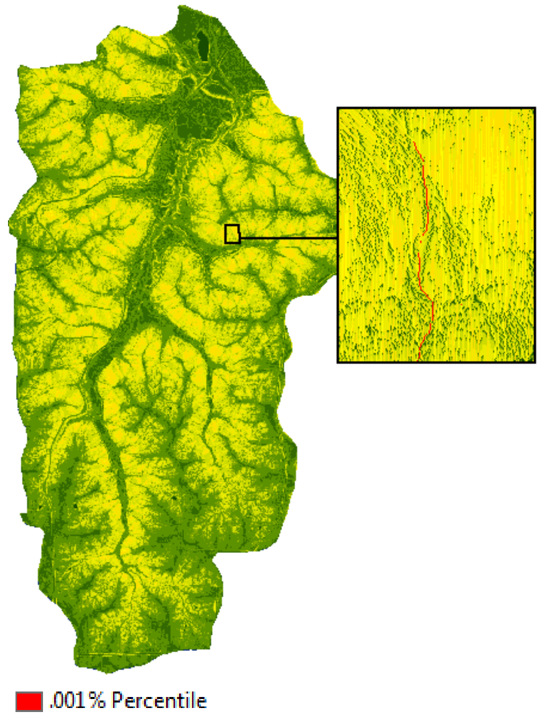

Figure 11. Stream Power Index results for the Gilmore Creek watershed. Red symbolization indicates where a SPI value is at or above the .001 percentile of all SPI values throughout the watershed.

Results/Discussion

This study applied the SPI model to a whole watershed; field verification of a significant area was unreasonable. As such, a combination of aerial photo/satellite imagery interpretation and less intensive field verification were used to analyze the results from the SPI model. Three areas were chosen for verification (Figure 12). Verification sites were chosen based upon SPI values and accessibility (e.g. by foot or by of aerial photo/satellite imagery).

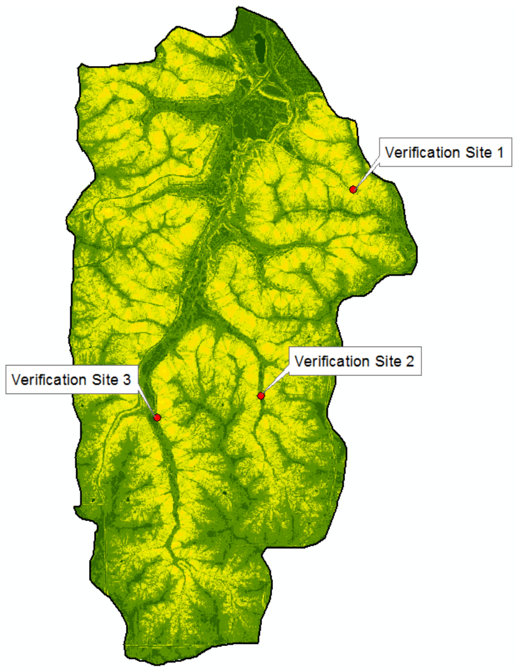

Figure 12. SPI model verification sites.

Verification Site 1

This site was chosen for its high SPI value and because it lies within the Saint Mary's University of Minnesota trail system, allowing easy access for field visitation. Because of the thick canopy of this area few conclusions could be made from interpreting the aerial imagery for this site, other than noting several residential lawns drained into this verification site (Figure 13). Figure 13 shows the top .001% of SPI values in red and the top .01% of SPI values in yellow.

While conducting fieldwork, it was noted that although the grade of the surrounding landscape was high, there were very few areas with notable/visible erosion. Upon arrival at the verification site, it was possible to see erosion both up hill and downhill from the site. This was likely to be more attributed to the topography (slope) rather than land cover or land use because this was an undeveloped area with near complete natural coverage of the immediate area (Figure 14 and Figure 15).

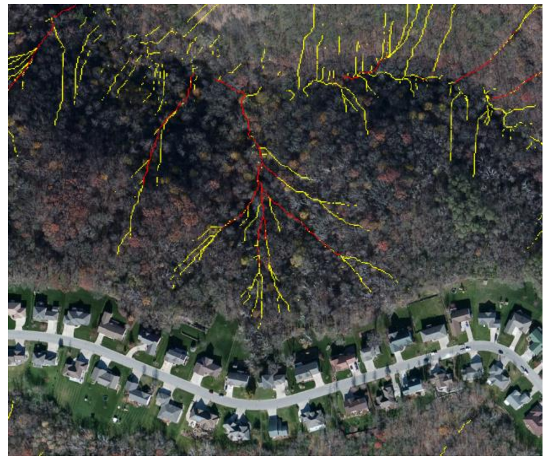

Figure 13. Verification site 1 Aerial (Bing Aerial Imagery). Red and yellow symbolization indicates where an SPI value is at or above the .001 and .01 percentiles (respectively) of all SPI values throughout the watershed.

Figure 14. View downhill from verification site 1.

Verification Site 2

Verification site 2 had multiple high SPI valued catchment areas converging on a conservation dam (Figure 16).

This site allowed for observations of how the conservation dam affected

Figure 15. View uphill from verification site 1.

Figure 16. Verification site 2 Aerial (Bing Aerial Imagery). The conservation dam is in the upper left corner of the figure. Red and yellow symbolization indicates where a SPI value is at or above the .001 and .01 percentiles (respectively) of all SPI values throughout the watershed.

overland flow. When viewing the area immediately 'upstream' from the conservation dam with .001% and .01% SPI values overlaid, it was apparent the dam is serving its purpose of slowing the flow (by reducing the grade) and then releasing the water in a controlled manner in an area where there was sufficient ground cover and a lack of high slope to accommodate the out-flow in a controlled fashion.

Because pit filling was used during the preprocessing steps the full picture of this site may not be represented. Pit filling over-generalizes the landscape and does not allow the model to include the benefit of the conservation dam. This over-generalization is evident after closer inspection of the aerial imagery. The SPI model did not predict erosion in an area where erosion was obviously present from the aerial image (Figure 17). This error is possible because pit filling increased the elevation of the sink and in doing so created an area that was flat and did not fully represent the landscape.

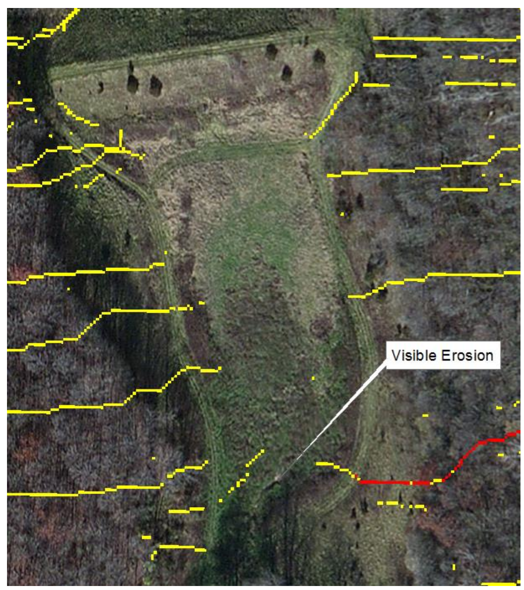

Figure 17. Visible erosion at verification site 2**.** Red and yellow symbolization indicates where a SPI value is at or above the .001 and .01 percentiles (respectively) of all SPI values throughout the watershed.

Verification Site 3

Verification site 3 was chosen because the catchment area for this site is annually cultivated land with no visible erosionmitigating structures present, while still having a high SPI value (Figure 18).

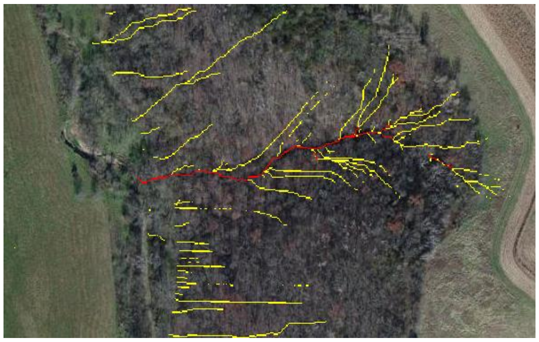

Figure 18. Verification site 3 Aerial (Bing Aerial Imagery). Red and yellow symbolization indicates where a SPI value is at or above the .001 and .01 percentiles (respectively) of all SPI values throughout the watershed.

Upon analysis of the aerial imagery for this site it was apparent a large amount of erosion was occurring at the 'downstream' end of the high SPI values (Figure 19).

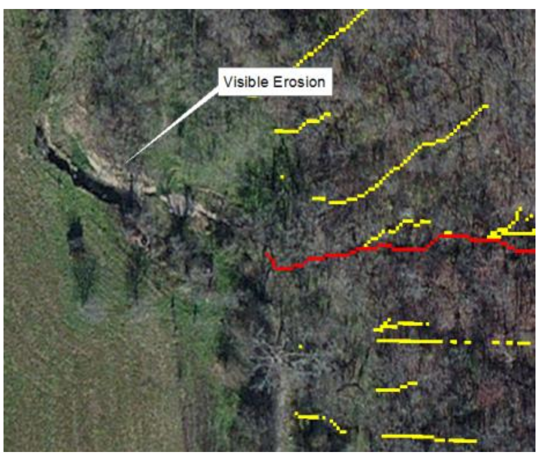

Figure 19. Visible erosion at verification site 3. Red and yellow symbolization indicates where a SPI value is at or above the .001 and .01 percentiles (respectively) of all SPI values throughout the watershed.

This site is particularly interesting because the visible erosion is in Gilmore Creek itself. This would suggest during large rain events that this area experiences unimpeded overland flow entering Gilmore Creek and adding too much flow for the natural creek banks to accommodate. It also suggests if the flow was contained and released in a controlled manner, less erosion might occur where this flow enters Gilmore Creek.

Conclusion

The SPI model has not been extensively used to predict erosion areas over whole watersheds and as such it is possible that modifications to the equation, analysis, or verification could improve the results.

With regards to the SPI model itself, it is apparent that land use and land cover can have a large impact on the erodibility of the landscape. When the SPI model is used on a small mostly homogeneous area where land cover and land use are similar throughout, it may not be as important to factor. However on a larger, more diverse landscape such as the Gilmore Creek watershed, land cover and land use become more important.

Another point of concern with using the SPI model over a whole watershed is how pit filling skews results near erosion control structures such as conservation dams. Further, developing the model to include the steady release of overland flow from conservation dams, terracing or other conservation measures could help give a more complete picture of how current erosion mitigation measures are impacting overland flow and, in turn erosion, on the landscape.

Acknowledgments

I would like to extend a special thank you to the Department of Resource Analysis at Saint Mary's University of Minnesota, especially department chair John Ebert for support and guidance. I would also like to thank Tex Hawkins (Retired, USFWS) and Barry Drazkowski (Director, GeoSpatial

Services) for project development assistance and discussions. Finally, I would like to thank my family, especially my sister, Lindsey, who pushed, taught and motivated me to both attend graduate school and complete my project.

References

Dogwiler, T., Dockter, D., and Omoth, D. 2010. Rush-Rine Creek Watershed Digital Terrain Analysis Overview and Procedure Guidelines: WRC Report 2012-02, Southern Minnesota Water Resources Center, Winona State University, Winona, MN.

Environmental Systems Research Institute (ESRI). 2013a. GIS Dictionary. Retrieved February 16, 2013 from http://support.esri.com/en/knowledgebase/Gisdictionary/browse.

Environmental Systems Research Institute (ESRI). 2013b. ArcGIS Resource Center. Retrieved February 16, 2013 from http://resources.arcgis.com/en/home.

Martinez-Casasnovas, J.A. 2003. A spatial information technology approach for the mapping and quantification of gully erosion. *Catena, 50*, 293-308.

Meyer, L.D. 1984. Evolution of the Universal Soil Loss Equation. *Journal of Soil and Water Conservation, 39,* 99-104.

Moore, I.D., Grayson, R.B., and Ladson, A.R. 1991. Digital terrain modeling: A review of hydrological, geomorphological, and biological applications. Hydrol. Processes. 5:3-30.

Nelson, J. 2010. Digital Terrain Analysis with LiDAR for Clean Water Implementation – Workshop April 7, 2010. Minnesota Department of Agriculture. Acquired during MN Dept. of Ag. Workshop in Winona, MN April 7, 2010. A Similar copy can be acquired from http://www.mda.state.mn.us/protecting/cleanwater/pilotprojects/~/media/Files/protecting/waterprotection/lidarworkshopshow.ashx

Renard, K.G., Foster, G.R., Weesies, G.A., and Porter, J.P. 1991. RUSLE Revised Universal Soil Loss Equation, *Journal of Soil and Water Conservation, 41*, 30-33.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C. 1993. *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE),* Handbook No. 703, Washington D.C.: United Sates Department of Agriculture.

Renard, K.G., Foster, G.R. Yoder, D.C., and McCool, D.K. 1994. RUSLE revisited: status, questions, answers, and the future, *Journal of Soil and Water Conservation*, *49,* 213-220.

United States Department of Agriculture (USDA). 2013. Revised Universal Soil Loss Equation 2, Retrieved February 16, 2013 from http://www.ars.usda.gov/Research/docs.htm?docid=6014.

Wilson, J.P., and Lorang M.S. 2000. Chapter 6, Spatial Models of Soil Erosion and GIS. *Spatial Models and GIS: New Potential and New Models*, 83-86.

Wischmeier, W.H. 1976. Use and misuse of the universal soil equation. *Journal of the Soil and Water Conservation, 31*, 5-9.

Wischmeier, W.H., and Smith, D.D. 1965 *Predicting Rainfall-erosion Losses from Cropland East of the Rocky Mountains*, Handbook No. 282, Washington D.C.: United States Department of Agriculture.

Wu, S., Li, J., and Huang, G.H. 2008. A study on DEM-derived primary topographic attributes for hydrologic applications: Sensitivity to elevation data

resolution, *Applied Geography*, *28*, 210-223.
Yoder, D., and Lown, J. 1995. The future of RUSLE: inside the new Revised Universal Soil Loss Equation, *Journal of Soil and Water Conservation, 50*, 484-489.