Estimating Soil Erosion Within the French Creek Subbasin Using the Revised Universal Soil Loss Equation (RUSLE) and Geographic Information Systems (GIS)

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April, 2017

Submitted in fulfillment of the senior thesis requirements of the Department of Environmental Science at Allegheny College and approved by the senior thesis committee.

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Pledge 5-1-2017

Abstract:

The French Creek subbasin is an ecological treasure found within northwestern Pennsylvania. An extensive variety of fish and freshwater mussels have made their home within the 1,200 square miles of the subbasin. Soil erosion poses a potential threat to this significant waterway as the resultant sedimentation can disrupt breeding grounds and alter the watershed's ecosystems. The revised universal soil loss equation (RUSLE) in combination with the computing capabilities of geographic information systems (GIS) were used to predict areas at high risk of soil erosion. The RUSLE consists of six variables which include rainfall/runoff erosivity, soil erodibility, slope length, slope steepness, cover management, and support practices. Data for each variable were collected from online databases and processed to create six raster layers which were multiplied together to produce an average annual soil loss map of the subbasin. The results show that low soil erosion is fairly consistent across the subbasin with some small areas showing up as at risk of high soil erosion. One watershed, Little Sugar Creek, had a substantially higher average than the rest of the watersheds but still falls below the classification of high risk. Water samples should be taken throughout the subbasin in order to test the accuracy of the results, especially in areas marked as high average annual soil loss.

Introduction:

The French Creek watershed is one of the most ecologically significant waterways in Pennsylvania as it is home to more species of fish and freshwater mussels than any other stream comparable in size in Pennsylvania (Conservancy, 2002). The watershed is home to more than 80 species of fish which includes 15 species of darters. More notably, eight of the darter species are listed as endangered or threatened in Pennsylvania (Darter, nd). The watershed also provides habitat for 27 species of freshwater mussels, which is a little under half of Pennsylvania's 65 species of freshwater mussels (Freshwater, nd). There are no other streams further north or east throughout the nation with a more diverse population of freshwater mussels (Freshwater, nd). With such a diverse population of fish and freshwater mussels, it is important to keep pollutants from entering French Creek and its tributaries to ensure that the watershed remains clean and healthy.

The health of the watershed is largely determined by how the land within the watershed is utilized. When land is modified from its original state it can cause unforeseen consequences. When not properly practiced and managed, agricultural land use is a leading contributor to pollutants found within water systems. Agriculture contributes several kinds of pollutants, with the most common being sediment (Zimmerman et al., 2003). When agricultural land is not properly managed or riparian zones along waterways are destroyed, sediments and the chemicals found within the sediments can be be moved into the water systems through runoff.

Erosion is a problem many farmers face when their properties are located near waterways. Most farmers find soil erosion to be a problem because it can cause a loss in profit and revenue. These losses are generally less than what the landowner would spend on preserving or restoring riparian zones, which is a reason why many farmers continue to allow soil erosion to occur on their property. The costs associated with the movement and deposition of sediment within watersheds often outweigh the costs of long-term agricultural loss (Morgan, 2009). The driving force behind soil erosion is precipitation and the subsequent runoff, which is determined by the terrain of the land and what the land is being used for. Human interaction at the landscape scale poses many threats to the river ecosystems such as destruction of riparian zones and the resultant sedimentation and pollution (Allan, 2004). When land is changed from its natural state to suit the needs of humans, there are no longer natural barriers in place to keep soil from being moved by erosional processes.

Understanding the topography and climate of the region is also important to the understanding of soil erosion. The topography of French Creek watershed is the result of glacier

activity and consists of gently rolling hills and broad valleys (Hasse, 1994). The watershed is relatively flat with the valleys providing the main source of topographic relief. Erosion will be more prevalent in these valleys as slope is directly related to soil erosion. As slope steepness and length increase, the risk of erosion increases as a result of the increase in velocity and volume of surface runoff (Morgan, 2009). Climate plays a major role in erosion and relocation of sediments throughout the watershed. The intensity and amount of precipitation directly affects the amount of sediment that goes into the waterways (Carroll, 1997). Both rain and snow contribute to erosion with rain generally having a greater effect. The force of rain detaches the soil which allows surface flow to transport the soil in downhill directions (Ellison, 1948). Snow does not have the force to detach soil as it falls and thaws at a substantially lower rate than rainfall. However, the soil is generally frozen or saturated with water when the snow is thawing which causes minimal infiltration (Zachar, 2011). With little infiltration, the amount of runoff is generally higher than that for rainfall runoff. Snow thaw can affect areas protected by a small amount of vegetation which can cause soil dispersion (Zachar, 2011). The geographic extent of the French Creek watershed is such that it experiences only a small change of precipitation from the headwaters to the mouth. There is a higher rate of precipitation near the mouth of the watershed and therefore should experience slightly higher erosion (PRISM, 2010)..

Soil erosion not only has a visual effect on the topography and shape of the land, but it also can have a profound effect on the river ecosystems. When soil erosion turns into sedimentation, streams and rivers can be seriously degraded. Some effects of sedimentation are: murky waters caused by turbidity, a collapse of the food web as food quality and diversity decreases, in-filling of interstitial habitat harms crevice-occupying invertebrates and gravel-spawning fish, and reduction of stream depth diversity, leading to decrease in pool species (Allan, 2004)(Henley et. al, 2000). Sedimentation can cover and fill stream beds with soil that are vital for the reproduction of many species. Changes in the structures of streams often result in reduced diversity of fish and a less complex size structure of fish populations (Zimmerman et al., 2003).

Since the French Creek watershed is home to such an extensive list of freshwater mussels and fish, it is important that their habitats are not disrupted. Sedimentation threatens to change the habitats of these organisms resulting in reproduction problems for many of the species. Agricultural land use provides one of the greatest risks of sedimentation, however, from 2007 to 2012, Chautauqua County was the only county in the study region that showed an increase in agricultural lands (USDA, Pennsylvania, 2007)(USDA, Pennsylvania, 2012)(USDA,

New York, 2007)(USDA, New York, 2012). Crawford, Erie, Mercer, and Venango counties in Pennsylvania all showed a decrease in the amount of agricultural land use. Even though there was a decrease, there still could be a risk of sedimentation depending on where the remaining farmland is located. To help minimize the amount of sedimentation into the French Creek watershed, areas of possible heavy soil erosion need to be discovered and monitored.

Finding areas of possible high soil erosion requires an analysis of the entire watershed based on several factors. The most efficient way to analyze different geographic factors together is through the use of geographic information systems (GIS). This study incorporates GIS and the revised universal soil loss equation (RUSLE) to predict annual soil loss within the region. The RUSLE is the most widely used model to predict soil erosion loss because of its efficiency and ability to cover large areas (Lu et. al, 2004). The RUSLE incorporates six variables, including rainfall/runoff erosivity, soil erodibility, slope length, slope steepness, cover management, and support practices. The result of this equation can help aid in the identification and prioritization of soil erosion hotspots within the French Creek watershed.

Methods:

Study Region

With its headwaters in Chautauqua County, New York, French Creek flows southwest into Pennsylvania (Conservancy, 2002). The main stem is 117 miles in length and passes through parts of five counties: one county in New York (Chautauqua) and four counties in Pennsylvania (Crawford, Erie, Mercer, and Venango)(The French Creek, nd). French Creek is fed by ten major tributaries which can be found in Figure 1. These ten tributaries and their watersheds cover approximately 1,235 square miles while draining portions of 72 townships, cities, and boroughs (Conservancy, 2002).

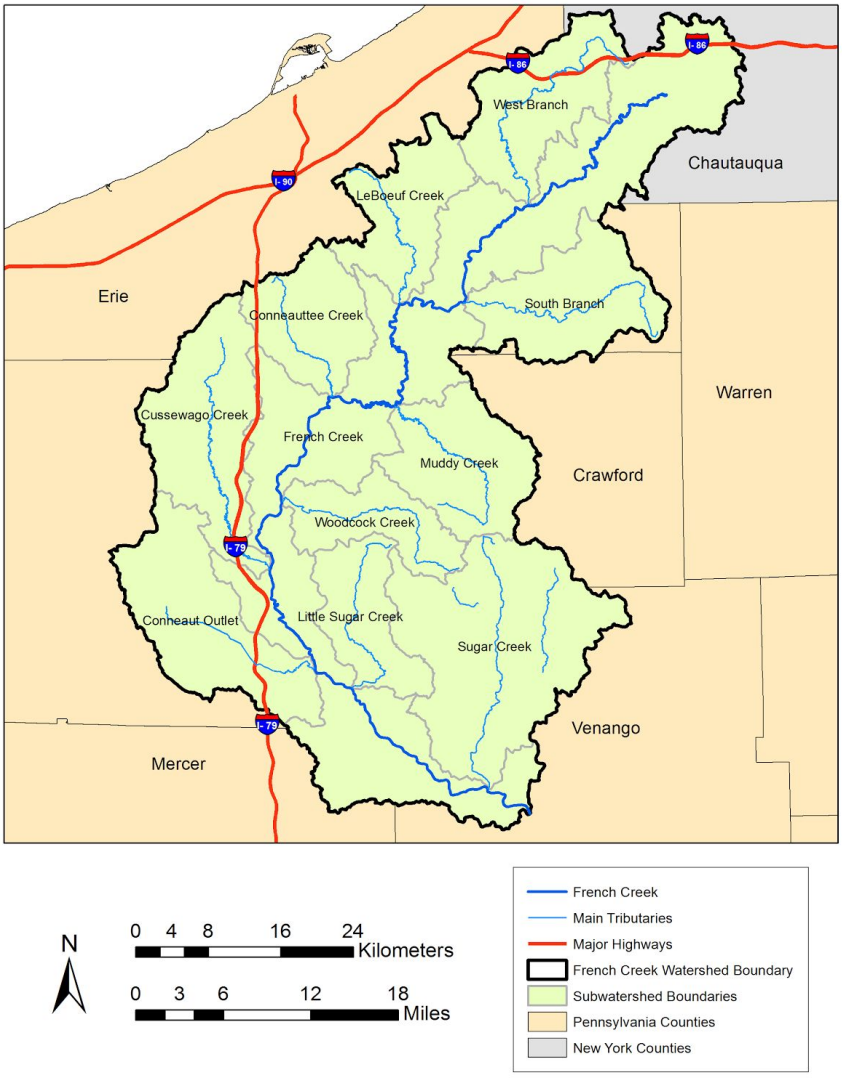


Fig. 1. French Creek Watershed and its Subbasins

Data Sources

The RUSLE is an adaption to the original Universal Soil Loss Equation (USLE) to include the precision of computer programming to create more exact models. The RUSLE is used to predict expected long term average soil loss based on six different variables (Renard et. al, 1997). The RUSLE is given by the equation:

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

Where A is average annual soil loss as tons per acre per year; R is the rainfall-runoff erosivity factor; K is the soil erodibility factor; L is the slope length factor; S is the slope steepness factor;

C is the cover-management factor; and P is the support practice factor (Renard et. al, 1997). Data for these variables were collected, formatted in GIS, and then multiplied together through the RUSLE. These five variables and their sources can be seen in Table 1.

Data	Data Type	RUSLE Factor	Source
1981-2010 Annual Average Raster Precipitation for Pennsylvania	Precipitation	R	Oregon State University and the Oregon Climate Service at Oregon State University
Soil Survey Geographic Database (SSURGO 2.2) for Crawford, Erie, Mercer, Venango, and Chautauqua	Soil	K	U.S. Department of Agriculture, Natural Resources Conservation Service
National Elevation Dataset (NED) 30m for all Counties	Elevation	LS	U.S. Geological Survey (USGS), EROS Data Center
2011 National Land Cover Data Set (NLCD) 30m for Pennsylvania	Vegetation	C	U.S. Geological Survey, National Land Cover Data (2011)

Table 1. Digital Data

Precipitation (R-Factor)

The R factor represents rainfall/runoff erosivity and includes the two major storm characteristics, amount of rainfall and peak intensity of the storm (Kelsey and Johnson, 2003). The equation for the R factor is given by

$$R = \Sigma EI_{30}(10^{-2})$$

Where R is rainfall/runoff erosivity, E is the total storm kinetic energy, and I_{30} is the maximum 30 minute rainfall intensity (Renard et.al, 1997). There were not sufficient data to use this equation so isoerodent maps were used. The equation for R is used to create isoerodent maps that represent the average EI_{30} value and was calculated over 20 years of data (Kelsey and Johnson, 2003)(Cooper, 2011)(Renard et. al, 1997).

The isoerodent map was originally in a pdf and had to be converted from a jpeg image. The jpeg image was uploaded to GIS and georeferenced to the polygons of Pennsylvania and

New York. Once georeferenced the isoerodent lines were digitized using heads-up digitizing. The polyline feature was then run through the TOPO to RASTER tool which interpolates the area between the isoerodent lines (Khosrowpanah et. al, 2007). This gives a complete raster layer for the R factor which can be seen in figure 2b.

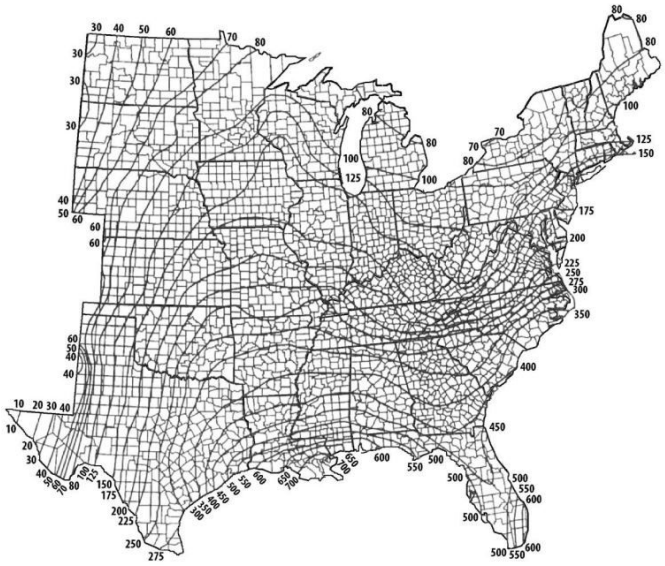


Figure 2a: Isoerodent Map

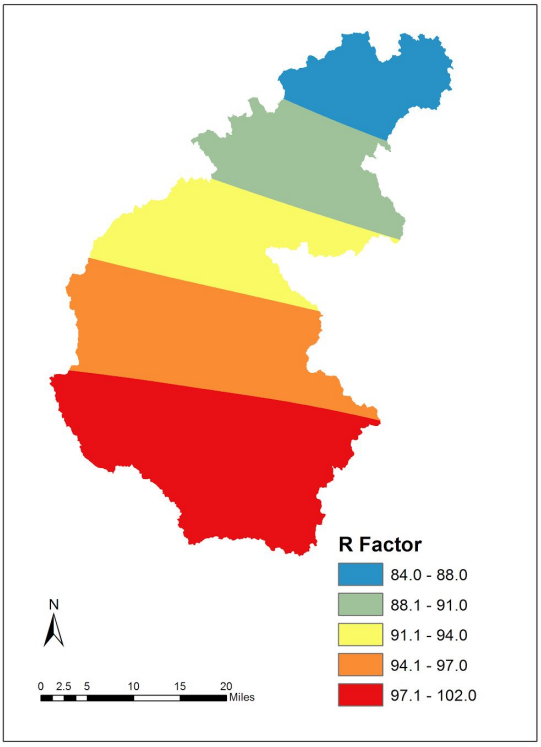


Figure 2b: R Factor Map

Soil (K-Factor)

Soil maps were retrieved from the Natural Resource Conservation Service (NRCS) and were used to find the K-Factor. The K-Factor represents the susceptibility of soil to erosion and the rate of runoff. It is determined by the composition of the soil and its texture. Soils with fine textures tend to have low K-Factors while soils with coarse textures tend to have high K-Factors (Institute of, 2002). K-Factors can be acquired through the soil data acquired from the NRCS in the form of tabular data. The tabular data was joined with the soil map vector layers for each county. Since soil data was retrieved from five different counties, there are some small discrepancies between how the soil zones were classified and what k value each soil zone received. This created a distinct boundary between the counties but does not affect the outcome

of the RUSLE. The joined soil map vector layer was converted into a 30m raster layer, using the joined K-Factor field, by the feature to raster function which can be seen in Figure 3.

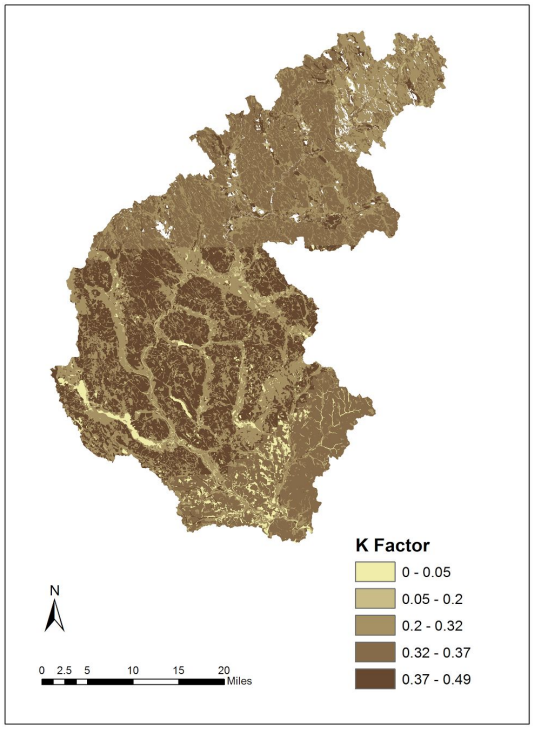


Figure 3: K Factor Map

Slope Length and Slope Steepness (LS-Factor)

The L and S factors represent slope length and slope steepness which shows the effect of topography on soil erosion (Haan et. al, 1994). Slope length represents the distance from where surface flow starts to where the slope gradient decreases enough to allow for deposition (Wischmeier et. al, 1978). The L and S factors are a ratio of soil loss under certain conditions compared to a site with standard slope steepness of 9% and slope length of 22.1 meters (Stone and Hilborn, 2000). As slope steepness and length increase, the flow velocity of runoff increases which can create more soil erosion.

The Unit Stream Power Erosion and Deposition (UPSED) method was used to calculate the L and S factors because it could be done within GIS. This method requires the use of tools found within the spatial analyst extension and the equation for L:

$$L = (m+1)\left(\frac{\lambda_A}{22.1}\right)^m$$

Where the variable m is an adjustable value depending on the soil's susceptibility to erosion and λ_A is the area of upland flow.

And the equation for S:

$$S = \left(\frac{sin\,(0.01745 \times \theta_{deg})}{0.09}\right)^{n}$$

Where the variable n is an adjustable value depending on the soil's susceptibility to erosion, 0.09 is the slope gradient constant, and θ is the slope in degrees. Both of these equations and suggested values for n and m can be found in Mitasova et. al, 1996. For this study region the value for m was chosen to be 0.4 and the value for n was chosen to be 1.4 based on the land use and slope found within the French Creek subbasin.

The UPSED method requires a digital elevation model (DEM) and a depressionless DEM. A National Elevation Dataset (NED) at 30m was used and sinks were filled using the FILL (Spatial Analyst) tool. With the two DEMs, the LS factor was found using the following steps (Pelton et. al, 2015):

1. Calculate the flow direction using the filled dem with the FLOW DIRECTION (Spatial Analyst) tool. This creates the flow direction layer as seen in figure 3a.
2. Calculate the flow accumulation using the flow direction layer and the FLOW ACCUMULATION (Spatial Analyst) tool. This creates the flow accumulation layer as seen in figure 3b.
3. Calculate the slope of the watershed using the unfilled DEM with the SLOPE (Spatial Analyst) tool. This creates the slope layer as seen in figure 3c.
4. Use the RASTER CALCULATOR (Spatial Analyst) tool with the equation:

   Power("flowacc"*[cell resolution] / 22.1, m) *
   Power(Sin("sloperasterdeg" * 0.01745)) / 0.09, n) * (m+1)

5. "Flowacc" should be replaced by the flow accumulation layer and the "sloperasterdeg" should be replaced with the slope layer. The values for m were replaced with 0.4 and the values for n were replaced with 1.4.

Running this raster calculation provides a map layer for the LS factor (Figure 3d) which can later be used in the final RUSLE calculation.

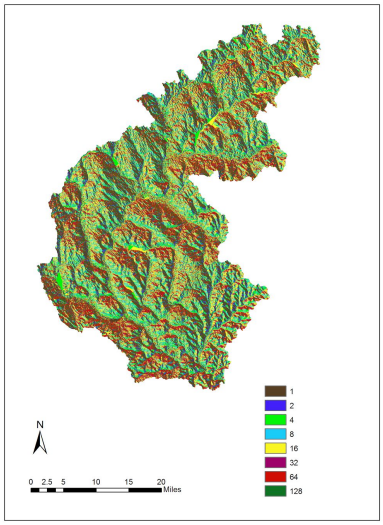


Figure 4a: Flow Direction

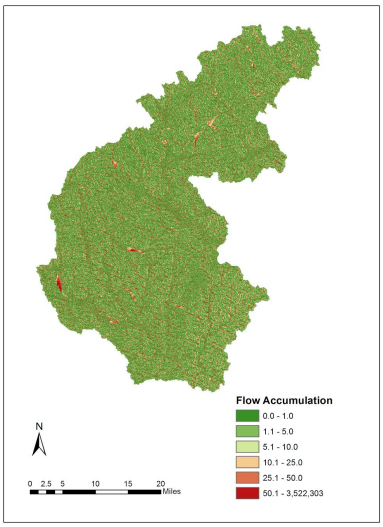


Figure 4b: Flow Accumulation

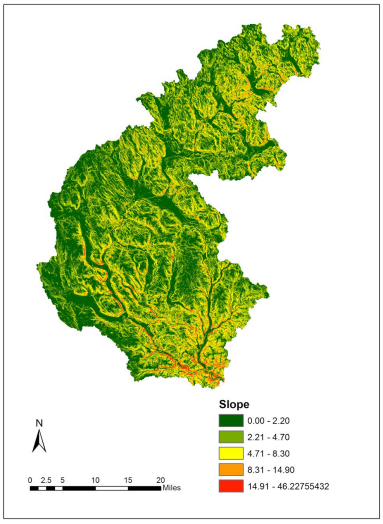


Figure 4c: Slope

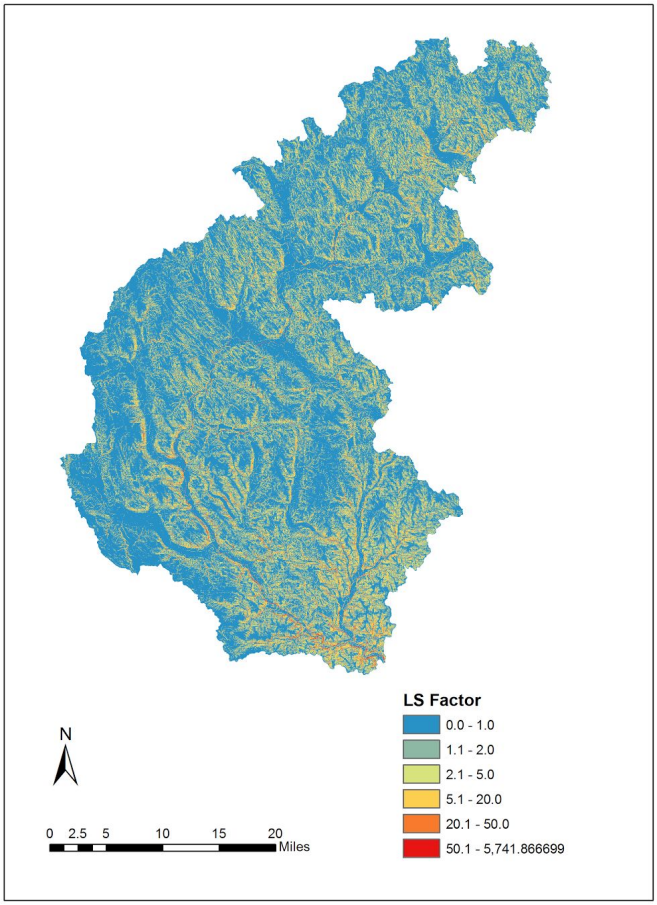


Figure 4d: LS Factor Layer

Vegetation (C-Factor)

Land cover data from the 2011 National Land Cover Dataset (NLCD) was used to model the vegetation factor. For this data to be usable in the RUSLE, the different land cover classes were assigned a specific C-Factor value. The C-Factor, or cover factor, accounts the effects of aboveground cover, surface/ground cover, and below surface factors which can cause a land cover class to have a range of C Values (Haan et. al, 1994, p. 267). Average C Values were assigned to each land cover class based on values given by Haan et. al (1994, p. 266) and can be found within Table 2. The C Values for cultivated crops for the study region were determined by the average C Values for corn and soybeans since they account for most of the cropland within the study region. The NLCD was then converted into a 30m raster using the added C-Factor field.

Land Cover	C Factor
Open Water	0
Developed, Open Space	0.003
Developed, Low Intensity	0.013
Developed, Medium Intensity	0
Developed, High Intensity	0
Barren Land	0.9
Deciduous Forest	0.005
Evergreen Forest	0.003
Mixed Forest	0.001
Shrub/Scrub	0.012
Herbaceous	0.02
Hay/Pasture	0.013
Cultivated Crops	0.3
Woody Wetlands	0.003
Emergent Herbaceous Wetlands	0.003

Table 2. Landuse C-Factor

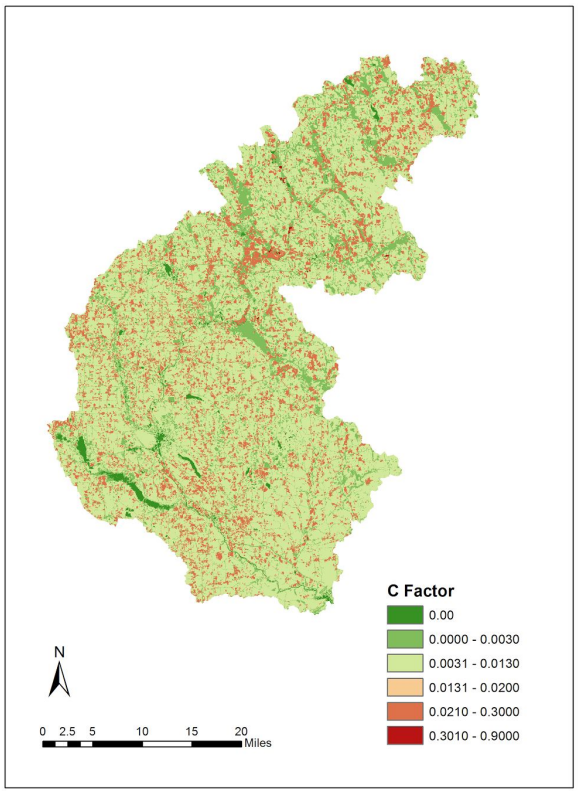


Figure 5: C Factor Layer

Support Practice (P-Factor)

There was not sufficient data about support practices within the study region to include a P factor. The P factor layer was set at 1 to prevent changing the outcome of the final erosion map.

2.4 Data Analysis

The RUSLE is a simple equation that involves the multiplication of its six variables which was carried out in ArcGIS Desktop 10.4.1 (ESRI, 2017). In order for these variables to be multiplied together they all needed to be in raster form and have similar pixel resolutions. Once all of the layers properly formatted, the RASTER CALCULATOR tool was run to create a soil erosion map of the French Creek subbasin. With the soil erosion map created, watersheds within the subbasin could be compared to determine if there are any watersheds at high risk of

soil erosion. This comparison can be done by using the EXTRACT BY MASK tool to break up the soil erosion map into the smaller watersheds.

Results

The average annual soil loss for the French Creek subbasin is 2.10 tons per acre per year with a standard deviation of 21.1. An estimated total of 1,660,890 tons of soil are lost each year from the 790,900 acres found. Estimated soil loss totals and averages for each of the watershed can be found within Table 3. Soil erosion is estimated to be fairly consistent across the entire study region with no watershed showing great risk of erosion. Little Sugar Creek had the highest average soil loss at 3.83 tons per acre per year and is almost double the average for the entire subbasin. Little Sugar Creek and French Creek watersheds had very high max soil erosion values with Little Sugar Creek having a maximum of 9705.9 t/ac/yr while French Creek had a maximum of 17,621.3 t/ac/yr of soil erosion.

Figure 6 shows the final soil erosion map of the French Creek subbasin. There are no watersheds within the subbasin that stick out as having a high risk of soil erosion. Areas of low soil risk are shown by the different shades of light blue. Light blue can be found in all portions of the map. Areas at high risk of soil erosion are shown by brown. There are a few small patches of brown but there are no large regions that shows high risk of soil erosion.

Watershed	Average Soil Loss (t/ac/yr)	Total Soil Loss (t/yr)	Maximum Soil Loss (t/ac/yr)	Land Area (Acres)	Percent of Watershed
Conneaut Outlet	1.43	92,658	488.6	64,796	8.2
Conneauttee Creek	1.99	76,993	491.5	38,690	4.9
Cussewago Creek	1.73	107,635	538.3	62,217	7.9
French Creek	2.35	612,081	17,621.3	260,460	32.9
LeBoeuf Creek	1.76	71,465	865.8	40,605	5.1
Little Sugar Creek	3.83	129,293	9,705.9	33,758	4.3
Muddy Creek	2.39	116,305	827.1	48,663	6.2
South Branch	1.83	95,145	2,187.5	51,992	6.5
Sugar Creek	1.85	198,533	1,653.6	107,315	13.6
West Branch	1.65	82,213	1001.0	49,826	6.3
Woodcock Creek	2.43	79,206	5,294.7	32,595	4.1
French Creek Subbasin	2.1	1,660,890	17,621.3	790,900	100

Table 4: Results

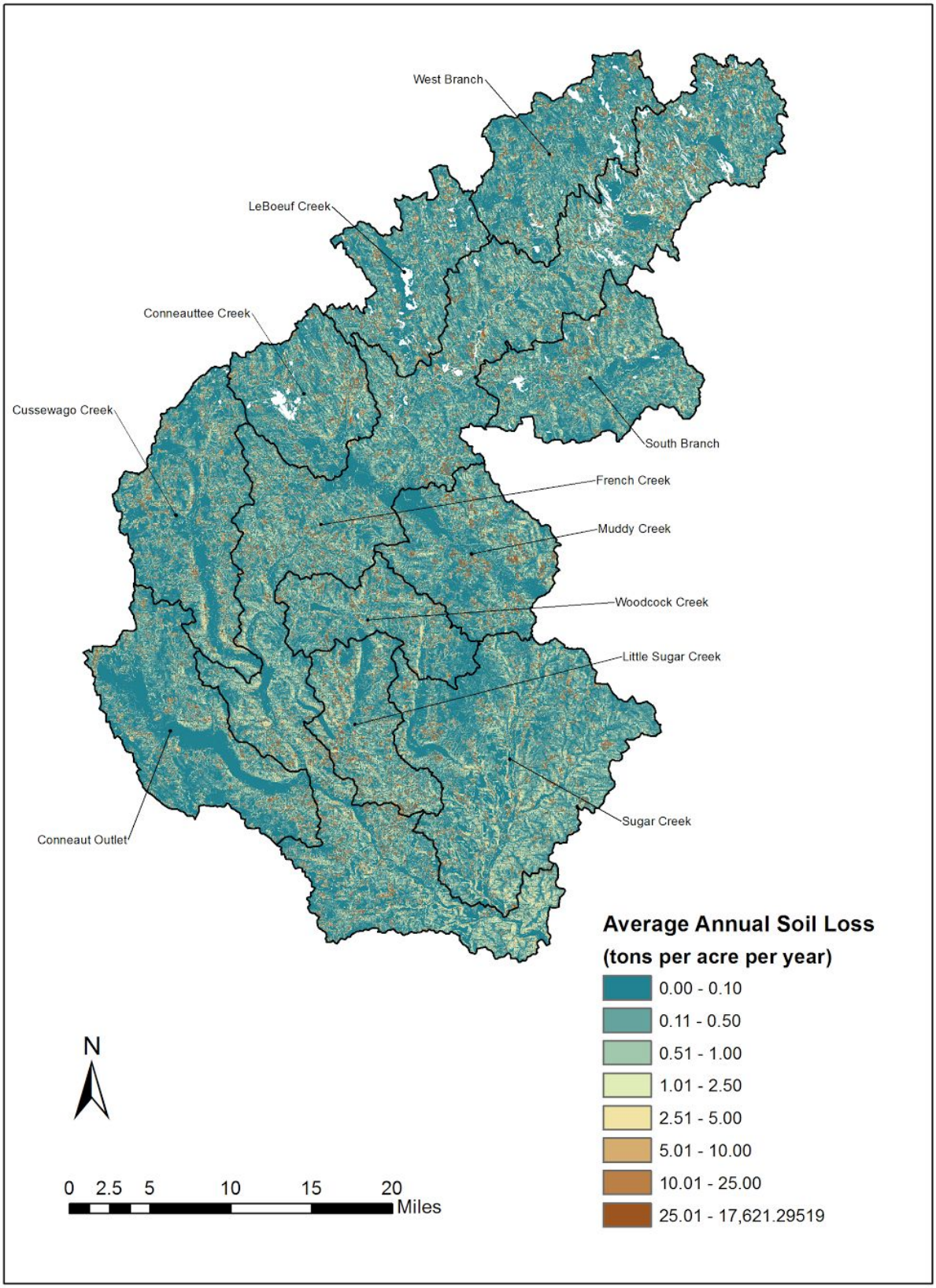


Figure 6: Average Annual Soil Loss within the French Creek Subbasin and its 11 watersheds

Discussion and Recommendations

The results of this study reveal there are no major watersheds within the subbasin that pose a high risk of soil erosion. All of the watersheds had an average soil loss below 5 tons of soil loss per acre per year which classifies them as medium to low risk for soil erosion. Figure 6 shows that a majority of the French Creek subbasin falls under the classification of 0 - 2.0 tons/acre/year for soil loss. The northern portion of the subbasin appears to have more soil erosion potential, classified as 2.5 - 5 tons/acre/year, compared to the southern part of the subbasin. This could be contributed to a larger amount of land being classified as agriculture and pasture/hay in the north. The differences between the overall subbasin only vary slightly as you move from the the headwaters of the subbasin to the mouth. However, there are some smaller areas spread across the subbasin that classify as a higher potential for soil erosion. These areas are shown as 10 plus tons/acre/year of soil loss. These areas tend to have high LS factors and high C factors. High LS factors can be contributed to an uneven topography while high C factors can be contributed to areas with land use classifications of agriculture and pasture/hay.

A large portion of the land that is considered high risk for soil erosion are agricultural lands that are on or near stream banks with steep slopes leading into the streams. With large amounts of sediment and soil eroding into streams near or next to agricultural land, there is a risk of pollutants also being loaded into the streams.

Highest Risk Subbasins

Little Sugar Creek had the highest average rate of predicted soil loss at 3.83 tons/acre/year and was substantially higher than any other watershed. The watershed with the next highest rate of predicted soil loss was Woodcock Creek at 2.43 tons/acre/year. Both watersheds have high very high maximum soil loss values which could have been the cause of their high average soil loss values. Both watersheds are located in the middle of the French Creek subbasin and are adjacent to each other. There is a decent amount of agriculture in the Little Sugar Creek watershed with less in the Woodcock Creek subbasin. Figures 7 and 8 show the LS factor, C factor, and the annual soil loss for the Little Sugar Creek subbasin and Woodcock Creek watershed. Areas of high annual soil loss are areas where there are high LS factors and high C factors.

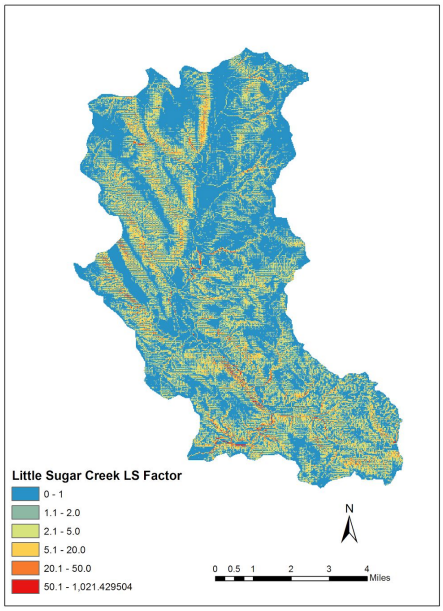


Figure 7a: Little Sugar Creek LS Factor

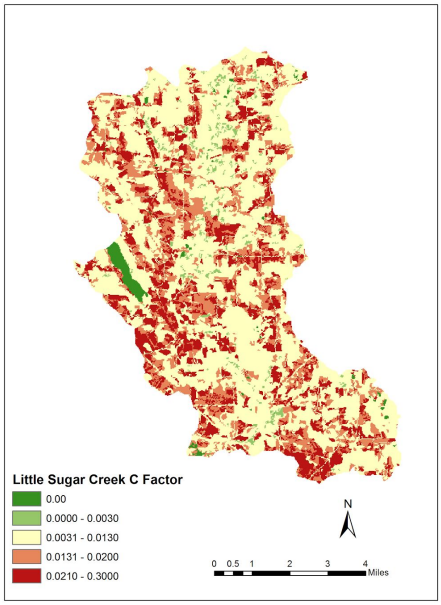


Figure 7b: Little Sugar Creek C Factor

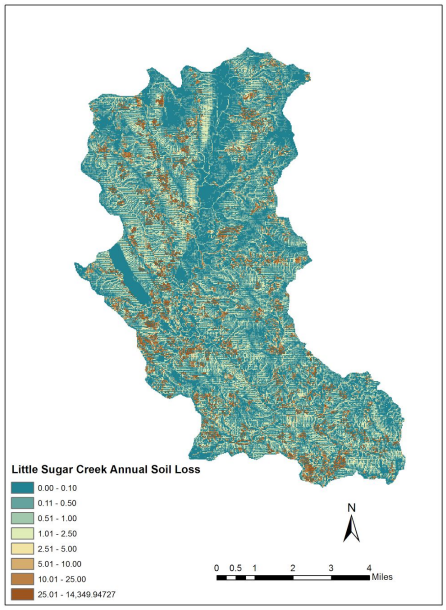


Figure 7c: Little Sugar Creek Annual Soil Loss

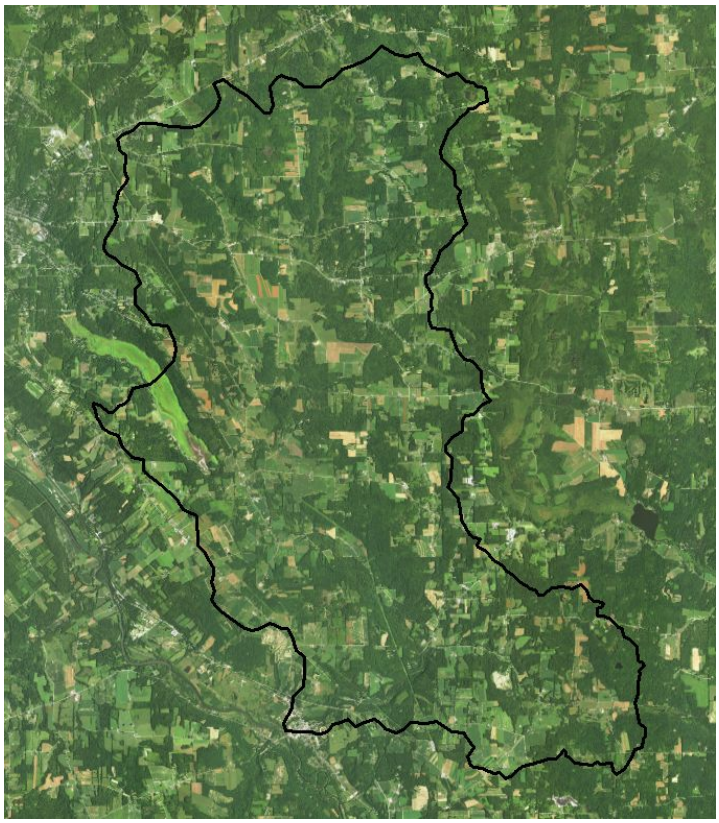


Figure 7d: Aerial Imagery of Little Sugar Creek (NAIP 2015)

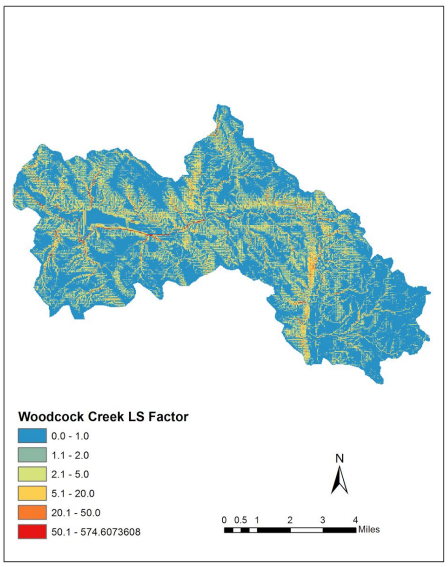


Figure 8a: Woodcock Creek LS Factor

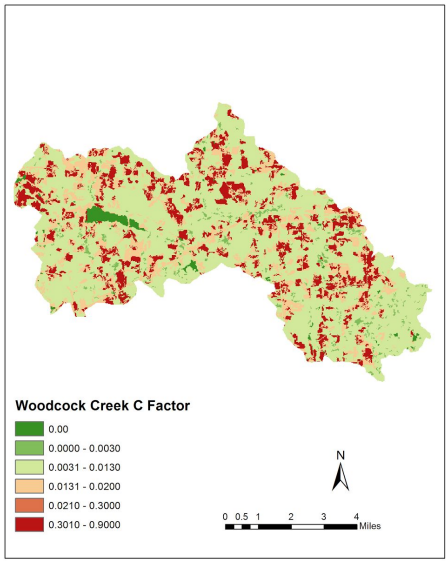


Figure 8b: Woodcock Creek C Factor

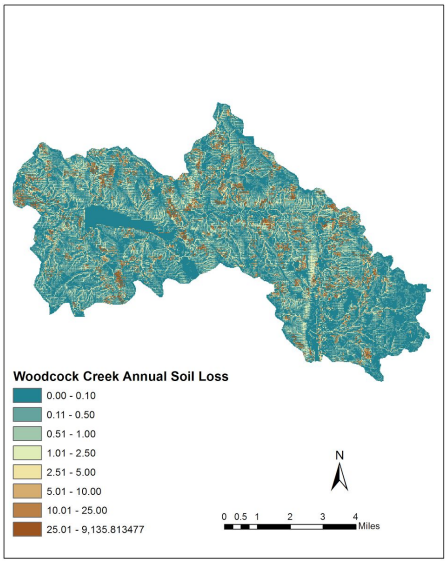


Figure 8c: Woodcock Creek Soil Loss

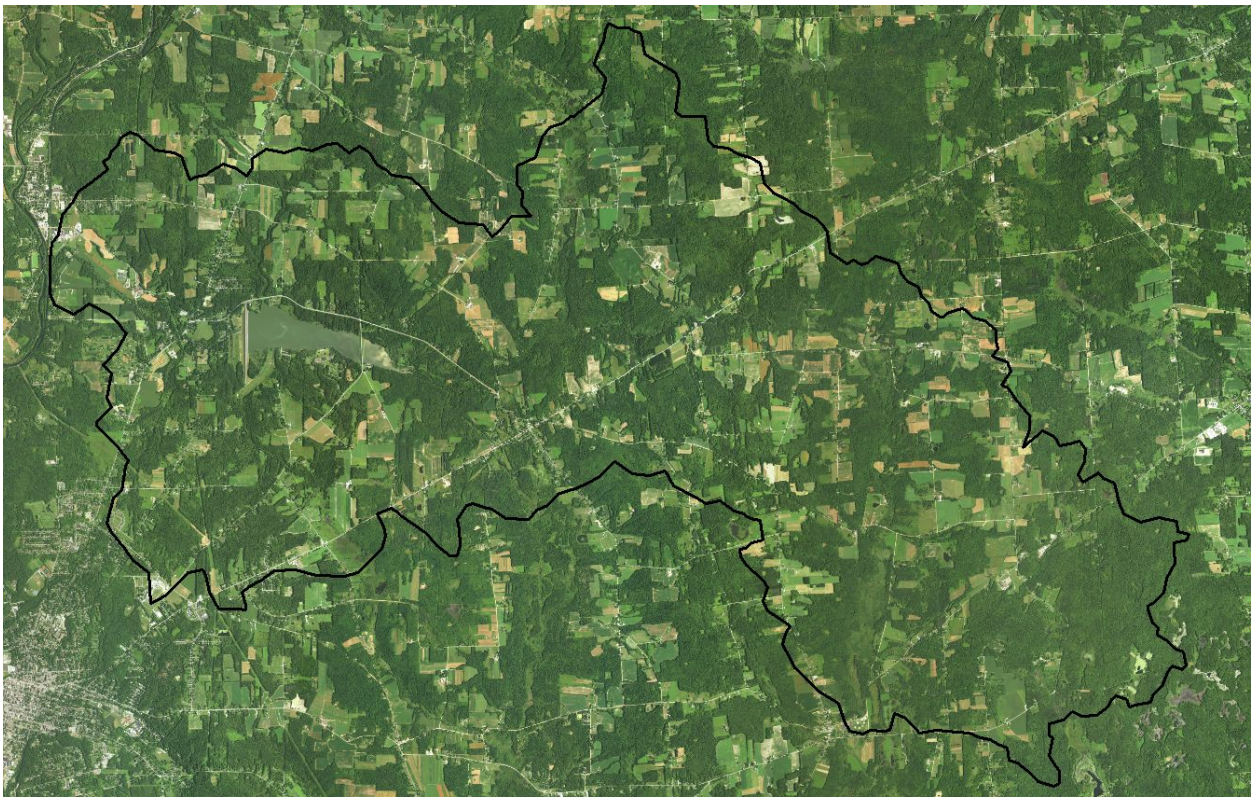


Figure 8d: Aerial Imagery of Woodcock Creek Subbasin (NAIP 2015)

Limitations

There are several limitations that come with using the RUSLE with GIS with the main one being the size of the study region. The RUSLE is a very complicated combination of variables that takes a lot of time to collect. The RUSLE is often used for construction sites or private land where data can be collected from the field. When using the RUSLE on a study region of 1200 square miles it becomes almost impossible to account for all of the different variables. Instead, averages for the study region were used to get an idea of where high rates of soil erosion may occur.

The C factor is one factor that becomes very difficult to precisely calculate on a large scale. The C factor of agriculture has a huge range of values and depends on what is growing and how the owner takes care of the land. The C factor of corn can range from 0.08 to 0.78 depending on what time of year it is and how much corn is being grown (Haan et. al, 1994). It is not reasonable to try to get that level of detail for a study region the size of the French Creek subbasin so averages based on what is typically agricultural use were used.

Another factor that is difficult to calculate with a study region as large as French Creek is the L and S factors. The calculation of these factors can change fairly significantly from one part of the study region to the next. When using the equations to solve for the L factor and the S factor, averages had to be used for the m and n variables. Since averages had to be used, the accuracy of the results could vary across the study region.

Testing stream turbidity to determine if the model correctly predicted areas of high soil erosion was not possible within the timeframe of this project. Since the RUSLE calculates the average annual soil loss, stream samples would need to be collected for an entire year to see if the model predicted accurate numbers of soil loss. Collecting stream samples during December would produce much different results than collecting stream samples in May. With the project only lasting about 6 months it would not be possible to check the accuracy of the predicted soil loss.

Future Research

This study provided results that show areas at high risk of soil erosion based on the six variables of the RUSLE. The RUSLE can closely predict how much soil will be eroded if all of the variables are accurately accounted for. However, with a study region the size of French Creek the very high variable accuracy may not be achievable. Future research could be done to test the areas that showed a possibility for high soil erosion. If the results are proven to

accurately predict soil erosion, the results could be used to target landowners and help educate them on how to reduce soil erosion on their property.

Future research could also include the study of the health of streams near areas at high risk of soil erosion. Water quality could be checked and inventories of the species that live in areas of high soil erosion could be taken and compared to historical inventories. Areas with high risk of soil erosion that are also farms could load chemical pollutants as well as soil into the streams which could be harmful for the ecosystems within the watershed. Studying how high risk land is used could prove important to the future health of the streams and their watersheds.

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