SPATIO-TEMPORAL MODELING OF SOIL EROSION AND CONTAMINATED SEDIMENT TRANSPORT IN LAKE ERIE COASTAL AREA

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ABSTRACT

This paper presents the results of a research project that monitors the soil erosion and contaminated sediment transport using a spatio-temporal modeling approach. The erosion in the study area is mainly precipitation-based runoff erosion and direct soil discharge caused by shoreline/bluff line erosion. The research has made use of periodical aerial photographs to monitor terrain surface and shoreline changes and to model soil runoff and direct soil discharge from the eroded shoreline. Estimation of the amount of contaminated sediments transported in the study area and its impact is also studied here. Aerial photographs acquired by the National Geodetic Survey of NOAA and GPS ground survey data by OSU are used for a photogrammetric adjustment and further for extracting terrain surface models and shorelines. The soil runoff information within the study area is obtained considering the spatial-temporal characteristics of erosion using a RUSLE (Revised Universal Soil Loss Equation) model. The monthly precipitation grids are created using the digital Parameter-elevation Regressions on Independent Slopes Model (PRISM). These episode-based climatic grids are treated as time-pounded individual layers to represent the temporal information associated with them. Using regression analysis, mathematical relationships between rainfall and surface runoff and between eroded mass of soil and the measured sediment load are established. Phosphorus concentrations and actual soil loss models are developed consequently. The spatial and temporal correlation between the actual soil loss due to water erosion that is transported in terms of sediment load and the phosphorus concentration is found weak both globally and locally as tested on a cell-by-cell basis in this research. We will conduct further analysis of the relationship in terms of percentages of landuse in the area, and the sediment contribution from the cropland and other landuses. The relationship will be examined again when the coastal erosion modeling will be performed. The significance of this research is clearly depicted by the results of the models developed here for the assessment of water quality parameters and for modeling coastal terrain surface change in the study area.

INTRODUCTION AND BACKGROUND

Some attempts have been made to provide spatio-temporal GIS models by event-based (Peuquet and Duan, 1995) or object-oriented data models (Worboys, 1992, Rapper and Livingstone, 1995). This study aims to discuss applicability and possibility of applying temporal GIS data models to facilitate spatio-temporal analytical modeling of soil erosion and sediment transport with surface flow. Traditional GIS models emphasize static representations of reality. The geographic representation of a given area is decomposed into a set of single-theme layers as raster or vector models. These layers constrain GIS capabilities to represent dynamic information, such as transitions and motion. Raster cells encode attribute values at every given location with no considerations of the spatial characteristics of the theme they represent. On the other hand, geometrically indexed vector objects separate entities into layers whenever they interact in time or space: adopting this representational method forces compromises on most environmental modeling.

Many researchers have considered GIS when coupled with environmental and hydrologic models to be suitable for this purpose and have adopted them in a wide range of studies (Goodchild, et al., 1993). It is clear that the use of GIS places some constraints on the representational scope of the coupled system that is because GIS are layer based geometry-indexed systems. However, it is not often difficult to be linked to the existing environmental models. The importance of this study comes from the fact that less research work has been done for large scale modeling for such applications using the methods investigated here. The aim of this project is to describe the amounts of eroded soils and the distribution of sediment and nutrient loads spatially and temporally over a small region in Lake Erie coastal areas using the most large scale data set that is available. Numerous studies have been performed at a small scale to estimate soil erosion and sediment transport from croplands. But until recently few

studies have been conducted to evaluate the contamination of water bodies such as Lake Erie from the nutrient-enriched sediment transported by surface flow from croplands.

Soil erosion and sedimentation are primary sources of non-point source pollution degrading water quality in the area. The environmental, economic, and aesthetic impacts caused by these processes make them a formidable regional problem. While soil erosion and sedimentation are to some degree caused by natural factors such as surface runoff and wind, they are accelerated by land use practices such as intensive agricultural production, construction and other development activities. When land use practices are conducted improperly, the consequences would be in several forms, which include water quality degradation, fish and wildlife negative impacts, and nutrient-deficient soils.

The Ohio Geological Survey estimated that more than 3,200 acres of Ohio's Lake Erie shore have been lost to erosion since the 1870s. Approximately 10 million tons of soils are eroded annually in the Ohio portion of the Lake Erie Basin. This translates to a loss of soil equivalent to 19 tons per minute. The economic and environmental costs of soil erosion and sedimentation are severe, taking their toll on every individual in Ohio, both directly and indirectly. Therefore the analysis of erosion cause will utilize natural process information, such as shoreline deposits, coast material, and slope of near-shore zone. Monitoring of coastal erosion needs a long-term commitment and is based on the erosion modeling of Lake Erie using a GIS database. Objective decisions should be made based on erosion monitoring data that are usually acquired cumulatively over a long period of time. To update the erosion data more frequently, high-resolution satellite imagery will be used in the future for erosion monitoring (Li, 1998, Liu, 1998).

The study area

The study area is a coastal strip of Lake Erie that is located in Huron in northern Ohio. Its approximate height is 820 feet above sea level and it encompasses an area of 1.125 square miles. It extends 0.75-mile east and 1-mile west of Old Woman Creek between longitudes 82° 30' and 82° 31' 38.5? west and latitudes 41° 22' 30? and 41° 23' 22? N. This area has been chosen for this study for the reason that many parts of it are croplands, where major crops are receiving applications of chemical fertilizing especially phosphorus based fertilizer. Also the Ohio Environmental Protection Agency has reported this area as having serious surface erosion problems and therefore supplies the Lake Erie hydrologic system with considerable quantities of contaminated sediment. In this area, the till plain is predominantly Mahoning-Bogart-Haskins-Juntown Association of soils. These soils are mainly loams and silty loams, which are easily eroded. Approximately 70% of the land associated with this soil type is used for cropping. The lake plain soils are primarily Kibbie-Tuscola-Colwood Association. They contain a large amount of poorly compacted organic material (up to 50% dry weight). Over the past 150 years, the organic content of the sediments has been reduced. This is primarily due to increased erosion rates in the area caused by greater agricultural activities.

The identification of the extent of the study area as well as its boundary has been done using certain criterion. That has been done using the contour lines and the DEM as it is the case for any hydrologic study, but because the scale of this study is large (1:24,000), the rational method for estimating the peak discharge has been used here. The rational method is used to find the surface area that discharges to the gage station at the Old Woman Creek and US route 6. The discharge used in this method is the difference between the measured discharges at the mentioned gage station and a gage station at Old Woman Creek and Berlin Road. The later gage station is not within the study area, but it is just next to the study area southern boundary. Figure 1 shows approximately the location of the study area.

METHODOLOGY AND RESULTS

The process of digitally simulating and/or modeling a hydrologic phenomenon starts with the digital elevation model (DEM) of the study area. Actually three sets of digital elevation models have been used for this study. The first one from the United States Geological Survey (USGS), which is the USGS 7.5-minute DEM, which has a 30m square cell size. Arc/Info *fill* command is used to remove sinks in the DEM. The *fill* command redefines the elevations of each of the sink points to be equal to that of its lowest elevation neighbor. The second one have been created in Arc/Info using the 7.5-minute USGS DLG file for the study area as input with 30m square cell size. For our study area DEM, the number of rows and columns is 58 and 87 respectively which will approximately give 5046 cells that cover the whole area. Most processing stages are done using Arc/Info Version 7.2.1 GRID module. The third DEM has been created using a set of Aerial photos acquired by the National Geodetic Survey of NOAA in mid 1997 and a GPS ground control network surveyed by our GIS research team at OSU.

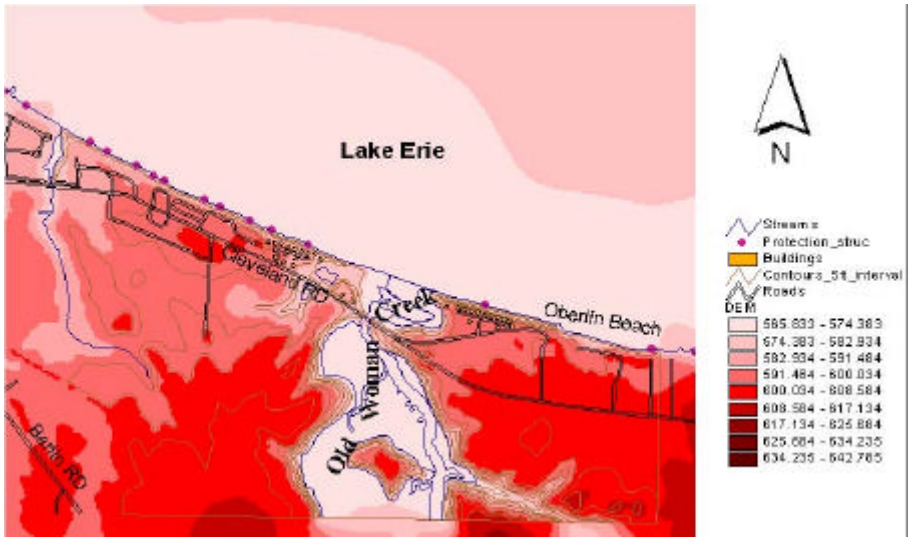

Figure 1: A map showing the location of the study area

Once the filled hydrologic digital elevation models have been created, they can be processed to determine the direction of the flow of water from cell to cell and to determine, for each cell in the grid, the number of cells that are upstream. The *flowdirection* and *flowaccumulation* functions are used for these purposes. The basis for this process relies on the 8-neighbor concept. The output of the *flowdirection* function is an integer grid whose values range from 1 to 255. If a cell is lower than its 8 neighbors, that cell is given the value of its lowest neighbor and flow is defined towards this cell. If multiple neighbors have the lowest value the cell is still given this value, but flow is defined with one of the two methods explained below. This is used to filter out one-cell sinks, which are considered as error or noise within the grid. A digital representation of the stream network in the study area is established by generating the accumulated surface flow in the creek and streams. The Arc/Info *conditional* function is used to extract the flow accumulation cells that have value greater than a certain threshold, which is set to 300 for this study.

Determining Average Rainfall in the study area

Precipitation data for this study are obtained from the Oregon State University Forestry Sciences Laboratory Web site in Arc/Info interchange format (E00) and are imported as coverage's using the *import* command. This data set was developed at the Oregon State University Forestry Sciences Laboratory. These files are part of the Parameter-elevation Regressions on Independent Slopes Model (PRISM) which covers the whole United States. PRISM is an analytical model that uses precipitation data measured at over 7,000 National Weather Service and cooperator stations, 500 SNOTEL stations, and some selected State network stations (Daly et al., 1994). Estimated precipitation values are established for intermediate grid-cells that have been created from these coverage's through the use of a regression function, considering the measured precipitation point data along with digital elevation model data to account for topographic effects (modified from Daly et al., 1994). The result of this process is a completely grid surface of average precipitation across the study area. This data is provided as monthly and annual depth of precipitation in millimeters (mm) averaged over the 30-year period from 1961 to 1990.

This data set is available in a geographic coordinate system, NAD83 datum using the GRS1980 ellipsoid. The method used for calculating average rainfall for this study is called the weighted flow accumulation. This method is similar to the regular *flowaccumulation* method in Arc/Info. However, instead of counting the number of cells that occur upstream of each particular grid cell, the *weighted flowaccumulation* function uses a second grid, called the weight grid, and sums the weight grid values of the cells that occur upstream. For this study, precipitation grids are used as weight grids to generate the grids that represent monthly and total annual runoff in the study area. Then the weighted flow accumulation grids are overlaid by the USGS stream gage coverage to obtain values for the average annual and monthly rainfall values at the gage station. Dividing the potential rainfall values by the delineated drainage area, average annual and monthly depths of precipitation (mm) are obtained for the study area.

To calculate the runoff volumes from the study area, the average daily stream flow values of the USGS stream flow gage station at Berlin Road that is located at the south border of the study area are subtracted from the values of the USGS stream gage station at the Old Woman Creek which represents the outlet of the study area. The measured stream flows for these stations are available for the period 1987-1993 only. The result of subtracting those measured stream flows at the two station represents the runoff corresponds to the study area.

Establishing Rainfall -Runoff Relationship

Using the values for average annual precipitation and the values for projected 6-year average annual depth of stream flows, a regression analysis is performed to determine the best-fit curve between the two data sets. This analysis tool performs linear regression analysis by using the *least squares* method to fit a line through a set of observations. Assessments of the best linear, best quadratic, and best exponential fits show that the linear relationship most accurately reflects the rainfall-runoff relationship in the study area. The correlation coefficient is found to be 0.99525, which indicates that the best-fit line approximates the actual data well. Based on the regression output, the linear relationship that best approximates the rainfall/runoff relationship in the study area is:

$$Q\ (mm) = 0.789617 \times P\ (mm) - 1.65499 \qquad (1)$$

Where Q is the Runoff depth in terms of depth of flow in the Old Woman Creek and P represents the precipitation, where both Q and P are in units of millimeters (mm). In order to create an Arc/Info grid of runoff, this relationship would be applied to every cell in the precipitation grid. However, since the precipitation grid has an effective range of values between 1.75 mm and 3.75 mm, it is noted that there is a small range of cells that is less than or equal to 2.0-mm for which the relationship produces negative numbers. In order to avoid that, the rainfall-runoff relationship of equation (1) above is only applied to precipitation cells with value greater than 2.1-mm. Rewriting equation (1), the rainfall-runoff relationship becomes:

$$Q\ (mm) = 0.789617 \times P\ (mm) - 1.65499, \quad P > 2.1\text{-mm}$$
$$Q\ (mm) = 0, \quad P < 2.1\text{-mm} \qquad (2)$$

The limitation of this linear modeling function results in runoff values of Q = 0 or even negative for precipitation values that are less than or equal to 2.1-mm. The study area receives more that 2.1-mm when considering the grid-based model results. This will just affect the resulted runoff values when considering the measured precipitation values for January and February which are both equal to 1.75-mm. Therefore the adjusted linear model results are acceptable as long as we will be using the grid-based model values. The reason for this is that runoff only happens after surface soils reaches a saturation state and also because runoff varies over time with rainfall events.

Using the rainfall-runoff relationship of equation (2) in connection with the precipitation grids and Arc/Info *conditional* statement, grids of runoff are produced. Then the subsequent flow accumulations may be performed on this grid without encountering cells of no-data value. The *Isnull* command is used with a second *conditional* statement to fill by zero all the no-data cells resulted from application of the rainfall-runoff relationship. Then equivalent annual and monthly coverages of runoff are created using the *gridpoly* command. Figure 2 shows the resulted annual runoff coverage.

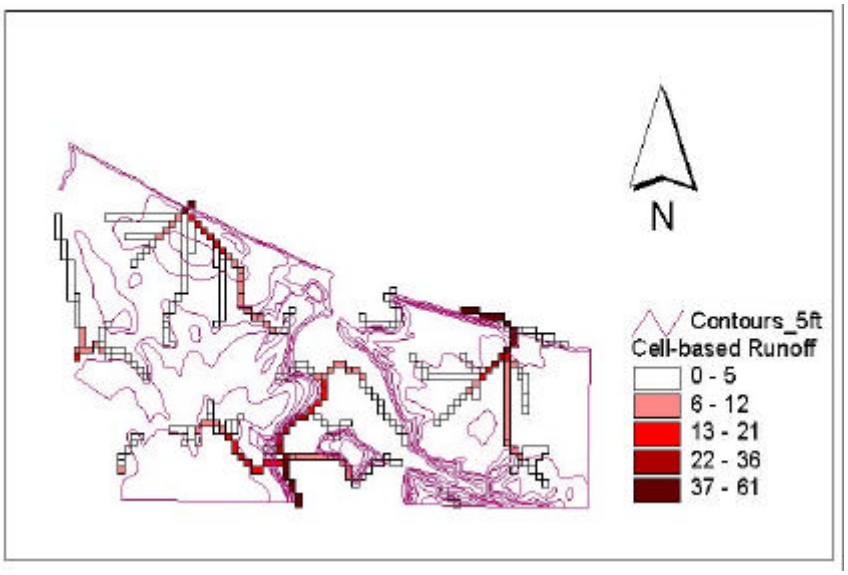

Figure 2: Estimated Annual Runoff depth (mm) in the study area

Modeling Phosphorus Concentration in the study area

It is obvious that the available phosphorus in the outer most soil layers is washed away by the natural process of precipitation and is then transported with surface runoff towards the study area outlet as long as the identification of the study area limits is hydrologically correct. Therefore establishing a relationship between the phosphorus load and the surface runoff both measured at the study area outlet should determine on cell-by-cell basis the amount of phosphorus that each cell in the study area contributes to the measured value at the outlet. This could be described in the following simple mathematical form as we think at this stage:

$$\text{Phosphorus load} = f\,(\text{Runoff}) \qquad (3)$$

The mathematical relationship of equation (3) above states that phosphorus load is a function in the surface runoff. To see to what extent the above relationship is correct, measured values of phosphorus load that represent the study area were obtained from the USGS database for the period of (1987-1993) applying the same strategy described in the previous section. Using these values for phosphorus load and the values for projected 6-year runoff, which is the stream flow records correspond to the study area in this case, a regression analysis is performed to determine the best-fit curve between the two data sets. The following second-degree polynomial is found to be the best-fit for the relation between the two data sets with a correlation coefficient of 0.9752:

$$PL = 0.0881*Q^2 + 39.594*Q - 355.48 \qquad (4)$$

Where PL is the phosphorus load in units of milligrams per liter and Q is the Runoff depth in terms of depth of flow in units of mm per year (or mm per month). Using the runoff- phosphorus load relationship of equation (4) in connection with the runoff model and Arc/Info *conditional* statement, phosphorus concentration models are produced. The *Isnull* command is used with a second *conditional* statement to fill by zero all the no-data cells resulted from application of the runoff- phosphorus load relationship. Then equivalent annual and monthly models of phosphorus load are developed using the *gridpoly* command. Figure 3 shows the annual phosphorus load model for our study area produced using the approach described above.

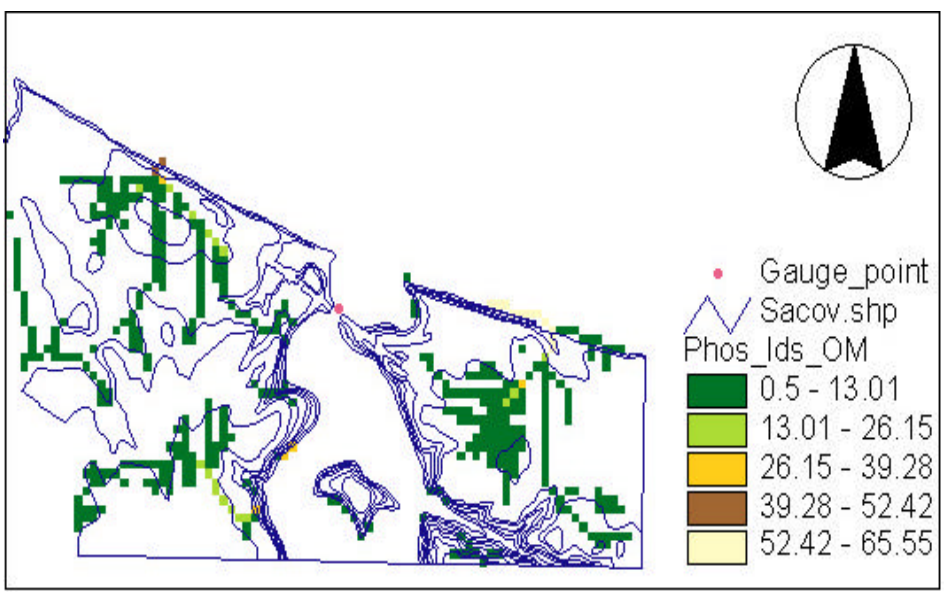

Figure 3 the cell-based phosphorus load model for our study area

To check our resulted phosphorus model, a set of expected mean phosphorus concentrations resulted from a previous National Estuary Program analysis (Baird et al., 1996) were applied to the land uses in the study area to generate an expected phosphorus load model. Table 2 below shows the phosphorus concentrations values that correspond to the land use categories in the study area as resulted from that study.

Land Use Category	Total Phosphorus Concentration (mg/l)
Urban – Residential	0.57
Urban – Commercial	0.32
Urban – Mixed	0.35
Transportation	0.22
Croplands	1.30
Undeveloped/Rangelands	0.12
Water Bodies	0.00

Table 2. Phosphorus concentration values used for this study

Since the phosphorus level that occurs during runoff events is measured in terms of the expected mean concentration, it is defined as the mass of phosphorus transported per volume of runoff. The phosphorus loading that each cell contributes to the study area outlet is calculated by taking the product of the expected phosphorus concentration and the runoff depth corresponds to that cell as follows:

$$L\ (\text{kg/year}) = K \times Q \times PC \times A \qquad (5)$$

Where

Q: is the runoff in units of mm per year or mm per month,
PC: is the phosphorus concentration in units of milligrams per liter,
A: is the area of each grid cell (900 square meters), and
K: is a constant that equals 10^{-6} in units of kg.l/mg.mm.

An assumption is made here before adopting this approach to get phosphorus loading at the study area outlet. This assumption states that no phosphorus consumption occurs during the course of flow to the outlet. This assumption is appropriate for this study when considering that the size of the research area is small, which obviously results in short flow-paths. Then cell-based phosphorus-loading models are developed as product of the expected concentration grids and the runoff grids. Figure 4 below shows the model of annual estimated phosphorus concentrations in our study area.

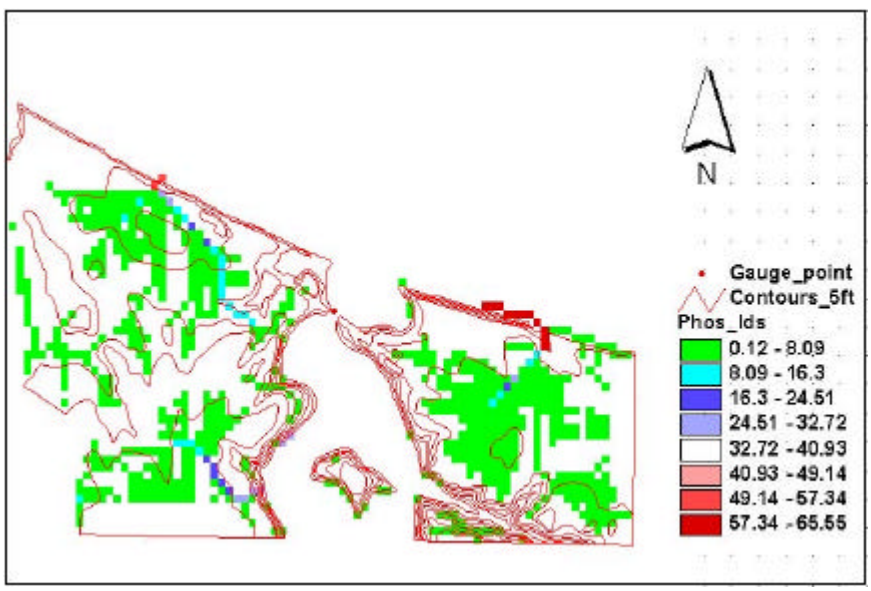

Figure 4. The resulted cell-based annual estimated phosphorus concentration model

We can easily notice that this model agrees with our model in most of the central regions east of the creek, northwest portions of the study area, and in the southwest portions of the area. If we take in consideration the assumption on which the development of the estimated phosphorus model is based we can easily conclude to the

fact that our model is a reasonable representation to the actual load of phosphorus measured on a cell-by-cell basis in the study area with respect to the measurement at the gage station at the outlet.

Soil loss Modeling using the Revised Universal Soil Loss Equation (RUSLE)

RUSLE is an erosion model designed to predict the monthly and annual soil loss (E) carried by runoff from specific field slopes in specified cropping and management system as well as from rangeland. Widespread use has substantiated the usefulness and validity of RUSLE for this purpose. It is also applicable to non-agricultural conditions such as construction sites. Soil loss due to water erosion is modeled in this study using the Revised Universal Soil Loss Equation (RUSLE) which computes both the average monthly and annual expected erosion in the study area. It has the general form shown below (???, 19???):

$$E = C \times R \times K \times LS \times P \qquad (6)$$

Where

E is soil erosion (ton/ha),
C is the cover management factor (dimensionless),
R is the average annual rainfall erosivity factor (MJ.mm/ha.h),
K is the soil erodibility factor ((ton. ha. h)/(ha. MJ. mm)),
LS is the slope length and steepness factor (dimensionless), and
P is the erosion support practice factor (dimensionless).

The values for these factors have been obtained considering the local characteristics of the study area and linked to the digital elevation model of the study area as spatio-temporal attributes. Figure 5 below shows estimate of soil loss due to water erosion in the study area as modeled using RUSLE model.

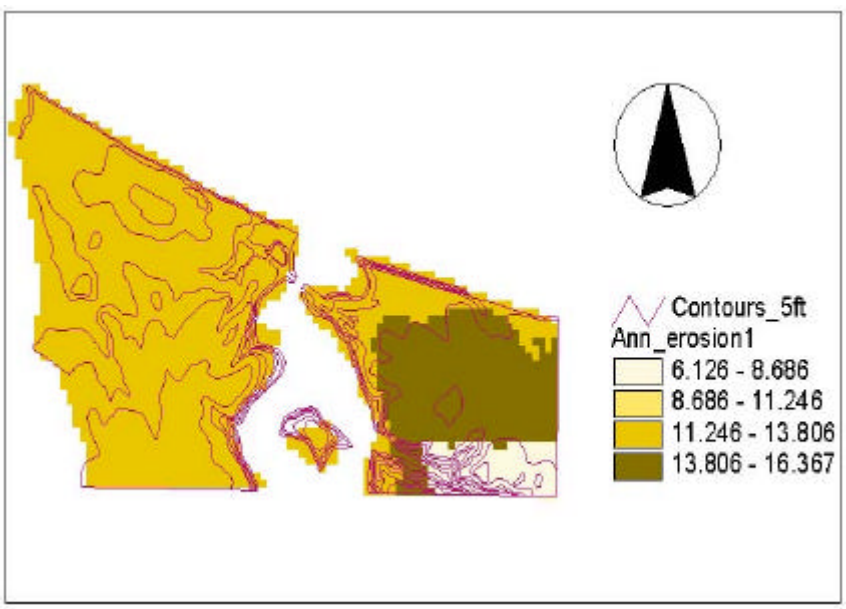

Figure 5. Soil Loss due to water erosion as resulted from RUSLE model

Determination of Soil-Loss/Sediment-Load Relationship

To calculate the actual amount of soil loss from the study area in terms of amounts of transported sediment, the average daily sediment loads obtained from the USGS suspended sediment database are used in this study. Values for total monthly and average annual sediment loads from the study area are obtained. The idea used here to estimate the actual amounts of soil loss from the study area is very simple. The measured amounts of sediment loads at the gage station are just treated the same way as flow runoff to establish a mathematical relationship between sediment loads and eroded soils to get the actual amounts of eroded soils.

Assessments of the best quadratic, best exponential and best polynomial fits showed that the third degree polynomial best fits the relationship between recorded sediment loads and the eroded soils that are estimated using RUSLE. The correlation coefficient was found to be 0.97921, which indicates that this third degree polynomial approximates the actual data sets to an acceptable extent. Based on the least squares solution, the polynomial that approximates the Sediment Loads-Eroded Soil relationship in the study area is of the form:

$$S = a_0 + a_1 \times E + a_2 \times E^2 + a_3 \times E^3 \qquad (7)$$

Where S represents the mass of actual soil loss as measured at the gage station in units of kg and E represents the mass of eroded soils as estimated using RUSLE in units of kg. The least square adjustment is applied to estimate the value of the parameters a_0, a_1, a_2, and a_3 as shown below:

$a_0 = -6.572*10^4$ $\quad a_1 = 2.498$ $\quad a_2 = -2.251*10^{-5}$ $\quad a_3 = 6.329*10^{-11}$

The residuals have been estimated and found in the range from $-3.742*10^{-3}$ to 0.38 kilograms. A residual analysis show that February has the highest value and November has the lowest while June, which has a residual of -0.136, is comparatively high. To create an Arc/Info grid of actual soil loss, this relationship has to be applied to every cell in the erosion grid. Using the relationship of equation 7 in association with the erosion grid and Arc/Info *conditional* statement, grid of actual soil loss is produced shown on figure 6 below. It is clear that the soil loss volumes are comparatively small in the northwestern parts of the study area for the reason that the Lake Erie shore there is completely protected, which will reduce the volume of transported sediment as a result of soil erosion. It should also be noted that the croplands in the south parts the study area contribute heavily to the soil loss volumes.

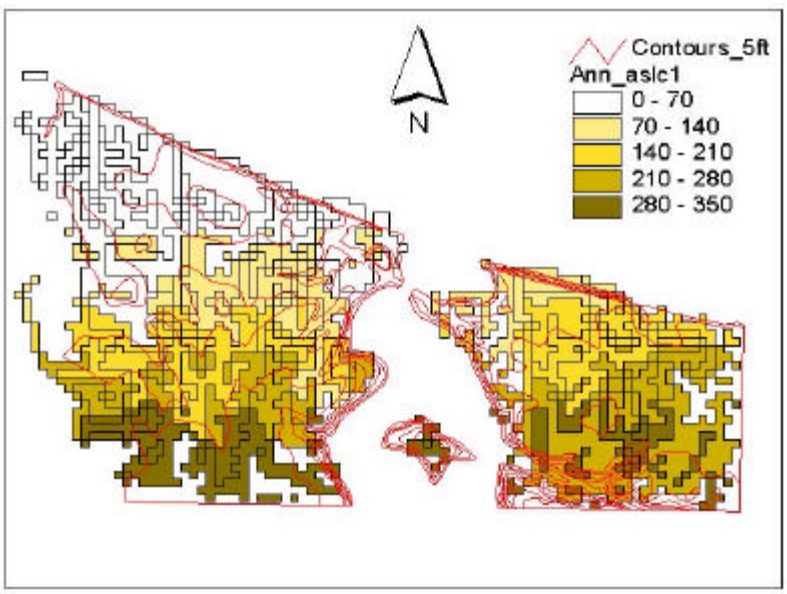

Figure 6. The annual soil loss model for our study area

Discussion and Conclusions

The phosphorus concentration model developed here gives estimates of the actual spatial contributions of phosphorus that transport from each cell to the study area outlet. Therefore it doesn't count for the spatial phosphorus content of the surface soil layer that doesn't contribute to the actual transport process. Consequently it is found that as result of this research that phosphorus concentration is not only a function in land uses or soil types, but it is also a function in other spatial factors that affect phosphorus concentration variation in the study area.

It is clear that the phosphorus load model produced in this research gives a very good representation for the actual phosphorus load that each cell in the study area contributes to the outlet as compared to the estimated

phosphorus model which is developed using estimated phosphorus concentration values resulted from the previous National Estuary Program analysis (Baird et al., 1996).

This model could be used as an analytical tool to determine the phosphorus load in similar areas as long as we can delineate the hydrologic boundaries. The Actual soil loss model developed here is based on the eroded-soil/sediment-load relationship that has been established in this study. The third degree polynomial that found to best fit the two data sets of eroded soils and measured sediment with acceptable residuals is used to model the soil-loss/soil-gain process and consequently an actual soil loss model is developed. The significance of this model comes from the fact that soil loss volume estimated using models like RUSLE, for example doesn't consider the spatial interaction between the different spatial entities that compose the study area.

To analyze the soil-loss/phosphorus-concentration relationship, the *correlation* function of Arc/Info is used to calculate the cross correlation between phosphorus loads model and the actual soil loss model in this study. The correlation coefficient between these two models is found to be 0.0105023661, which reflects a weak correlation between phosphorus loads and actual soil loss models. We will conduct further analysis of the relationship in terms of percentages of landuse in the area, and the sediment contribution from the cropland and other landuses. The relationship will be examined again when the coastal erosion modeling will be performed.

These results have shown a possible method of characterizing the process of transportation of sediment and phosphorus as they actually contribute to the non-point source pollution in coastal areas. Among the advantages of the method adopted in this study that the method makes use of all recorded stream-flow and phosphorus concentration data at hand and synthesizes the data in a consistent and logical way across the study area.

ACKNOWLEDGMENTS

We greatly appreciate the support provided by Lake Erie Commission through the Lake Erie Protection Fund. The project is also partly supported by Sea Grant, NOAA/NGS, NOAA/OCS, and NOAA/CSC. We would like to thank Dr. S. Mackey of ODNR/Lake Erie Geology Group and Mr. B. Kuenzli of OEPA at Bowling Green, OH for their cooperation. We also thank Dr. D.M. Klarer of Old Woman Creek Research Center and Prof. C.E. Herdendorf for their valuable discussions.

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