TITLE

Modeling Sub-Basin Scale Erosion Using DEMs and Land Use Grids

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ABSTRACT

Suspended sediment concentration is an important factor that affects stream ecology and morphology. To determine how urbanization will affect stream dynamics an understanding of sediment production and supply that results from increases in development is essential. The use of ArcGIS and Digital Elevation Models (DEMs) allows topographic analysis to be conducted on a watershed or sub-basin scale using the Arc Hydro extension and various techniques for watershed characterization. This study also looks at changes in time of land use patterns using land use grids and spatial analyst. Values obtained from the GIS are used as parameters in an erosion model. The model is calibrated to reflect land use variations, since observed sediment yields exist for the years that land use data is available.

INTRODUCTION

The desire for healthy ecosystems within the Chesapeake Bay watershed has spawned thoughtful discourse regarding the management of water resources on a watershed basis. This has led to the need for management of sediment yields in urbanized watersheds. The conversion of forested and rural landscapes to residential and commercial uses results in an increase in upstream sediment supply that ultimately affects fluvial systems. These effects are reflected in changes in the morphology of the stream in response to changes in sediment loads as well as a decline in overall stream health. Suspended sediment concentration is one of the most ecologically important factors that affects stream ecology (Palmer et al., 2001). To determine how urbanization may affect the health of small streams in many developing watersheds, an understanding of sediment production and supply is essential, so a method for modeling watersheds without extensive fieldwork would be extremely useful.

Erosion models and computer applications presently exist to predict sediment yields. The Water Erosion Prediction Project model (WEPP) was designed by the USDA to predict soil erosion as overland flow from agricultural fields. The model simulates climatic, hydraulic, hydrologic, and soil erosion processes within small watersheds to predict sediment yield per acre. Manipulations to storm, soil, and topographic input can be performed by the user in an attempt to simulate specific study basins. This is where GIS most useful for describing these characteristics.

The modules within the model were not written for urban landscapes. Certain parameters within the soil input file are designed to describe scalar erodibility values for soil types of varying textures. Erodibility parameters are available for various soil types, but not for impervious surfaces. Upon initial inspection, the lack of parameters for quantifying the erodibility of impervious surfaces negates the utility of WEPP for predicting effects of urbanization on soil erosion. After consideration of other erosion models, WEPP was determined to be the best model to use with GIS for predicting sediment yields from hillslopes with varying land uses. Land use type was portrayed in soil variables.

Using Geographic Information Systems (GIS), allows input values describing topography, land use patterns, and soil distribution to be obtained per hillslope. Research conducted at the Soil Erosion Laboratory by Cochran (2001) analyzed the efficiency of using a Geographic Information System to obtain physical parameters for the WEPP model from Digital Elevation Models (DEM). Overall, he showed that automated delineation of input parameters was valuable and efficient for accurately representing topographic features. Cochran determined that 10-meter resolution DEMs, if available, would be more effective than the 30-meter resolution data (Cochran, 2001). An interface called GeoWEPP exists for ArcView that allows the user to easily derive input parameters for the WEPP model. GeoWEPP was designed to import DEMs and delineate watershed boundaries and channel networks. Presently GeoWEPP does not support variability of land use and soil type upon a single hillslope. The use of GeoWEPP allows the user to choose the method of watershed delineation and topographic analysis and query soil and land use data for input values.

The goals of this study are to use GIS and Spatial Analyst instead of GeoWEPP to obtain input parameters for the erosion model WEPP. The use of GIS automates data collection and makes more efficient the analysis of multiple years of data layers that are needed for such a modeling exercise.

In an attempt to quantify the effects of urbanization on sediment yields, early studies attempted to relate sediment discharge rates to stream morphology. A study of the effects of urbanization on stream discharge by Anderson (1968) found significant increases in peak discharges per storm event in basins displaying varying degrees of development. He also discovered that an increase in impervious surfaces greatly increased mean annual floods and flash flooding (Anderson, 1968). He concluded that the increase in peakedness alone, all other things equal, should increase the steady state sediment delivery from urban areas. Likewise, Carter (1961) measured changes in lag time as a percent of impervious cover and showed that the degree of urbanization increased flood peaks by 80% (Dawdy, 1967). These ideas spawn questions concerning the relation between increased peakedness of runoff and total sediment yields. Although it was shown how runoff responded to urbanization by looking at water level and stream responses, actual sediment measurements remained deficient (Dawdy, 1967).

In an attempt to satisfy the deficiency, Yorke and Herb (1974) conducted research that measured, for ten years, the total suspended sediment yields for varying degrees of urbanization within nine sub-basins of the Rock Creek and Anacostia River watersheds. As a result of the Yorke and Herb (1974) study, valuable data exists describing 10 years of storm intensities, storm runoff, sediment concentrations, and peak discharges. Although direct measurements were made that related urbanization with sediment yields, the problem of predicting the amount of sediment from urbanizing watersheds remained unsolved.

STUDY AREA

The rapid development of many upstream areas within the Chesapeake Bay watershed necessitates understanding the effects of urbanization on sediment discharge to its streams. The small watershed in this study drains its sediment load to the Chesapeake Bay through the Potomac River.

The catchment that was studied is the Lutes Run sub-basin within the North Branch Anacostia River basin in Montgomery County, Maryland, north of Washington D.C. (Figure 1). Past research in this and surrounding basins was conducted to monitor effects of development on sediment discharge and stream morphology. The data from a previous USGS study by Yorke and Herb yielded data for ten years of sediment discharge on a per storm basis for the Lutes Run sub-basin and surrounding basins. Data was collected on sediment yields per storm with a description of vital storm characteristics.

GIS data for the years the study was conducted exists in the form of Digital Elevation Models, Land Use Land Cover data, SSURGO soil data, and parcel data that was linked to census data to describe construction activities for given years.

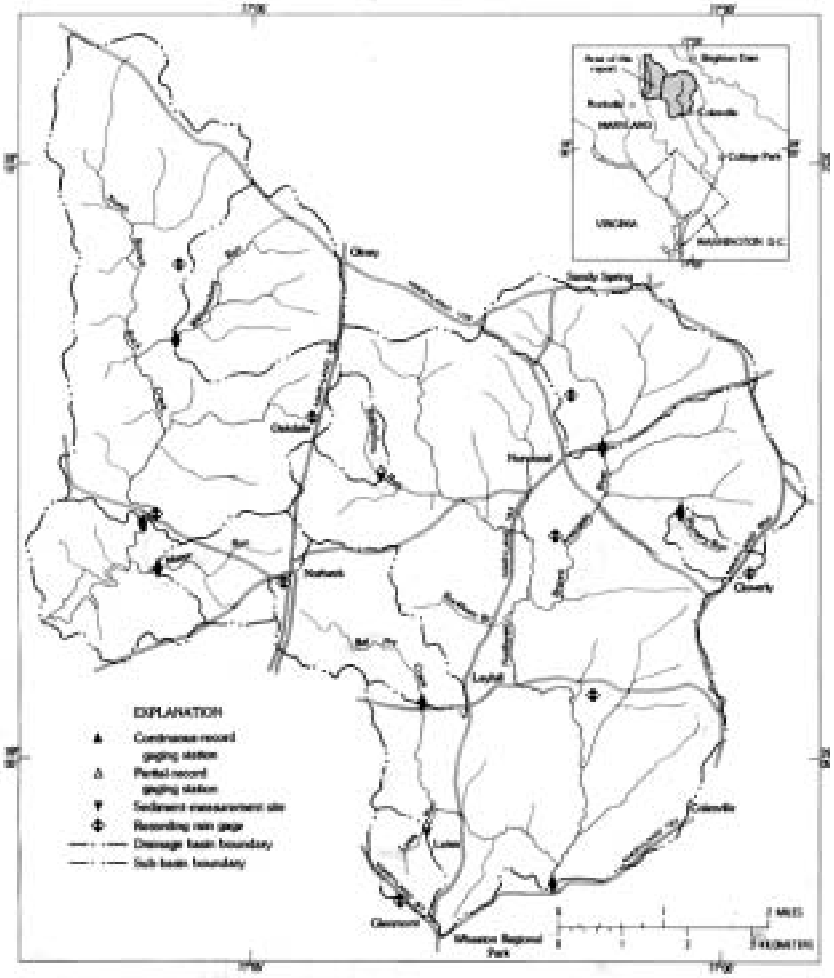

Figure 1. Map of study area showing Rock Creek and Anacostia River basins.

RESEARCH GOALS AND OBJECTIVES

The purpose of this study is to understand the efficacy of GIS for obtaining input values for WEPP in an attempt to predict erosion processes in urbanizing and urban watersheds. Adjustments to soil inputs were made based on land use factors that would affect soil detachment resistance and soil transport. The model does not explicitly support urban watersheds. No algorithm exists that would adjust values to express the erodibility of urbanized or urbanizing landscapes. It was up to the user to depict soil characteristics based on variability in land use for the sub-basins for each year of study.

The input and output of WEPP is on a per Overland Flow Element (OFE) basis. OFEs are normally delineated by uniform slope or soil type with the assumption that land use will be cropland, rangeland, or other related use. In this study, land use determined the delineation and spatial expanse of the OFE. This was reflected in the manipulation of erodibility values since these variables will reflect the increase in detachment resistance of different hillslope surfaces.

The objectives of this study are to:

- Determine the role and efficacy of GIS and available digital data for obtaining topographic, soil, and land use input values.
- Analyze percent construction areas to calibrate erodibility parameters.
- Acquire an erodibility index for urbanizing and impervious land surfaces in urban and suburban watersheds to be used the future.

METHODS

Four input files are required by the WEPP model; slope, soil, management (land use) and climate. The following sections will depict the methods used to acquire each of three of these input files excluding management, since this will remain "tilled fallow" for each OFE. GIS was first used for initial delineation of the sub-basin, and then for acquiring representative slope profiles and soil inputs based on land use.

Initial delineation of the Lutes sub-basin was accomplished using 30 meter Digital Elevation Models of Beltsville, Clarksville, Kensington and Sandy Spring quadrangles were obtained from the United States Geological Survey (USGS). The Lutes sub-basin was delineated from the gaging station that was used by Herbe and York. This gauging station location was obtained by requesting the latitude and longitude from the USGS and creating a point. The point was then converted to a grid in order to be utilized as a pour point when running SNAPPOUR and BASIN commands. This allowed the shape of the basin to be created and used as a mask for all other data. This allowed all analysis to be done on this small area of land.

The next step was to delineate hillslopes. To do this, the BASIN command, was again used, but this time with two new pour points. The creation of new pour points was accomplished by first idealizing the channel as two linear segments and creating pour points at the head of the stream and at the point between the initial pour point and the initial outlet, so that a total of five hillslopes were delineated as shown in figure 2. The outlets 1, 2, and 3 indicate the pour points used.

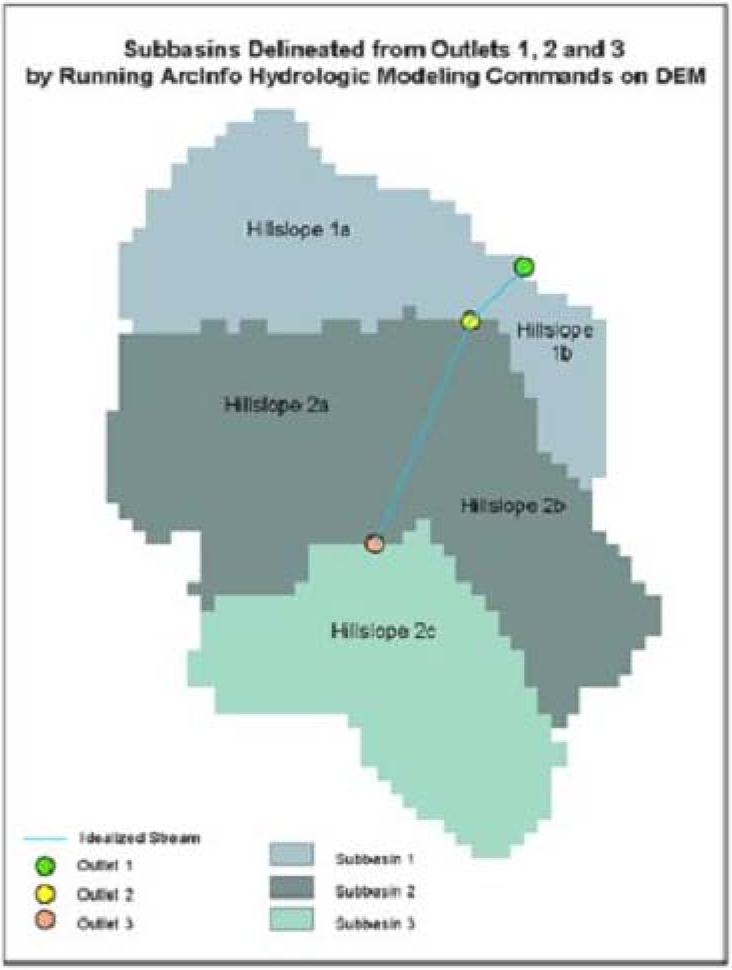

Figure 2.

Once each of the five hillslopes were delineated, OFEs could be chosen following visual inspection in ArcMap of the topography, soil and land use traits of each hillslope. OFEs were delineated primarily based homogeneity of land use pattern from the top of the hillslope to the bottom. Where a change in land use began, a line was drawn to separate it from the previous OFE. Figure 3 shows the final delineation for the year 1974.

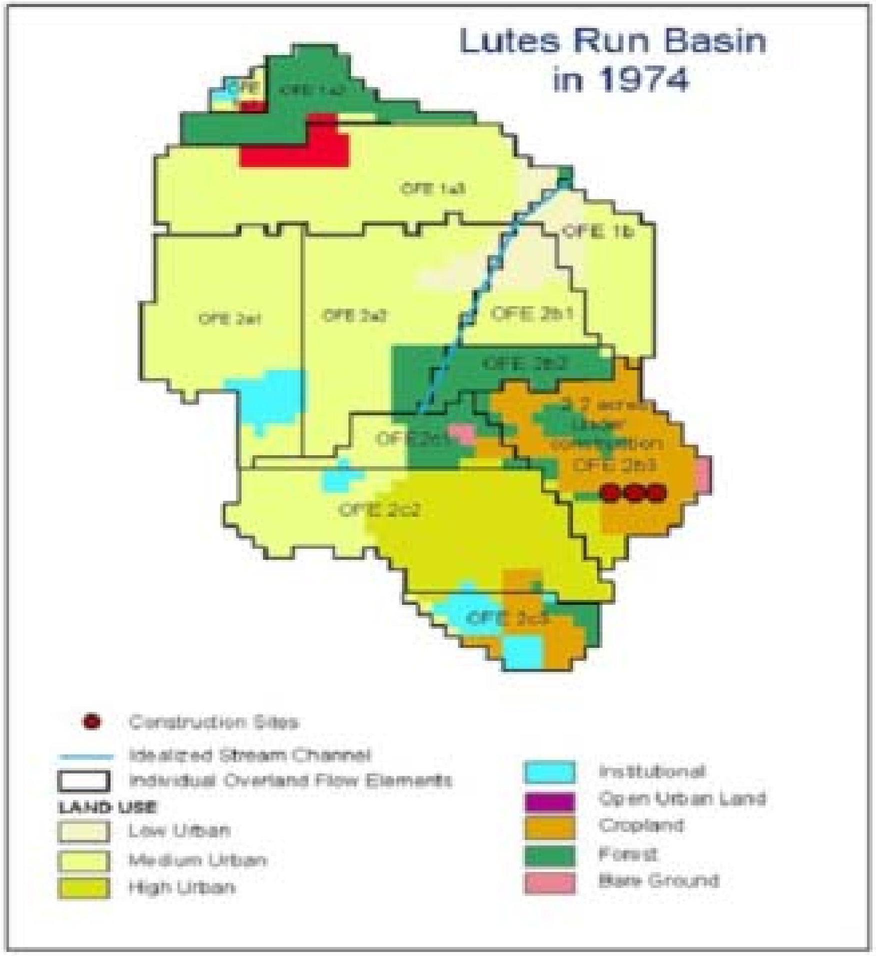

Figure 3.

SLOPE INPUT

The various topographic analysis functions within the Spatial Analysis raster calculator were utilized to obtain a representative slope profile down each hillslope. For acquiring topologic inputs, mostly used were SLOPE, ASPECT, FLOWACUMMULATION, FLOWDIRECTION, FLOWPATH, COSTPATH, and FLOWLENGTH functions. The WEPP model requires that the slope profile be entered as percent slope values at distance from top of hillslope down at various distances up to twenty points. The model requires slope length for these segments as well as aspect. All of these values were obtainable using SLOPE, ASPECT, and FLOWLENGTH functions.

The slope profile that is created must be a representative profile, which means that it should be a best representation of each flow path down the hillslope. GIS allows for each of these flow paths to be depicted. It also allows for slope, slope length and aspect values to be obtained at every pixel distance down the flow path. After reading the literature on how to acquire the most representative profile, it was decided to incorporate into this study an equation first created by Cochrane and Flanagan. The equation was found while reading a paper entitled "Representative Hillslope Methods for Applying the Wepp Model with Dems and GIS" (Cochrane and Flanagan, 2003).

Cochrane and Flanagan state that a successful method for obtaining a representative profile is the weighted average method. They wrote Fortran code that would utilize output from the raster data and would yield representative slope values at distances down the idealized hillslope.

For this study the Fortran code was not used to obtain the data point values, instead the values were obtained manually utilizing Arc Hydro commands and were entered manually into the equation written by Thomas Cochrane and Dennis Flanagan to obtain an average representative slope profile.

GIS was used in the following way to obtain the values to plug into the equation. First using the DEM from the delineation of the sub-basin, and the flow accumulation grid, all cells with flow accumulation greater than three were selected. This >3 cell accumulation grid, highlighted cells that were receiving higher amounts of runoff from pixels above, which deemed them more valuable in terms of water flowing into the cells. From this point the flow direction raster was turned into a grid of arrows depicting direction of flow from each cell. Utilizing these flow direction arrows, each of the paths for each hillslope was traced to the very top of the hillslope. Once the top of the hillslope was determined for each path, a point was created and then converted to a grid to be used as a source grid for the FLOWPATH function. This created multiple flow paths for each hillslope, as many as 25 flow paths. Each flow path for each hillslope was then used as a mask to obtain values from slope, flow length and aspect grids. Figure 4 depicts the masked slope grids.

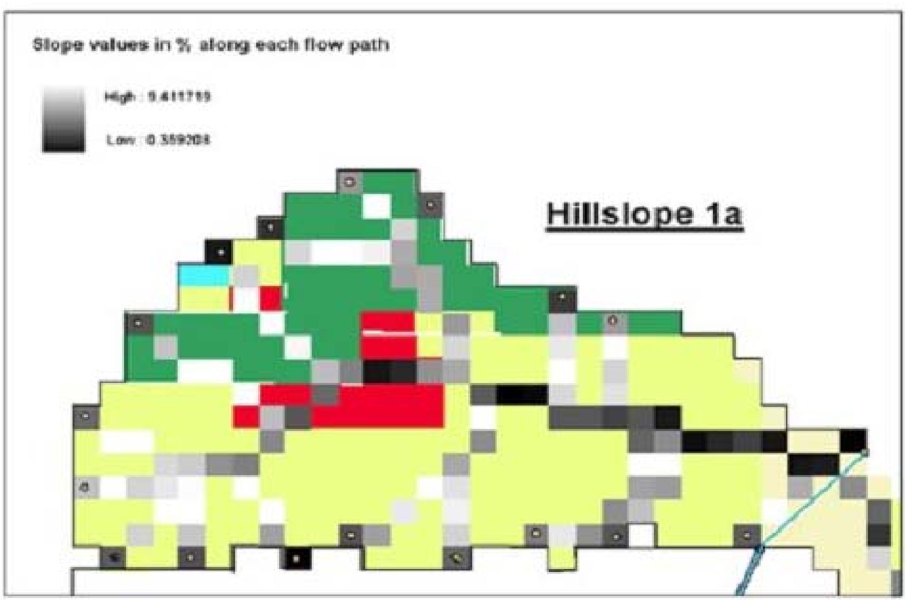

Figure 4.

Each slope pixel for each flow path was then entered manually into excel as well as the corresponding length in order to calculate an average slope value for every segment of the hillslope. To obtain the average value for each segment down the hillslope the equation equation $E_i = \frac{\sum_{p=1}^{m} z_{pi} \times k_p}{\sum_{p=1}^{m} k_p}$ from Cochrane and Flanagan was used, where E_i is the weighted slope for all paths at distance *i* from the channel, z_i is the slope of the flow path *p* at distance *i* from the channel, and k_i is the area of cells in flow path *p* times flow path length.

To get the weighting factor k_i, the number of cells above each point was multiplied by 900 and its flow path length at that distance. The result for hillslope 1A is shown in figure 5. This image depicts the slope points down the entire hillslope. The dashed line in figure # shows the aspect and direction of the representative slope profile. Figure 5.

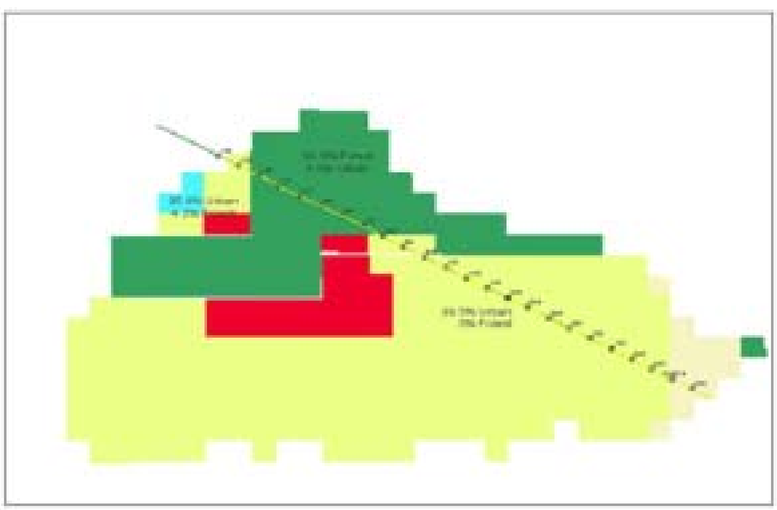

Figure 6 depicts the representation of the slope points entered into WEPP for hillslope 1A, which is shown in Figure 5.

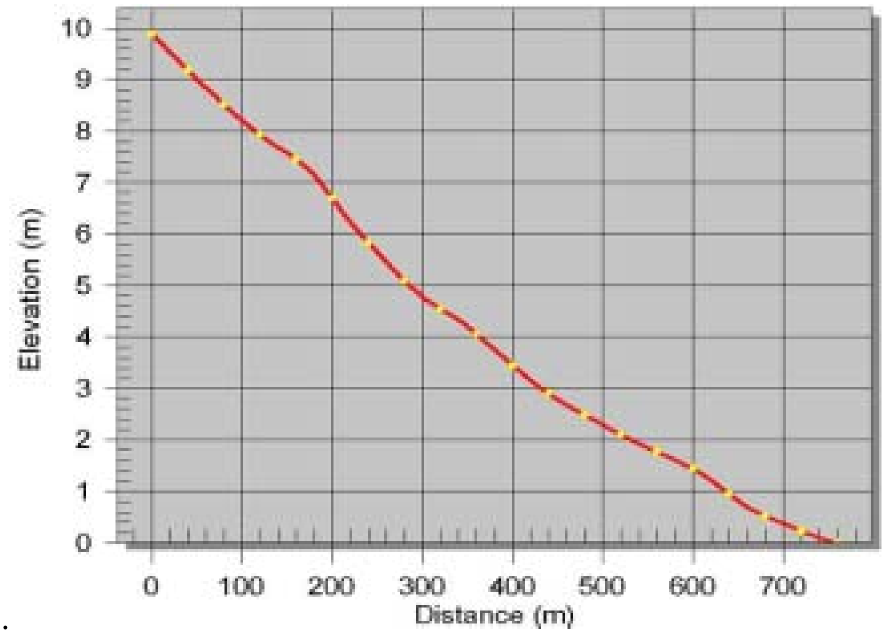

Figure 6 .

SOIL INPUT

The erodibility parameters are located within the soil input file, therefore the soil file and the methods of obtaining input parameters were of greatest importance in this research. Soil erodibility values were a function of land use characteristics at the time of study. A number of soil input files for various series are already available within the WEPP model. The user may also create new files with soil information for a given area. The files are edited in a text editor and saved with a .sol extension. The parameters that can be manipulated are the albedo, the initial saturation level, effective hydraulic conductivity, the critical shear stress, the interrill and the rill erodibility values, and percents of sand, clay and organic matter in the soil.

For all soils it was assumed that the initial saturation level is 75% and that the soil albedo is .28. These values were intrinsic to the WEPP model’s soil files. The critical shear stress remained 3.12 for each file, since this was the shear stress value for the Glenelg-Manor-Chester series. The secondary values that were manipulated to represent land use were the effective hydraulic conductivity, the percent of sand, the percent of clay and the amount of organic material. Values for agricultural or forested land utilized values intrinsic to WEPP, since these management types are available internal to the model.

Construction OFEs are described as any OFE containing greater than one acre under construction during a given storm even. This was determined by calculating the area of land under construction by analyzing total area and the area under construction for a given year in the parcel data table. When construction was present within a hillslope the percent of sand entered was in proportion to the percent of construction present as to mimic higher detachment rates that would exist on disturbed soils. The clay content was lowered.

For urban soils or soils with high amount of impervious cover, the amount of clay was much higher in an attempt to mimic the low infiltration rates associated with impervious surface. The amount that the percent of clay was increased was directly proportional to the percent of impervious surface within the hillslope for each given storm. Table 1 details the amount of impervious cover for each urban OFE for each of the years of the study, and hence the percent of clay entered in the soil file.

	Percent	Year	Percent	Year
OFE	Impervious	Calculated	Impervious	Calculated
1A1	37.0%	1965-1968	39.6	1969-1974
1A3	31.7%	1965-1968	58	1969-1974
1B	36.9%	1965-1974		
2A1	43.0%	1965-1974		
2A2	37.0%	1965-1974		
2B1	37.0%	1965-1974		
2C2	46.0%	1966-1974		

Table 1.

The percent of impervious surface for each urban ofe was determined in order to best simulate the percent of ground that would hinder infiltration and erosion. The method used to calculate impervious surface may not be the most accurate method, as this task is still being perfected by those to whom it is of interest. The method used here is that which is used by the Water Resources Agency at the University of Delaware when utilizing Land Use Land Cover Classification.

The main value that was calibrated based on amount of construction and hence detailed the highest erodibility of the land use types was the interrill erodibility value. The interrill erodibility value was manipulated based on the percent of construction within the basin for a given storm. First, I selected values of interrill erodibility until I found the one that would give 100% sediment yield, meaning that all of the sediment was eroded from the hillslope. I accomplished this task for each of the 5 hillslopes, therefore it was determined for each hillslope the interrill erodibility value that would mimic 100% construction within the hillslope. This was the interrill erodibility value for 100% construction. Secondly, I ran the model with decreasing interrill erodibility values for each hillslope until I found that value that would give me 0% percent sediment yield, meaning that no sediment was eroded or deposited at the base of the hillslope. This value mimicked 0% construction on the hillslope.

Then I created the graph shown in Figure 7, so that I could obtain the interrill erodibility value for various percents of impervious cover as calculated with the GIS.

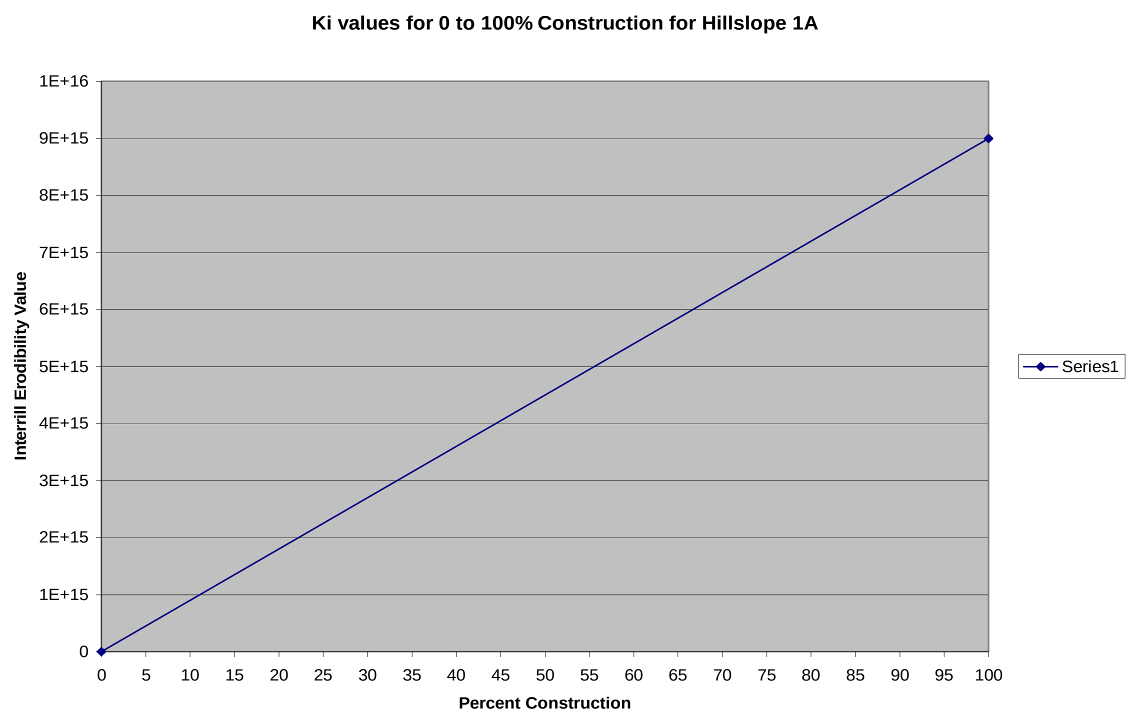

Figure 7.

The soil file was created differently for each land use type. The effective conductivity value for construction sites was chosen to reflect a highly erodible sandy soil to mimic the high yields expected from soil disturbance. Hydrologic soil group A was chosen to simulate the soil type on a construction OFE. These soils have high infiltration rates, even when deeply wetted and consist mainly of sands and gravels. For a soil of hydrologic group A on fallow land, the effective conductivity is 14.2. This was the effective conductivity value that was entered into every construction soil input file.

The effective conductivity value for Urban designated OFEs was determined by using the method outlined in WEPP. This method consists of two steps. The first step is to determine the hydrologic group that best describes the soil. The soil group for urbanized land use was determined to be soil group D. These soils have low infiltration rate, consist chiefly of clay or are shallow soils overlying a nearly impervious material (much like concrete). For hydrologic soil group D, the effective conductivity is 0.34. The second step as outlined in the WEPP manual on page 223 of the users summary is to adjust the effective conductivity value found in step one based on management of the land.

These determined effective conductivity values will remain the same. The parameter that will change and is most effective for determining greatest variances in sediment yield was the interrill erodibility value. The interrill erodibility parameter is a measure of the soil resistance to detachment and is determined by composition of the soil. This value determines how sheet erosion will act upon the hillslope.

The WEPP model allows the user to divide the slope into sub-sections. The subsections indicate changes is soil type. If no subsections were added than uniform soil type down the entire slope would be assumed. In this case the soil subsections are varied according to the land use occurring on the subsection during periods the time that each storm occurs.

CLIMATE INPUT

GIS was not used for obtaining the climatic input file, therefore the discussion of this will be very minimal. The WEPP model can simulate sediment yields on a per storm basis. The user must enter 5 pieces of information about each storm. These five items are the date of the storm, the duration of the storm, the peak intensity of the storm, the percent of time till peak intensity and total precipitation. All of these were obtained from a nearby gagging station and entered manually into the WEPP model.

Discussion

CONCLUSIONS

The use of Arc Hydro functions to perform sub-basin delineation from known gaging stations worked well, when viewed against the hypsography of the area, although field-testing would be ideal for verification. Selecting Hillslopes and OFEs and classifying Overland Flow Elements by land use patterns and percent of construction was very useful for correlating erodibility values. Future research will use these input values to calibrate erodibility for each land use class. More accurate predictions can be made with greater resolution and more sophisticated methods for determining impervious surface percents per hillslope as well as more definite temporal accuracy of construction percents per storm. The method used for calculating the amount of impervious surface may not be the best method that can be utilized. Further studies can utilize aerial photography or satellite imagery with software that allows supervised or non-supervised techniques of impervious surface classification. This may possibly be accomplished with newer version of ArcGIS and the Feature Analyst extension or Imagine classification software. Higher resolution elevation data would allow modeling to be conducted in much flatter areas. The 30-meter resolution DEM made it difficult to choose correctly the most representative slope values at distance *i* down the slope. Overall, GIS is a versatile and important tool for acquiring the topographic and land use characteristics of hillslopes. If time permitted, this project would endeavor to create a model using only GIS and numeric equations once higher resolution elevation data was obtained. Continuation of this research will produce further evaluation of GIS and WEPP for predicting sediment loss in urbanizing watersheds.

ACKNOWLEDGEMENTS

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