Urban Erosion Potential Risk Mapping with GIS

Amanda M. Weikmann

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Civil Engineering

Randel L. Dymond, Chair
Clayton C. Hodges
Kevin D. Young

December 15, 2017
Blacksburg, VA

Keywords: stormwater, erosion, erosion potential, risk mapping, geographic information systems (GIS)

Urban Erosion Potential Risk Mapping with GIS

Amanda M. Weikmann

ACADEMIC ABSTRACT

With increased regulatory focus on eroded sediment and its bound pollutants, methods are needed to predict areas with high erosive potential (EP) in urbanized areas. Using EP to prioritize urban areas for maintenance, installation of Stormwater Control Measures (SCMs), stream restoration or monitoring is crucial. This study utilizes commonly available geospatial layers in conjunction with a computational procedure for prioritizing the contribution of splash and transport erosion to compute relative EP risk throughout a target urban watershed. Contributing erosive factors evaluated include local cell slope, soil erodibility, land cover, runoff volume, distance and slope to nearest stormwater conveyance point along a surface flow travel path. A case study of the developed methodology was performed on a watershed in Blacksburg, VA, to generate EP risk maps. Results of the study indicate areas of erosive potential within the target watershed and provide a methodology for creating erosion potential risk maps for use by municipal planners and engineers.

Urban Erosion Potential Risk Mapping with GIS

Amanda M. Weikmann

PUBLIC ABSTRACT

Federal, state and local governments are increasingly focused on the effects of development on water quality and quantity. With waterbodies being especially sensitive to certain pollutants, such as sediment and nutrients, regulations have been put in place to control the amount of pollutant that gets discharged. Sediment is a cause for concern as it originates during both rural and urban activities, and often carries other pollutants (metals, nutrients, etc.) with it. Existing erosion models focus primarily on estimating erosion from agricultural watersheds. Methods are needed to predict areas with high erosive potential (EP) in urban watersheds. Highlighting highly erosive areas in urbanized watersheds allows for the prioritization of maintenance and installation of Stormwater Control Measures (SCMs), and monitoring of sediment by municipal planners and engineers. This study utilizes commonly available geospatial layers in conjunction with a computational procedure to compute relative EP risk throughout a target urban watershed. A case study of the developed methodology was performed on a watershed in Blacksburg, VA, to generate EP risk maps. Results of the study indicate areas of erosive potential within the target watershed and provide a methodology for creating erosion potential risk maps for use by municipal planners and engineers.

ACKNOWLEDGEMENTS

The support and guidance of many people were instrumental to the completion of this thesis project. I would first off like to thank my thesis advisor, Dr. Randel Dymond, for serving as my committee chair and believing I would be a worthy addition to his research group. The experiences I have had as a result have been amazing and it feels impossible to express my gratitude for the opportunity. I want to thank Clay Hodges for being available, what seemed to be 24/7, to help with questions and give advice allowing for the progression of my project. I also want to thank Kevin Young for his interest in and support of my thesis, and for being a great supervisor while I worked as his teaching assistant.

I feel fortunate to have been able to work with not only such a great committee but overall research group. I am grateful to Marcus Aguilar for always having a word of encouragement or constructive conversations about my research and Walter McDonald, who's supervisory role during my undergraduate research assistantship helped pave the way for my thesis topic. For the friendship of the other Masters students – Lauren, Meghan, Melissa, and Zack – I could not have done it without their encouragement and support. I am thankful that we were able to navigate the graduate school and thesis writing worlds together. Lastly, for the love and encouragement of my family and friends, who believed in me even when I did not.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

a. BACKGROUND

The history of soil erosion prevention in the United States begins amid the Dust Bowl, evolving still today as the effects of soil erosion spread beyond dust storms to several aspects of the environment. Then President, Franklin D Roosevelt formed the Soil Erosion Service (SES) in 1933 to "conserve soil and restore the ecological balance of the nation" (Natural Resources Conservation Service n.d.; Virginia Department of Environmental Quality n.d.). Hugh Hammond Bennett, first Chief of the SES, was a crusader for the consequences of wind and water erosion on soils in agricultural areas. From the SES and cross-country effects of the Dust Bowl, Bennett persuaded Congress to create a permanent conservation agency: the Soil Conservation Service (SCS) under the United States Department of Agriculture (USDA) (Natural Resources Conservation Service n.d.). At the state level, states such as Virginia and Maryland were passing laws and regulations for soil and water conservation, and sediment control starting in the 1930s. In Virginia, the Soil and Conservation District Law (1938) established soil and water conservation districts for local leadership. Its addendum, the Virginia Erosion and Sediment Control Law (1973), established statewide standards for soil erosion and nonagricultural runoff from land disturbing activities (Virginia Department of Environmental Quality n.d.). The SCS started working on soil and water conservation at a watershed scale after the passage of the Watershed Protection and Flood Control Act (1954). With its expanding direction, the SCS was reorganized into the Natural Resources Conservation Service (NRCS) to more accurately represent its mission of protecting multiple natural resources (Natural Resources Conservation Service n.d.). The primary focus of the first soil conservation laws were to protect agricultural fields from degradation due to soil erosion from exposed land surfaces. With major urban development, soil is often exposed during construction activities. Sediment eroded from land surfaces, in both rural and urban areas, migrate downstream creating multiple problems in waterways.

Channel morphology and water quality are strongly influenced by sediment originating from erosion (Krug and Goddard 1986; Paul and Meyer 2001; "Sediment" n.d.). Erosion of both coarse and fine sediments from bare land, streambanks or during construction activities have various consequences downstream of the point of erosion (POE). Aggregation of heavier particles, more likely to be deposited along the travel path, alter channel morphology and dimensions and can landlock ports (Reshetiloff 2004; “Sediment” n.d.; Walsh et al. 2005). High amounts of suspended fine sediments result in turbid waters, blocking necessary sunlight from traversing the water column and smothering certain aquatic organisms (Chesapeake Bay Program 2017; Reshetiloff 2004; “Sediment” n.d.). Further, fine sediments allow for the transport and deposition of bound or absorbed pollutants, such as nutrients and chemicals (toxins, metals etc.) to the Nation’s waters (Hogarth et al. 2004; Reshetiloff 2004; “Sediment” n.d.).

Sediment is considered a major pollutant in terms of water quality of the Nation’s waters. As such, it has been and is regulated at several different levels. Laws to protect water from various pollutants have been in place in Maryland since the 1930s. The Attorney General of Maryland called out sediment as a pollutant in 1961, after authorizing the development of sediment control regulations in 1957 (Maryland Department of the Environment n.d.). The Federal Water Pollution Control Act first addressed water pollution and quality through regulation of pollutants discharging to waterways (Virginia Department of Environmental Quality n.d.). The Clean Water Act (CWA) initially placed controls on point source pollutant discharges, through permits via the National Pollutant Discharge Elimination System (NPDES). The CWA specifically targeted discharges from publicly owned treatment works (POTWs) (33 U.S.C §1251 et seq., 1972). The Water Quality Act (WQA) of 1987, an amendment to the CWA, worked to ensure that water quality standards are met through monitoring and assessment. The CWA required the establishment of Total Maximum Daily Loads (TMDLs) for the Nation’s waters, which guides restoration efforts to improve water quality to acceptable levels. Nutrients, metals and sediment are common TMDLs for impaired waters. Stormwater runoff, which can also discharge the previously mentioned pollutants, wasn’t addressed until the creation of Municipal Separate Storm Sewer Systems (MS4s) (Clarke 2003). MS4s allowed stormwater, a nonpoint source pollutant, to be included in the NPDES permit system or applicable state-level versions of NPDES (Such as the Virginia Pollution Discharge Elimination System (VPDES)). Statewide or local stormwater management programs (SWMPs) are set in place to meet pollutant discharge thresholds in stormwater, including sediment.

Sediment load is often controlled by use of stormwater control measures (SCMs, also best management practices (BMPs)) to meet sediment TMDLs. However, exemptions for certain agricultural practices from erosion control regulations, require municipalities to effectively control sediment migration to meet these goals. Entrapment and removal of sediment prior to reaching downstream receiving waters may also remove bound pollutants, such as nutrients and chemicals, as well (Reshetiloff 2004; Liu et al. 2003). Municipal planners and engineers must be able to predict and control sediment migration from regulated urban areas to meet local TMDLs.

b. PROBLEM STATEMENT

Advancement of knowledge regarding soil processes was one of the goals of the technical experts at the SCS (Natural Resources Conservation Service n.d.). The USDA has also been involved in soil erosion modeling; both the SCS and USDA is focused on soil erosion in agricultural environments. Protection of agricultural lands is a driving force behind research into soil erosion process and models. Therefore, current literature is comprised of studies applying these models to agriculture dominated watersheds (Balousek et al. 2000; Chang et al. 2015; Jain et al. 2001; Mattheus and Norton 2013; Nearing et al. 2005; Pandey et al. 2007; Prasannakumar et al. 2012; Šurda et al. 2007). The methods and models, resulting from these studies, vary based on input parameters and type of result (sediment yield vs erosion potential, by storm event vs annually). Very little literature exists describing a simplified process for utilizing commonly available geospatial datasets for predicting erosion potential in urban areas. With increased focus and established thresholds on eroded sediment and its bound pollutants caused by the effects of urbanization, methods are needed to predict land surface areas with high relative erosion risk in urban areas. Municipal planners will benefit from knowing the geospatial locations of high risk areas. The ability to prioritize urban areas for planning overlays, additional erosion control measures during construction, BMP installation, restoration or monitoring is crucial to ensure that municipalities continue to maximize their efforts in meeting their community TMDL goals.

c. PURPOSE AND OBJECTIVES

The objective of this study is to use commonly available geospatial layers to evaluate land surface erosion potential in urban areas. A procedure will be developed to create a theoretical raster based GIS model of urban erosion potential and test it on a case study in the Town of Blacksburg. The objectives for achieving this thesis research are to:

1. Investigate the important parameters of soil erosion prediction methods.
2. Develop a method for determining Erosion Potential (EP) through GIS and computational analysis of important factors.
3. Interpret results of the methodology.
4. Generate final erosion potential risk maps for the *Central Stroubles watershed in the Town of Blacksburg, VA.*
5. Create a procedure for municipal governments to produce EP risk maps.

2. LITERATURE REVIEW

a. EFFECTS OF SEDIMENTATION ON WATER BODIES

Eroded rocks and soils contribute loose particles of sand, silt and clay to waterbodies as part of a natural cycle of erosion and deposition. Primary sources of sediment within watersheds are agricultural fields, construction sites and streambank erosion. From developments, erosion can be 20,000 to 40,000 times more than amounts eroded from farms and woodlands (Leopold 1968). Within small urbanized watersheds, “sediment yield is larger by 10 to 100 times that of rural areas” (Leopold 1968). Excess amounts of sediment have negative consequences on channel morphology, ecosystems and water quality.

Fluvial geomorphology is dependent on sediment supply and bankfull discharge; these two factors are considered critical in the determination of stream channel dimensions (Paul and Meyer 2001). Altered sediment supply due to urbanization causes channel widening, changes in sinuosity, and incision, resulting in generally unstable channels (Krug and Goddard 1986; Leopold 1968; Paul and Meyer 2001). This suspended sediment in streams causes sedimentation in bays and waterways that can fill in and landlock channels and ports (Reshetiloff 2004). Fine sediments that don’t settle out along conveyances and remain suspended, disrupt underwater ecosystems.

Turbidity is the most discernable effect of suspended sediment and poor water quality, as caused by sediment pollution. Beyond decreased visibility, these high concentrations of sediment hinder passage of sunlight to bottom dwelling organisms. When these sediments start settling in larger bodies of water, such as the Chesapeake Bay, plants and shellfish can be smothered by excess sediment (Chesapeake Bay Program 2017; Reshetiloff 2004). Deposited sediments may increase nutrient and chemical concentrations as well. Nutrients (phosphorous and nitrogen) and chemicals (toxins, metals, etc.) bind or adsorb to the surface of particles, and are then transported and deposited with the sediment (Hogarth et al. 2004; Reshetiloff 2004).

b. ESTIMATING SOIL EROSION

Impact and transport erosion are the two overarching types of erosion, resulting from the (1) detachment and (2) transport of soil particles (Young and Wiersma 1973). Impact erosion is the dislodgement and movement of soil by the kinetic energy of rainfall (Quansah 1981). Transport erosion is driven by runoff and different types of flow, as well as the shear stress of the soil particles (Morgan et al. 1984; Zhang et al. 2003). Each of these types of erosion are influenced by different parameters, a few of which are discussed below. Splash erosion is heavily influenced by rainfall intensity as it determines the erosivity of the rainfall (Nearing 2001; Nearing et al. 2005). Slope steepness, a parameter crucial for both soil detachment and transport, has been positively correlated with soil erosion (Quansah 1981). The combination of various physical parameters and different types and components of soil erosion result in various methods for estimating soil loss or erosion potential (DeRoo et al. 1994; Jain et al. 2004; Leh et al. 2011; Morgan et al. 1984; Renard and Foster 1991; Williams 1982; Zhang et al. 2017; Zhang and Zhang 2012).

These models integrate the processes of detachment and transport to estimate soil loss from a watershed. Models are empirically, conceptually or physically based. The USLE and its derivations (RUSLE, MUSLE, etc.) are empirical models based on observational research (Merritt et al. 2003). Other common erosion models are physical (LISEM, WEPP), based in physical equations such as conservation of mass and momentum or sediment transport equations. Models can also be grouped by scale (catchment, hillslope, plot) or event type (long term or single event). They vary based on input, quality of input and processes modeled (Merritt et al. 2003). The Limburg Soil Erosion Model (LISEM) simulates an erosion process that falls between sheet and rill erosion using GIS maps and rainfall data (DeRoo et al. 1994). The Watershed Erosion Prediction Project (WEPP) focuses on sheet and rill erosion on hillslopes using physics based equations (Merritt et al. 2003). Models are limited by availability and quality of data and their outputs reflect those limitations and varying operational assumptions. Agricultural conservations and protection has led to the application of many of these models to watersheds dominated by agriculture.

Although developed to predict annual soil loss from fields, the Universal Soil Loss Equation (USLE) has been used in several other applications. Soil loss from forests, construction sites and mixed watersheds has been estimated by the USLE (Fraser et al. 1995; Mattheus and Norton 2013; Renard and Foster 1991). Developed by the United States Department of Agriculture, the USLE predicts long-term annual soil loss by combined rill and interrill erosion on agricultural hillslopes (Haan et al. 1994; Merritt et al. 2003; Wischmeier and Smith 1978). Refinements of the equation due to improving research over the years has resulted in the Modified USLE, MUSLE (Williams 1982), and the Revised USLE, RUSLE (Renard and Foster 1991), which make adjustments to the determination of the USLE parameters. The USLE parameters are based on driving factors that influence detachment and transport erosion.

The interactions of individual driving factors and types soil erosion has been investigated by various studies. Detachment and transport erosion can both be influenced by rainfall, water flow, slope and soil type (Merritt et al. 2003; Quansah 1981). Other factors including land cover/land use, rainfall interception, rainfall intensity and water regimes have effects on soil erosion processes (Leh et al. 2011; Morgan et al. 1984; Römkens et al. 2002; Zhang et al. 2017). Research has also examined the relationship between erosion and slope gradient and shear stress (Fox and Bryan 2000; Onstad and Foster 1975; Zhang et al. 2003).

1. *Influence of Rainfall*

Both rainfall intensity and amount are influential on soil erosion. Impact (splash) erosion is dependent on rainfall dislodgement. The energy of rainfall impact is the main driver of particle dislodgement (Young and Wiersma 1973). The energy and momentum of rainfall were found to be functions of rainfall intensity; raindrop size and velocity also influence splash erosion (Park and Mitchell 1983). Other studies have shown that while increased rainfall amount and intensity increase erosion, intensity has a larger influence (Nearing 2001; Nearing et al. 2005). Within soil erosion models, rainfall can be modeled as rainfall erosivity or just energy.

Rainfall erosivity, the kinetic energy of rainfall per unit of rainfall, stems from Wischmeier and Smith (1978) and the USLE. Rainfall erosivity is calculated using the product of rainfall energy and maximum 30-min intensity for all the storms over an individual year. The USLE uses isoerodent R factor maps for the United States, which have been improved upon by USLE revisions and modifications to account for different types of rainfall (southeastern USA) and freeze-thaw conditions (Pacific Northwest) (Haan et al. 1994; Renard and Foster 1991). To determine rainfall erosivity, as specified by the USLE, both rainfall intensity and depth data must be available for individual storms over a long period of time. As this extent of data may not be available in other locations, relationships have been formed to estimate rainfall erosivity. Renard and Freimund (1994) related rainfall erosivity to annual average precipitation and a modified Fournier index. Nearing (2001) expanded upon this research using two different climate change models to compare Renard and Freimund's methods of calculating rainfall erosivity, finding that there "is no rationale for favoring one over the other." Other equations have been used to estimate rainfall erosivity using monthly and mean rainfall (da Silva et al. 2012) and SCS Type storms (Cooley 1980).

Rainfall energy is calculated based on annual rainfall, rainfall intensity and a relationship developed by Wischmeier and Smith (Morgan et al. 1984). The Morgan-Morgan-Finney (MMF) model of soil erosion estimation uses energy of rainfall as a component of its water phase. LISEM uses rainfall gauge data to spatially distribute rainfall, as well as account for interception and infiltration, but ultimately calculates rainfall kinetic energy to estimate soil erosion (DeRoo et al. 1994). Runoff volume is another method to represent the influence of rainfall on soil erosion. The modified Universal Soil Loss Equation (MUSLE) replaces rainfall erosivity with a runoff energy factor (Williams 1982). The effect of rainfall, or water, on soil erosion can be modeled with relationships between erosion and flow type, flow velocity and flow depth (Fox and Bryan 2000; Hogarth et al. 2004; Römkens et al. 2002; Zhang et al. 2003).

2. *Influence of Slope*

Rainfall impacts interact with slopes to create different scenarios of erosion. Low slopes tend to be dominated by rainfall impact rather than surface flow (Hogarth et al. 2004). Slope steepness is considered to be an influential factor in soil erosion. Römkens (2002) found that total sediment yield increased with increased slope steepness. Other studies show that slope affects peak sediment concentrations for interrill erosion (Fox and Bryan 2000). Both detachment and transport by overland flow and rain impact are influenced by slope gradients. Combined with intensity and soil type, slope has significant effects on splash detachment and transport (Quansah 1981). Onstad and Foster (1975) found that flow characteristics on a slope correlate to transport capacity. For overland flow detachment, slope gradient impacts shear stress and energy, some of the variables used to estimate detachment by overland flow (Zhang et al. 2003). Runoff velocity, energy of rainfall impact, effective rainfall intensity and infiltration rate, are influenced by slope gradient but are also variables for determining soil erosion (Fox and Bryan 2000). The relationships between slope gradient, other variables and soil erosion are often determined in laboratory settings, by changing the slope and keeping other variables constant (Fox and Bryan 2000; Hogarth et al. 2004; Quansah 1981; Römkens et al. 2002; Zhang et al. 2003).

Onstad and Foster (1975) used the slope steepness factor from USLE and percent slope in their calculations to find detachment and transport capacities. The slope factor (S) of the USLE is often combined with a slope length factor (L) to form a topographic factor (LS) computed over a unit plot. The equation for slope steepness by USLE is for a slope length greater than 15 feet and varies based on sine of the slope angle. A different slope steepness equation is used for slope lengths less than 15 feet, as rilling is less likely to occur on shorter slope lengths (Haan et al. 1994). Adjustments by the RUSLE take into account that slope steepness has a greater effect on soil loss than slope length. Procedures exist to account for irregular slopes by dividing them into segments or using a slope length adjustment factor (Haan et al. 1994). Moore and Burch (1986) developed an equation for LS based on sediment transport equations and upslope contributing area per unit width of a contour. This equation has been used with DEMs and flow accumulation to estimate the LS factor for RUSLE (Moore and Wilson 1992).

3. *Influence of Soil Type*

Factors of the USLE are often carried over into other models and studies. Soil erodibility, K – factor, is often used to describe the ability of a soil to erode. It is based on properties of the soil itself and the influence that rainfall and runoff have on that particular soil (Haan et al. 1994; Wischmeier and Smith 1978). The K – factor is a ratio of soil loss per rainfall erosion index unit [ton·acre·hour/hundreds-acre-ft·tonf·inch] (Foster et al. 1981; Renard et al. 1997). A soil erodibility nomograph exists to determine the K factor by the percent silt & very fine sand, percent sand, percent organic matter, soil structure and permeability. For a specific site, soil erodibility may be determined via the nomograph; the Soil Survey Geographic Database (SSURGO) has soil erodibility factors for most mapping units.

The surface roughness, as a function of soil type, affects sediment concentrations by impacting the type of flow established over the surface. Rougher surfaces are more likely to form concentrated flow paths resulting in higher sediment concentrations, whereas uniform flow is common over smooth surfaces (Römkens et al. 2002). Once a surface has been cleared of loose particles and/or sealed by water, it becomes harder to erode and detachment erosion becomes more prominent (Römkens et al. 2002; Ziegler et al. 2000). Soil (and surface) type is a significant factor in determining soil erosion, especially if there is no other land cover.

4. *Influence of Land Cover/Vegetation*

The presence of land cover and/or vegetation changes the amount of soil that can be eroded. Prior to the establishment of land cover in urban areas, or vegetation, bare surfaces are prone to high amounts of erosion (Krug and Goddard 1986; Leopold 1968). After construction when surfaces are stabilized, streambank rather than surface erosion becomes a more significant contributor to sediment yields (Krug and Goddard 1986). Vegetative cover is a dominant factor in water erosion, where increased vegetation results in lower water erosion rates (Qichang et al. 2000).

The influence of land cover and vegetation on soil erosion is more difficult to quantify. The USLE combines the effects of vegetation and land cover into the Crop Management Factor (C – factor). In its original use, the C – factor describes ground cover, crop stage and soil moisture on a fallow field as one value; a table of C values for construction sites and woodland was developed as well (Wischmeier and Smith 1978). Land cover/land use categories have been fitted to C factors in several studies (Pandey et al. 2007; da Silva et al. 2012; Zhang et al. 2009). Remote sensing images have been used to estimate the C – factor using a normalized difference vegetation index (NDVI) (Karaburun 2010; Knijff et al. 2000). In the MMF model, percentage rainfall interception represents the effect of vegetative cover on splash detachment erosion (Meijerink et al. 1990; Morgan et al. 1984). Meijerink (1990) used terrain mapping units (TMUs) to estimate soil erosion with overlays of protective vegetation.

c. SUMMARY

Review of current literature shows a variety of methods and processes to describe soil erosion. No conclusive determination of the importance or influence for individual factors was found in the literature. Several models and equations have been developed to quantify and/or qualify soil loss from small plots to catchments (Merritt et al. 2003; Morgan et al. 1984; Wischmeier and Smith 1978) in agricultural environments. The most popular models are those that are easy to use and can be used on a broader range of environments, such as the USLE. No model has been proven to be superior to others, as each model varies by input and type of output. The known effects on water bodies by sediment include changes in channel morphology and water quality. (Leopold 1968; Paul and Meyer 2001). Federal and state regulations regarding stormwater management are driven by the negative consequences of soil erosion and warrant the importance of soil erosion estimation, especially in urban areas.

3. URBAN EROSION POTENTIAL RISK MAPPING WITH GIS

a. INTRODUCTION

The negative consequences imparted on streams due to urbanization is often referred to as the "urban stream syndrome" (Walsh et al. 2005). Sedimentation and erosion of streams through modified landscapes and stream hydrology are just some of the effects of the urban stream syndrome. Channel morphology and water quality are strongly influenced by sediment originating from erosion of bare land or streambanks, or during construction in urban areas (Krug and Goddard 1986; Paul and Meyer 2001; "Sediment" n.d.). Both coarse and fine sediments are eroded and have various negative consequences downstream of the point of erosion (POE). Heavier particles directly contribute to sediment deposition along the travel path, typically closer to the POE. Fine sediments, which remain in suspension until reaching receiving waterbodies, block sunlight from traversing the water column to reach bottom-dwelling plants and can smother certain aquatic organisms in waterways (Chesapeake Bay Program 2017; Reshetiloff 2004; "Sediment" n.d.). Aggregation of this suspended sediment in channels affects the morphology and dimensions of streams, and can landlock ports (Reshetiloff 2004; "Sediment" n.d.; Walsh et al. 2005). Further environmental degradation results from binding or absorption of nutrients and chemicals (toxins, metals, etc.) to the surface of sediment, allowing their transport and/or deposition with the sediment particles (Hogarth et al. 2004; Reshetiloff 2004; "Sediment" n.d.).

Sediment is transported primarily via surface stormwater runoff to receiving waterways, where it often becomes a regulated pollutant. Municipal governments are required to manage stormwater to comply with federal and state regulations regarding water quality and quantity. The Clean Water Act (CWA) initially placed controls on point source pollutant discharges, through permits via the National Pollutant Discharge Elimination System (NPDES). The CWA specifically targeted discharges from publicly owned treatment works (POTWs) (33 U.S.C §1251 et seq., 1972). The Water Quality Act (WQA) of 1987, an amendment to the CWA, worked to ensure water quality standards are met through monitoring and assessment. The CWA required the establishment of Total Maximum Daily Loads (TMDLs) for the Nation's waters, which guides restoration efforts to improve water quality to acceptable levels. Nutrients, sediments and metals are some common TMDLs that are often found in stormwater. Definition of stormwater runoff as a point source through Municipal Separate Storm Sewer Systems (MS4s) has led to their inclusion in NPDES regulation (Clarke 2003).

Erosion control regulations did exist prior to the WQA (1987); Franklin D. Roosevelt created the Soil Erosion Service in 1933 (now National Resources Conservation Service (NRCS), formerly Soil Conservation Service, under the Department of Agriculture) in response to the Dust Bowl, to conserve soil (Virginia Department of Environmental Quality n.d.). Both Maryland and Virginia established laws for soil and water conservation in the 1930s. Maryland authorized sediment control regulations in 1957 and Virginia created the Virginia Erosion and Sediment Control Law (VESCL) in 1973 (Maryland Department of the Environment n.d.; Virginia Department of Environmental Quality n.d.). In state regulatory codes, erosion and sediment control and stormwater management may be addressed in separate sections. Both sediment and stormwater are considered pollutants, where sediment can be discharged with stormwater. The creation of MS4s allows for concerted efforts in addressing community-scale stormwater management through the NPDES permit system or applicable state-level versions of the NPDES (such as the Virginia Pollution Discharge Elimination System (VPDES)). To meet regulatory requirements, statewide and/or local stormwater management programs (SWMP) have been implemented to meet thresholds of pollutant discharges in stormwater, including sediment.

Development of local TMDLs for impaired waters, as required by the CWA, set some of the pollutant discharge thresholds that municipalities are required to meet by their SWMP. The sensitivity of the Chesapeake Bay to nutrients and sediments has made these pollutants the focus of Virginia’s nonpoint source pollution prevention program (Chesapeake Bay Program 2017; Reshetiloff 2004). To meet sediment TMDLs, the sediment load is often controlled through use of best management practices (BMPs). Many of these BMPs are coordinated through United States Department of Agriculture (USDA) local Soil and Water Conservation Districts (SWCDs) with a primary focus on agricultural erosion reduction. While the control of sediment runoff from agricultural practices is paramount in meeting sediment reduction goals, many agricultural practices are exempt from regulatory erosion control guidelines, thus limiting their regulation by local jurisdictions. Due to this restriction, it is crucial that municipalities can understand, predict, and optimally control sediment migration from regulated urban areas in order to make progress in meeting their TMDL goals. Typically, the highest probability of mass soil migration is during land disturbing activities where surface vegetation and topsoil has been stripped to allow for mass grading. Entrapment and removal of sediment prior to reaching downstream receiving waters may also remove bound pollutants, such as nutrients and chemicals, as well (Reshetiloff 2004; Liu et al. 2003).

b. BACKGROUND

Soil erosion occurs through two main processes: 1) detachment and 2) transport of soil particles during rainfall events (Young and Wiersma 1973), resulting in impact (splash) erosion and transport erosion, respectively. Splash erosion is caused by the kinetic energy of rainfall, which results in the dislodgment of a soil particle (Quansah 1981; Young and Wiersma 1973). Rainfall intensity is often seen as a main parameter in determining the erosivity of the rainfall. Studies show that soil erosion is more sensitive to changes in rainfall intensity versus changes strictly based on total rainfall volume, due to a larger transfer of energy over a shorter period of time (Nearing 2001; Nearing et al. 2005). Slope steepness is another crucial factor affecting soil erosion, especially for flow (transport) erosion. Laboratory studies have found that slope steepness was positively correlated with both soil detachment and transport (Quansah 1981). Erosion by rainfall impact and surface water flow, in conjunction with various other physical parameters, result in varying potential rates of soil migration throughout a watershed. Dominant downstream migration through a watershed is via rills; erosion on surfaces between rills is considered interrill erosion. These two components of erosion are driven by different detachment and transport processes. Rill erosion is dominated by concentrated flow, and interrill erosion is dominated by rainfall (raindrop impact and flow from rainfall) (Zhang et al. 2003).

The challenges involved in modeling and estimating soil erosion have resulted in several models and methods to predict soil loss or erosion potential (DeRoo et al. 1994; Leh et al. 2011; Morgan et al. 1984; Renard and Foster 1991; Williams 1982; S. Zhang et al. 2017; X. Zhang and Zhang

2012; M. K. Jain et al. 2004). These models integrate the processes of detachment and transport to estimate soil loss from a watershed. Models are empirically, conceptually or physically based. The USLE and its derivations (RUSLE, MUSLE, etc.) are empirical models based on observational research (Merritt et al. 2003). Other common erosion models are physical (LISEM, WEPP), based in physical equations such as conservation of mass and momentum or sediment transport equations. Models can also be grouped by scale (catchment, hillslope, plot) or event type (long term or single event). They vary based on input, quality of input and processes modeled (Merritt et al. 2003). The Limburg Soil Erosion Model (LISEM) simulates an erosion process that falls between sheet and rill erosion using GIS maps and rainfall data (DeRoo et al. 1994). The Watershed Erosion Prediction Project (WEPP) focuses on sheet and rill erosion on hillslopes using physics based equations (Merritt et al. 2003). Models are limited by availability and quality of data and their outputs reflect those limitations and varying operational assumptions.

Historically, the most commonly used equation to estimate annual soil loss is through the Universal Soil Loss Equation (USLE). Its simplicity, relatively low data requirements, and generally wide application makes the USLE and its variations a popular choice. Developed by the USDA, the USLE predicts long-term annual soil loss by combined rill and interrill erosion on agricultural hillslopes (Haan et al. 1994; Merritt et al. 2003; Wischmeier and Smith 1978). The USLE was intended for agricultural watersheds, but applications have been extended to forests, construction sites and mixed watersheds (Renard and Foster 1991; Mattheus and Norton 2013; Fraser et al. 1995). Refinements of the equation due to improving research over the years has resulted in the Modified USLE, MUSLE (Williams 1982), and the Revised USLE, RUSLE (Renard and Foster 1991), which make adjustments to the determination of the USLE parameters.

Within the processes evaluated, there are driving factors. Detachment and transport erosion can both be influenced by rainfall, water flow, slope and soil type (Quansah 1981; Merritt et al. 2003). Other factors including land cover/land use, rainfall interception, rainfall intensity and water regimes have effects on soil erosion processes (Morgan et al. 1984; S. Zhang et al. 2017;

Leh et al. 2011; Römkens, Helming, and Prasad 2002). Research has also examined the relationship between erosion and slope gradient and shear stress (Fox and Bryan 2000; Onstad and Foster 1975; Zhang et al. 2003). Although a variety of factors influencing erosion have been investigated, no predetermined importance or influence for individual factors on soil erosion was found in the literature, even though it is accepted that the factors may vary by other preexisting conditions.

c. STUDY OBJECTIVE

Current literature is comprised of studies applying soil erosion models on mostly agricultural watersheds (Balousek et al. 2000; Chang et al. 2015; Jain et al. 2001; Mattheus and Norton 2013; Nearing et al. 2005; Pandey et al. 2007; Prasannakumar et al. 2012; Šurda et al. 2007). Input parameters vary based on the model chosen, but common factors that influence the total soil loss are topography, rainfall, slope, soil type and land cover (DeRoo et al. 1994; Jain et al. 2004; Leh et al. 2011; Renard and Foster 1991; Zhang et al. 2017). USLE is considered one of the most robust models with few input parameters and has been applied to watershed types that extend beyond its intended application. However, other models (LISEM, SedNet, WEPP, etc) do exist that leverage datasets related to erosion that are now commonly available. Long term rainfall data, digital elevation models (DEMs) and sediment delivery ratios are additional parameters required by other soil erosion models. Results for existing models of rural watersheds are often soil erosion loss, annually or by single storm event, or as erosion potential (Merritt et al. 2003).

Despite this, very little literature exists describing a simplified process for utilizing commonly available geospatial datasets for predicting erosion potential in urban areas. With increased focus and established thresholds on eroded sediment and its bound pollutants, caused by the effects of urbanization, methods are needed to predict land surface areas with high relative erosion risk in urban areas. Municipal planners and engineers will benefit from determining locations of high risk areas. The objective of this study is to use commonly available geospatial layers to evaluate land surface erosion potential in urban areas. A procedure will be developed to create a theoretical raster based GIS model of urban erosion potential and test it on a case study in the Town of Blacksburg. The ability to prioritize urban areas for planning overlays, additional erosion control measures during construction, BMP installation, restoration or monitoring is crucial to ensure that municipalities continue to maximize their efforts in meeting their community TMDL goals.

d. METHODS

1. *Data sources*

The Central Stroubles watershed, located in the Town of Blacksburg, Virginia was selected as a case study application of the methodology described in this section. This watershed contains a mix of commercial, civic, and residential areas with multiple land cover and slope conditions. Data used for the analysis was obtained from the Town's geodatabase ("Blacksburg GIS Database" 2015) or from online data repositories managed by the USDA and the U.S. Geological Survey (USGS). Specific datasets include:

- A polyline feature class representing 0.6 meter (2 foot) contours for the Town of Blacksburg.
- A point feature class representing stormwater infrastructure (inlets, manholes etc.).
- A polygon feature class representing the Town of Blacksburg's Detailed Land Cover Database (DLCD).
- A polygon feature class generated using the USDA Web Soil Survey (WSS) for Montgomery County and the Soil Survey Geographic Database (SSURGO) ("Web Soil Survey" 2017).
- A line feature class representing National Hydrography Database (NHD) Flowlines from USGS
- High resolution Aerial Imagery of the Town of Blacksburg

The USDA WSS enables download of soil data for an area of interested. Soil information downloaded for Montgomery County, VA includes polygons of soil type and map unit symbols and keys. Extended information about each map unit is found in the geodatabase included in the exported data acquired from the WSS.

2. *Parameter Characterization*

In development of the model, a number of important parameters are used to characterize soil erosion, as determined by literature review. These include:

- Soil Erodibility
- Local Cell Slope
- Land Cover
- Runoff Volume
- Distance to nearest stormwater conveyance point
- Slope along surface flow travel path to nearest stormwater conveyance point

These factors are input parameters used to determine the erosion potential (EP) within a raster cell. The watershed is analyzed using a 10 x 10-meter raster grid. After analysis, each of the parameters of interest are ranked from 1 – 10 for each 10-meter cell. For the target watershed, ranges corresponding to the various ranks are shown in Table 1.

Table 1. Summary table of established ranking thresholds 1 (least erosive) to 10 (most erosive) for the six parameters used to determine final erosion potential values

Rank	**2 Yr. Runoff Volume (m^3)**	**Local Slope (degrees)**	**Land Cover**	**Soil Erodibility**[a] $\left(\frac{t*ha*h}{ha*MJ*mm}\right)$[b]	**Distance to Inlet (meter)**	**Average Slope (degrees)**
1	14	6	Impervious	$9.1 * 10^{-3}$	23.7	6
2	38	12	*~ not assigned~*	$1.8 * 10^{-2}$	41.1	12
3	77	17	Dense Forest	$2.7 * 10^{-2}$	58.4	17
4	141	21	Light Forest/Tree Canopy	$3.6 * 10^{-2}$	75.7	21
5	231	27	Brush/Bush	$4.6 * 10^{-2}$	93.1	27
6	352	31	Open Space (Lawn)	$5.5 * 10^{-2}$	110.4	31
7	517	35	Gravel	$6.4 * 10^{-2}$	129.5	35
8	749	39	Light Bush/Dirt/Mulch	$7.3 * 10^{-2}$	150.5	39
9	1,111	42	*~ not assigned~*	$8.2 * 10^{-2}$	177	42
10	1,602	>= 45	Dirt	$9.2 * 10^{-2}$	232.6	45

[a] Conversion from U.S. Customary Units to SI Units (Foster et al. 1981)

[b] Mass per area per erosivity unit (Foster et al. 1981)

This analysis focuses on land surface erosion risk, so cells indicating stream locations are excluded from the raster image (and the analysis). These cells indicate areas of channelized flow and can skew the risk maps by presumed stream bank erosion. Streams within the watershed were estimated using a flow network. The flow network was identified using a non-weighted flow accumulation. For purposes of this study, cells exhibiting a DEM flow accumulation greater than 300 are removed from the analysis. The set of cells with accumulation values exceeding 300 generally correspond to stream locations based on visual examination of NHD flowlines and high resolution aerial photos, and contain the subset of points indicating channel cross-sections as catalogued in the Town of Blacksburg stormwater infrastructure geodatabase. The 0.6 meter (2 foot) contours for the Town of Blacksburg are converted in ArcGIS (ESRI 2016) to a digital elevation model (DEM) for the watershed extents. Depressions within the DEM are filled using the ArcGIS Hydrology tools; filled version of the DEM is used throughout the analysis.

Rainfall intensity was determined to be an important factor in soil erosion by the literature review but is not used in the study. It is assumed that the rainfall intensity is uniform across the area of analysis. As the aim is to create a relative erosion risk map, the effect of rainfall intensity will cancel out as the value is the same for each cell.

(a) Erosion Runoff Volume

Total runoff volume represents the accumulated water volume in a cell from all contributing upstream cells (inclusive). The NRCS runoff equation is used to calculate the volume of water generated by each contributing cell based on a total storm precipitation depth and the ArcMap Flow Accumulation function is used to aggregate upstream contributing runoff. The volume of runoff is influenced by curve numbers (CN) based on land cover and hydrologic soil group (HSG) of a cell. A runoff volume raster image was generated for the 2-year 24-hour storm (7.01 cm), based on NOAA Atlas 14 data for Blacksburg (3 SE 44-0766) (“NOAA Atlas 14” n.d.). The 2-year storm is the typical return period used to evaluate erosion in manmade channels in Virginia and many other states (New Jersey, Connecticut, etc.). Note that while the NOAA Atlas 14 dataset is sampled at a (~0.93 km latitude) resolution which would yield similar-scale, but varying rainfall depths across the watershed, the storm total was kept constant using the NOAA precipitation depth value at the centroid of the watershed. This was done to preserve the assumption of homogeneity of rainfall across the watershed, thus preserving the ability to compute relative risk across watershed cells.

Curve numbers are determined by land cover and hydrologic soil group. The SSURGO polygons, with the HSG value field, are intersected with the DLCD layer to create a raster which identifies both land cover and HSG for a polygon. Using TR-55 (SCS 1986), the following curve numbers were assigned to land cover types by hydrologic soil group. Unless specified in Table 2 below, fair condition was assumed.

Table 2. DLCD land cover types paired with a TR-55 cover type and their corresponding curve numbers

DLCD Code	Type	TR-55 Cover Type	Curve Number (TR – 55)			
			HSG A	HSG B	HSG C	HSG D
0	Assumed Impervious	Impervious Area	98	98	98	98
1	Sidewalk	Impervious Area	98	98	98	98
2	Road/Parking	Impervious Area	98	98	98	98
3	Building	Impervious Area	98	98	98	98
5	Other Asphalt/Concrete	Impervious Area	98	98	98	98
9	Dense Forest	Woods	36	60	73	79
8	Light Forest/Tree Canopy	Woods - Grass Combination	43	65	79	82
10	Brush/Bush	Brush	35	56	70	77
6	Open Space (Lawn)	Open Space	49	69	79	84
4	Gravel	Streets & Roads - Gravel	76	85	89	91
11	Light Bush/Dirt/Mulch	Open Space - Poor Condition	68	79	86	89
7	Dirt	Streets & Roads - Dirt	72	82	87	89

The NRCS runoff equation is used to compute runoff volume for each cell (Equation 1).

$$V = Q_{in-NRCS} * 10\ m * 10\ m * \frac{1\ m}{39.4\ inches} \quad \textbf{Eq. 1}$$

where,

V = runoff volume for a 10-m raster cell, in cubic meters

$Q_{in\text{-}NRCS}$ = runoff depth from TR-55, in inches

Once a runoff volume raster has been established, a weighted flow accumulation is created to account for all upstream contributing cells. Using the ArcToolbox Hydrology tool, a flow direction raster is created using the filled DEM. This flow direction raster is used to create two flow accumulations rasters. The first is an unweighted flow accumulation used for flow length and flow network calculations. The second is weighted by the runoff volume raster. This second raster, representing cubic feet of accumulated runoff volume, is ranked from 1 – 10 using Natural Jenks Breaks based on relative values – see Table 1.

(b) Local Cell Slope

The slope of the site (a raster cell) influences erosion potential and is modeled as the local slope parameter. The local slope (in degrees) is calculated from the filled DEM using the 3D Spatial Analyst tool. Local slope is ranked into 10 categories using the soil detachment rate presented by Zhang (2003) for shallow flow (Table 1). The equation provided by Zhang includes a flow rate variable along with the slope variable to estimate soil detachment. Assuming a near unit flow rate (1 m/s), resulted in a range of soil detachment between 1 and 10 for slopes angles 1 to 45 degrees. Angles greater than 45 degrees are assigned a value of 10; values up to 45 degrees are good assumed angles of repose for soil (United States Department of Agriculture 1994, 2007; Upadhyaya 2009).

(c) Land Cover

The DLCD for the Town of Blacksburg classifies land covers for the town under twelve different types. These types were ranked on a scale from 1 – 10 based on their erosive potential, where impervious surfaces are least erodible (1) and dirt is the most erodible (10) (Table 3).

Table 3. Land covers organized by their erosive potential on a scale of 1 to 10. All impervious surfaces are placed into the same erosive category

Erosive Potential	DLCD Code	Type
1	0	Assumed Impervious
1	1	Sidewalk
1	2	Road/Parking
1	3	Building
1	5	Other Asphalt/Concrete
3	9	Dense Forest
4	8	Light Forest/Tree Canopy
5	10	Brush/Bush
6	6	Open Space (Lawn)
7	4	Gravel
8	11	Light Bush/Dirt/Mulch
10	7	Dirt

In the ranking of land cover types, rank 2 and 9 were left empty to allow for other land cover types. If a municipality is using another land cover classification, such as the National Land Cover Database (NLCD), other land cover types may be used. Rank 2 was left empty to represent values that may exhibit low erosivity but not complete imperviousness (i.e. water based on NLCD) while rank 9 is highly erosive with some protection, such as agricultural land, based on NLCD cover types.

(d) Soil Erodibility

Polygons imported from the WSS outline areas of specific soil types with few soil parameter attributes included with the feature class. Although this information is not included in the layer by default, both soil erodibility, K_f, and the hydrologic soil group, necessary for the erosion potential calculation, can be found in the SSURGO database. The RUSLE2 Related Attributes Table, found in the SSURGO database, contains K_f and HSG fields for all the soil types and is joined with the polygon layer using the map unit symbol/key (mukey). Udorthents and urban land soil types were assumed to have a soil erodibility of 0.27 (Renard et al. 1997) as SSURGO places a "null" in this field; these values were manually updated. Polygons which represent impoundments were updated to have a soil erodibility of 0, as no surface soil erosion is expected within these polygons. For HSG, the worst-case scenario in terms of soil erosion assumes a soil group of "D" for urban land/udorthents and in any case where two HSGs are given (e.g. HSG B/D or C/D). A land cover type of "water" is also assumed to belong to HSG "D".

The soil polygons were converted to a raster image using the Polygon to Raster tool within ArcGIS using the soil erodibility, K_f, values. The K_f values are ranked on a scale of 1 – 10 based on the range of soil erodibility values consistent with the USLE nomograph (Wischmeier and Smith 1978). According to Wischmeier and Smith (1978), soil erodibility ranges from 0 to 0.7 ton·acre·hour/hundreds of acre-foot·tonf·inch so the ranks 1 – 10 as established by this procedure are defined as equal intervals spanning the erodibility range between 0 – 0.092 ton·hectacre·hour/hectacre·megajoule·millimeter (0 and 0.7 ton·acre·hour/hundreds of acre-foot·tonf·inch), see Table 1.

(e) Distance and Slope to Nearest Stormwater Conveyance Point

Once surface flow reaches a receiving channel, other factors such as bank stabilization, main channel flow, and other factors related to larger volumes of typically rapidly moving water begin to drive the erosion process. These factors, including stream bank erosion, are separate contributors to sediment loads that are not considered in this erosion potential calculation since the goal here is to find the highest EP risk in upslope areas. Due to this limitation, the distance to a receiving channel or point of entry to a conveyance network (storm sewer inlet) is considered important as it correlates with the risk that a particular cell will contribute to downslope erosion. In urban areas, stormwater infrastructure typically conveys runoff directly to receiving channels rendering distances to these inlets important. For this study, nearest stormwater conveyance points include stormwater infrastructure (inlets, catch basins etc.) and points along a stream network. Due to the complexity of calculating a distance-to-outlet for each 10-meter raster cell, the distance and slope to nearest stormwater conveyance point was calculated using a Python script, Distance to Inlet (Python Software Foundation n.d.). The Python script (described in detail in subsequent sections) evaluates the distance using a 'Near' Analysis on the points representing the nearest stormwater conveyance ("Near Analysis" 2017). Other factors such as elevation of the cell, rim elevation and flow lengths are considered when determining the most representative distance. This ensures that surface flow is not attributed to a nearest inlet that is upgrade from the elevation of the cell.

(1) Developing Stormwater Conveyance Point Layer

The Town of Blacksburg's stormwater geodatabase contains a stormwater nodes point layer that includes catch basins, manholes, junctions, inlets and other related stormwater infrastructure nodes. The 'Node ID' and Rim Elevation are required inputs for the Python analysis. Node types were limited to nodes representing catch basins, headwalls/endwalls, cross sections and pond outlet structures as they represent inlets receiving stormwater runoff. The flow network was used to supplement the known infrastructure locations with stream networks based on upper and lower threshold network values. For the Central Stroubles case study watershed, the upper threshold was determined by where the stream entered an underground system in the aerial photograph. Those cells that fall within that range of network values were assigned elevations using the DEM and then converted to points and used as additional outlet points for the analysis. Infrastructure nodes and stream network points are combined into one stormwater conveyance point layer with two fields, Node ID and rim elevations.

(2) Master Point Layer

The master point layer contains the fields: OBJECTID, Shape, pointid and grid_code, where pointid is the ID of the raster cell point and grid_code is the elevation of that cell point. Prior to running the Distance to Inlet script, the following fields are added to the master point layer, with pre-population of some fields (Table 4).

Table 4. Field names and description for the master point layer of the Python script calculating distance and slope to nearest inlet.

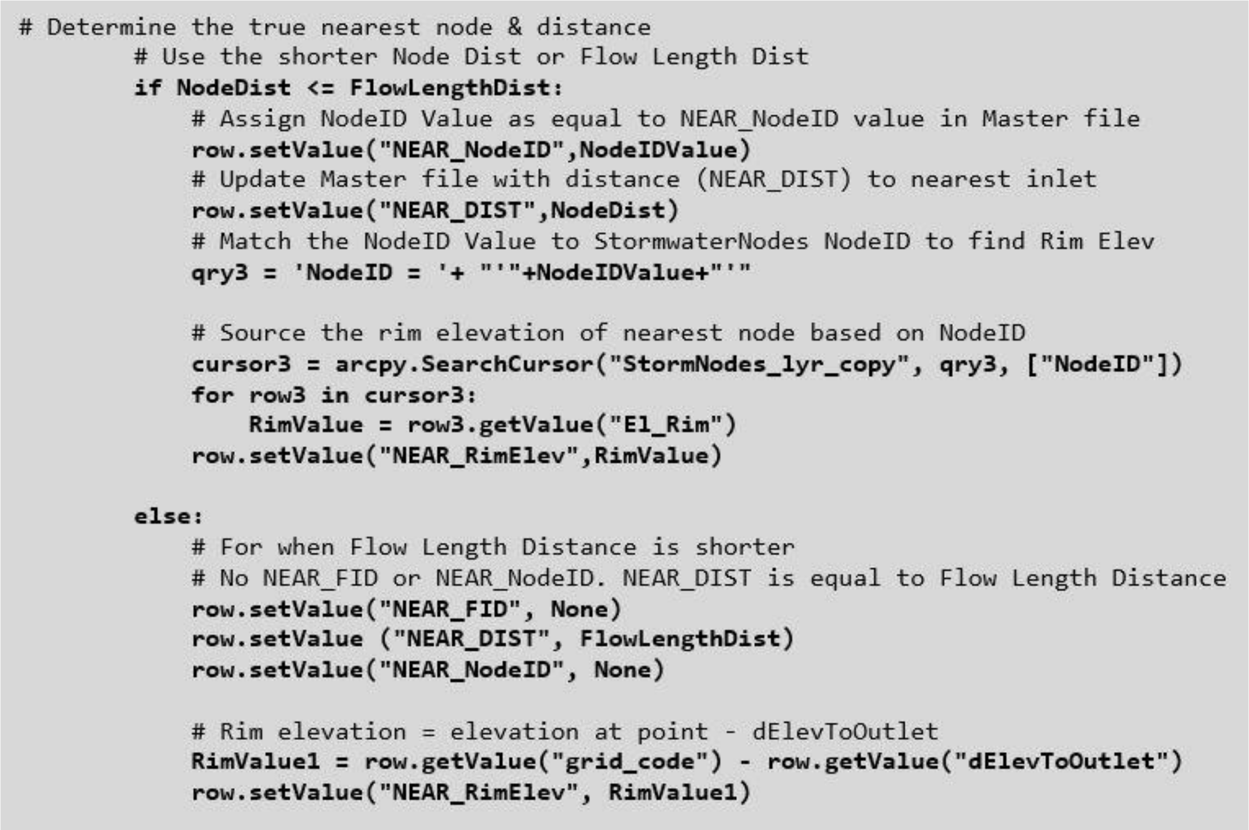
Field Name	**Field Description**
OBJECTID *	Default objectid value assigned when a layer is created.
Shape *	Default shape type assigned when a layer is created.
pointid	Default value assigned to points when created from a raster image.
grid_code	Default value of the cell assigned based on value (elevation) of the DEM raster
NEAR_FID	OBJECTID of the nearest stormwater conveyance point as determined by the NEAR analysis.
NEAR_DIST	Distance to the nearest stormwater conveyance point as determined by the Distance to Inlet Python script. NEAR_DIST can be the value determined by NEAR analysis or Flow Length Distance, whichever is shorter.
NEAR_NodeID	NodeID from the stormwater conveyance point layer that corresponds to the NEAR_FID as determined by a search cursor in the script.
NEAR_RimElev	The rim elevation corresponding to the NodeID in the stormwater conveyance point layer as determined by a search cursor in the script.
FlowLength	Flow length as determined by the flow length tool. Populated prior to running the script.
dElevToOutlet	Change in elevation between the cell point and its outlet, as determined by the flow length weighted by decimal slope. Populated prior to running the script.
Avg_Slope	Average slope between the point and the nearest stormwater conveyance point, calculated as part of the script.

(3) Flow Length Determination

The watershed boundary used is infrastructure corrected and does not necessarily follow the DEM which was created using surface contours. Due to these boundary deviations, for some raster cells, the nearest available stormwater conveyance may be outside of the boundaries of the watershed. Some of the points near the watershed boundary will therefore flow out of the watershed. To account for those situations, flow length for each cell was determined using the flow direction hydrology tool. The shortest distance, when comparing the NEAR distance and flow length, is used to represent the distance to nearest stormwater conveyance point. Because the average surface flow slope along this travel path (if flow length is the shortest distance) is a parameter of interest, the flow length weighted by decimal slope was also created. This weighted flow length raster represents the change in elevation between the current cell and its outlet, as determined by the flow length. If flow length is shorter, the near rim elevation is calculated as the difference between the cell elevation and this change in elevation. These flow lengths and change in elevation values are added to fields in the master point layer.

(4) Python Script

The script uses the Near Analysis to determine the nearest distance between a master point layer, representing each 10-meter cell, and the stormwater conveyance points described above. The master point layer is updated with the Near analysis results, while a copy point layer is used in conjunction with the search cursor. Iterating through each point in the watershed, the script steps through several layers to determine the nearest stormwater conveyance. The distance and average slope to the nearest node are returned from the script to be used as an erosion potential risk factor. The distance to the nearest node can be estimated using one of two methods: results from Near analysis or the flow length distance, described above. The script compares the two distances, as flow length distance is pre-populated in the master file and the NEAR_Dist is determined during the current iteration (Fig. 1)



```
# Determine the true nearest node & distance
        # Use the shorter Node Dist or Flow Length Dist
        if NodeDist <= FlowLengthDist:
            # Assign NodeID Value as equal to NEAR_NodeID value in Master file
            row.setValue("NEAR_NodeID",NodeIDValue)
            # Update Master file with distance (NEAR_DIST) to nearest inlet
            row.setValue("NEAR_DIST",NodeDist)
            # Match the NodeID Value to StormwaterNodes NodeID to find Rim Elev
            qry3 = 'NodeID = '+ "'"+NodeIDValue+"'"

            # Source the rim elevation of nearest node based on NodeID
            cursor3 = arcpy.SearchCursor("StormNodes_lyr_copy", qry3, ["NodeID"])
            for row3 in cursor3:
                RimValue = row3.getValue("El_Rim")
            row.setValue("NEAR_RimElev",RimValue)

        else:
            # For when Flow Length Distance is shorter
            # No NEAR_FID or NEAR_NodeID. NEAR_DIST is equal to Flow Length Distance
            row.setValue("NEAR_FID", None)
            row.setValue ("NEAR_DIST", FlowLengthDist)
            row.setValue("NEAR_NodeID", None)

            # Rim elevation = elevation at point - dElevToOutlet
            RimValue1 = row.getValue("grid_code") - row.getValue("dElevToOutlet")
            row.setValue("NEAR_RimElev", RimValue1)
```

Fig. 1. A sample Python code segment used for determining the nearest node distance based on one of two methods.

Depending which distance is shorter, different fields in the master file are updated. The calculation of the rim elevation, used to calculate the average slope, differs by distance method. As seen in the code excerpt above, the rim elevation is either sourced directly from the stormwater nodes file or calculated using a change in elevation to outlet. Near analysis results assume a straight-line distance between the cell and the nearest node, and not the DEM derived downslope distance. The actual flow path, as determined by ArcToolbox Flow Direction, may not result in the same nearest node. Topographic data, and therefore the DEM, are not infrastructure corrected, which warranted the inclusion of flow length in the Python script. Locations which represent inlets are not necessarily represented by DEM sinks, preventing flow being driven to them. Based on available data and processes available within the software, the straight-line distance is an acceptable approximation.

Final values for each parameter resulting from computations with the Python script were used in generation of raster grids for both distance to inlet and average slope. The distance to the nearest inlet was reclassified to rank 1 – 10 based on Natural Jenks Breaks applied to the range of calculated values. Average slope along the travel path to the nearest inlet is ranked 1 – 10 using the same scale as discussed previously for classification of local slope. For ranking thresholds, see Table 1.

3. Erosion Potential

Erosion potential (EP) of the watershed is evaluated using the following equation:

$$EP = (V_R * S_L * LC * K_f) + (D * S_A) \qquad \textbf{Eq. 2}$$

where,
EP = Erosion potential
V_R = Accumulated runoff volume
S_L = Local slope of the cell
LC = Land cover
K_f = Soil erodibility
D = Distance to inlet
S_A = Average slope to inlet

Erosion potential is divided into a site component (first term of equation 2) and a downstream transport component (second term). Lack of literature regarding the influence of these components on erosion potential prevent the assignment of relative weights to each. The individual parameters are equally weighted on a scale of 10. The site component is comprised on the accumulated runoff volume, land cover, slope and soil erodibility of the cell. These factors represent erosive processes occurring within the cell; the distance to inlet and average slope to inlet are indicative of the potential to transport sediment from the cell and into a receiving channel (right side of Eq. 2). All factors are ranked into categories 1 (least erosive) to 10 (most erosive), as described in Table 1, prior to use in Equation 2. Thus, the total EP is calculated as a unitless relative risk score. The resulting risk map generated from Equation 2 is not intended to quantify the amount of sediment eroded but instead a relative risk of erosion, as compared to other locations within a target area.

Per the equation, transport erosion appears to have much less weight than the site component. Unranked EP scores can range from 2 to 10,100 with the transport erosion component contributing a maximum 100. Transport represents the potential for eroded sediment from a cell to move into a receiving channel. Once in a channel, sediment often becomes a pollutant controlled by federal, state and/or local regulations. While erosion can occur during transport, the site is assumed to contribute more to the overall EP. The site component focuses on land surface erosion and the four interacting factors that contribute to this surface erosion. Most of the erosion will occur here before being transported downstream; therefore, when equally weighted, the site component should have higher values than the transport component. Cases where the transport component contributes a higher score to the EP value are discussed after application of the methodology to the case study watershed.

e. RESULTS

1. *Erosion Potential Risk Map*

Erosion potential is calculated for each cell in the watershed based on Equation 2. Relative erosive potential risk scores range from 2 (low) to 618 (high) for the watershed. Results are classified into 10 bins by Natural Jenks breaks based on the range of scores from the calculated EP (Fig. 2).

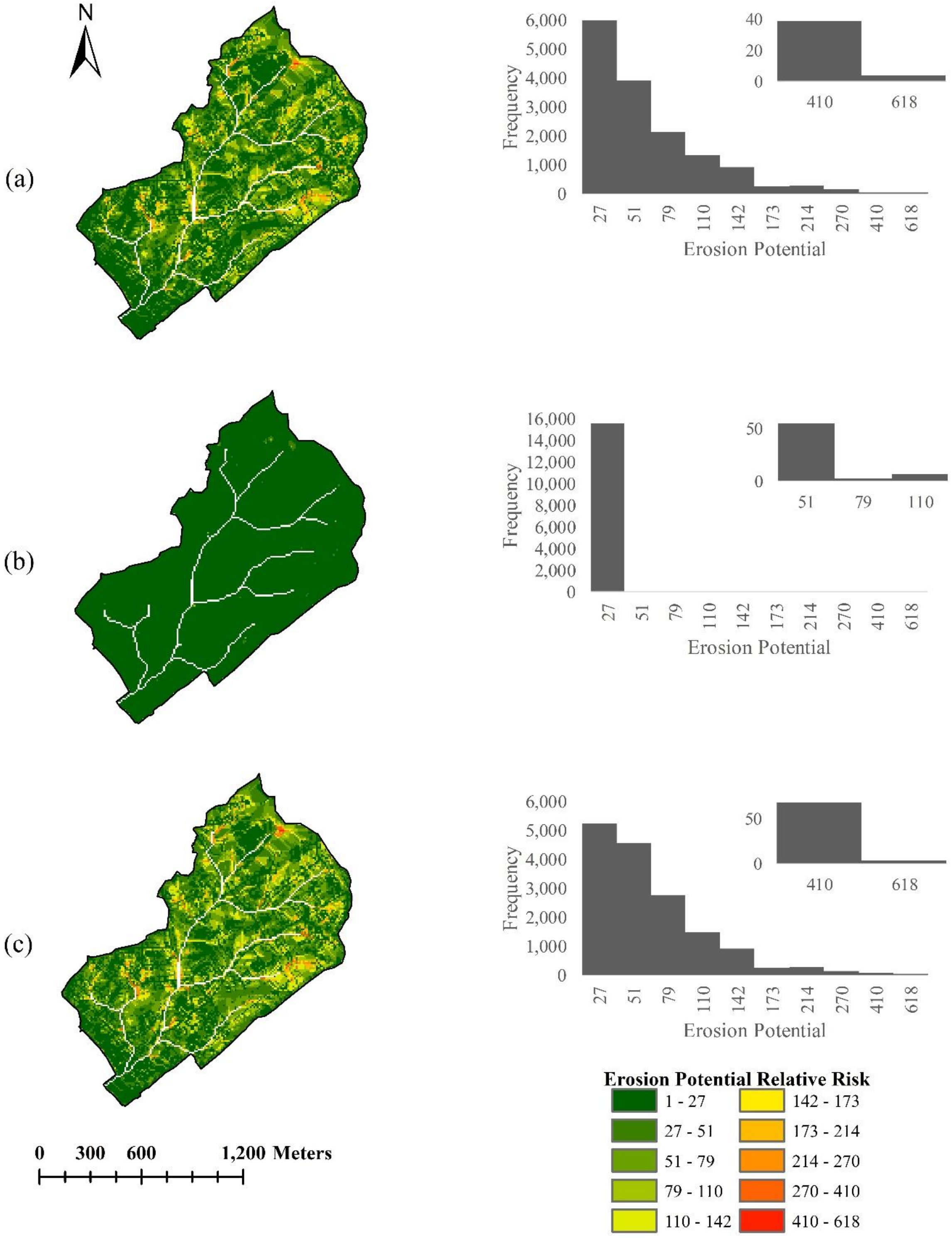


Fig. 2. Components of EP maps including (a) local site component $[(\boldsymbol{V_R} * \boldsymbol{S_L} * \boldsymbol{LC} * \boldsymbol{K_f})]$, (b) downstream transport component $[(\boldsymbol{D} * \boldsymbol{S_A})]$, and (c) final composite EP with frequency distributions.

The component maps, site (Figure 2a) and downstream transport potential (Figure 2b), are classified using the same scale as the total EP. Classification is performed using Natural Jenks rather than equal intervals to show more visual distinction of EP components. When using equal intervals of 60, the bins generated result in 99% of the downstream transport values falling in the lowest erosive potential category and all the values within the first two bins (Table 5). With classification according to the Natural Jenks breaks, the transport values fall within the first four bins. The site (cell) specific component has 75% of the values in the first bin using equal intervals; the same approximate percentage falls within the first three bins using Natural Jenks.

Table 5. Frequency distributions of two different classification methods, equal interval and Natural Jenks, for final erosion potential of Central Stroubles.

Erosion Potential	Equal Interval				Natural Jenks			
	Bins	Frequency			Bins	Frequency		
		Total	Site	Transport		Total	Site	Transport
Low	60	10,532	12,321	15,644	27	5,228	6,691	15,587
	120	3,507	2,560	7	51	4,546	3,920	55
	180	1,150	513	0	79	2,751	2,129	2
Medium	240	307	172	0	110	1,475	1,310	7
	300	107	66	0	142	910	901	0
	360	28	6	0	173	251	248	0
	420	10	7	0	214	284	281	0
High	480	0	0	0	270	128	126	0
	540	0	3	0	410	68	39	0
	600	4	1	0	618	4	4	0

Even using Natural Jenks, the range of values for downstream transport potential fall on the lower end of the ranking as the highest possible value of 100 falls in the fourth lowest bin. For the total EP and site component, values encompass the entire range. Looking at the EP risk map for the Central Stroubles watershed, the majority of the watershed falls in the lower risk category. The median EP score is 38 with a median site component value of 30 and transport component of 8.

A quick visual inspection of points across the watershed confirm that there are few visible signs of erosion. Ten sites with EP scores of 15 to 155 were chosen for field verification. Although this validation was considered an important step, the likelihood of finding major signs of erosion was considered small since active maintenance by landowners and/or the municipality can often reduce or eliminate erosion completely (Fig. 3).

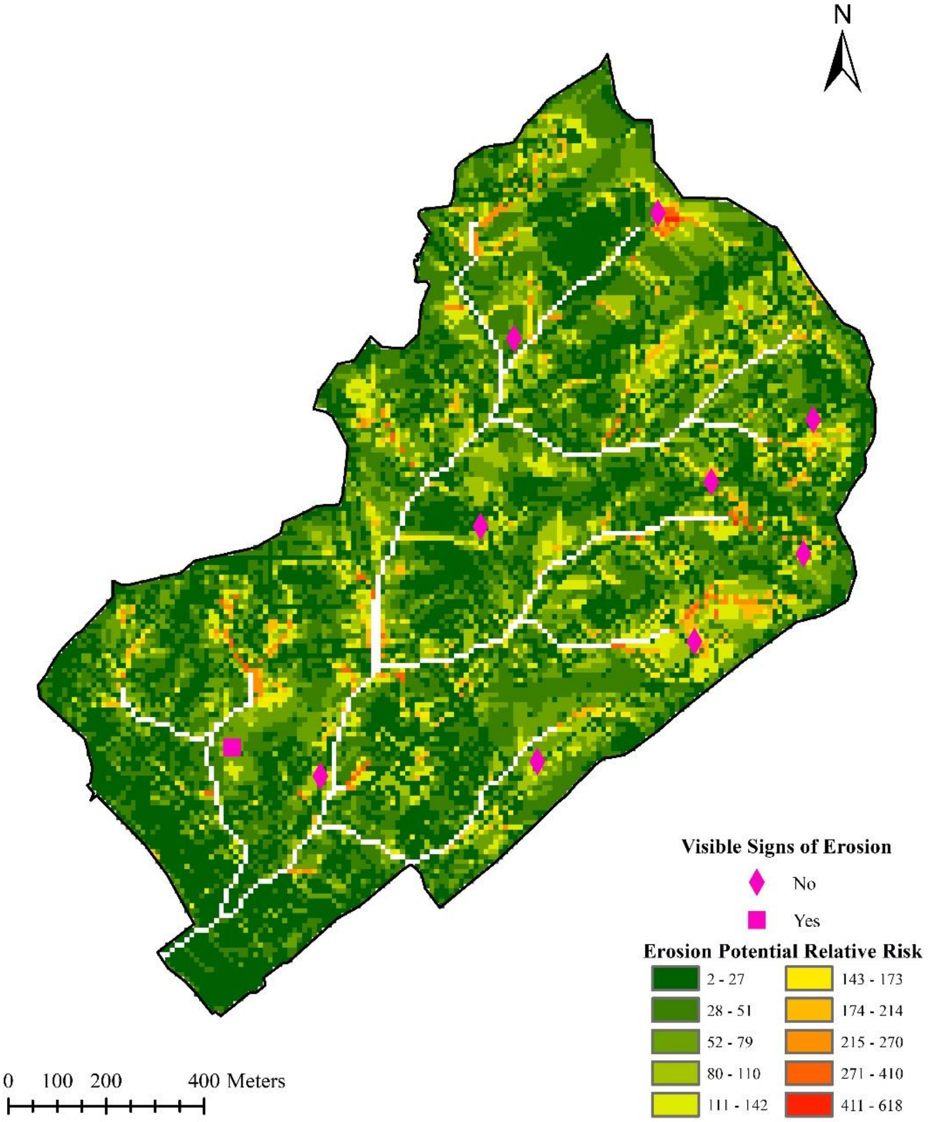


Fig. 3. Areas visually inspected for visible signs of erosion within the watershed.

Of the sites chosen, only one showed visible signs of erosion. The remaining 9 locations were stabilized grass (lawn) or brush/bush surfaces, well maintained by the property owner. The potential for erosion, though, exists whether the location does or doesn't show visible signs of erosion. The EP risk map does not quantify sediment erosion or determine if erosion is occurring, simply the relative risk of erosion when compared to other cells within the analysis area.

2. *<u>Influence of EP Components</u>*

The potential for erosion is divided into two components: site (cell) erosion and downstream transport potential. The site erosion carries more importance than downstream transport, per equation 2, as the components are not weighted (rather equally weighted). Visually, the site component features a distribution more similar to the total EP risk map, indicating its influence on the total value. Certain areas within the watershed have the transport component contributing a majority of the score to the overall EP risk (Fig. 4).

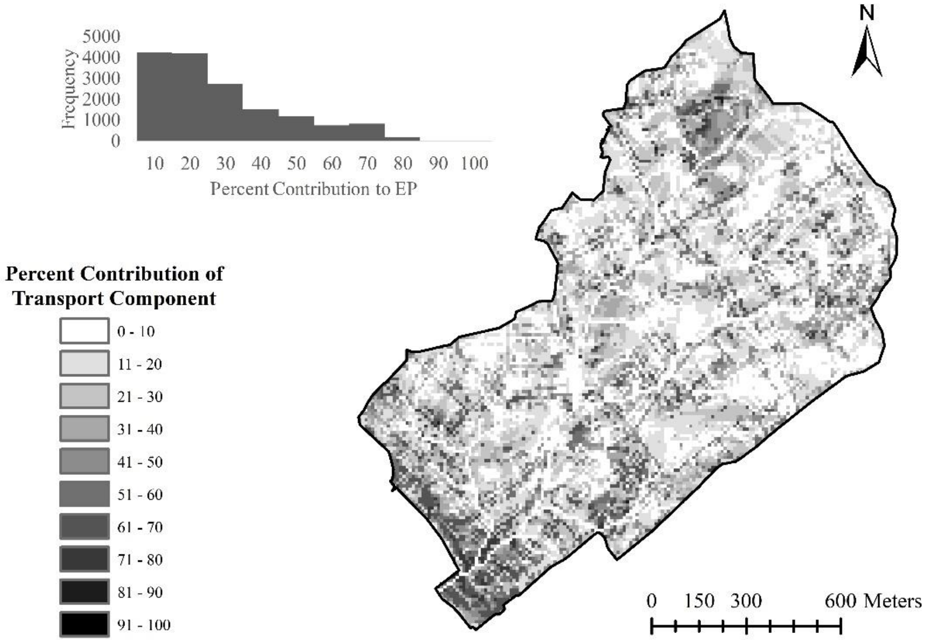


Fig. 4. The percentage contribution of the transport component toward the combined EP.

In approximately 14% of the cells within the watershed, the transport component contributes 50% or more of the score towards total EP. 75% of the cells have up to 33% of the EP as transport potential, and 25% of cells contribute less than 10% from transport potential towards the EP. The transport component often has less influence than the site component on total EP values, but in certain areas it is the driver of the EP value. These areas that are highly influenced by transport generally fall in the lower EP risk categories, based on Figure 2, above. The lower southwestern section of the watershed corresponds to the edge of downtown Blacksburg, an area that is mainly covered by impervious land cover. The northeastern corner is an old high school campus that, besides the sports fields, is impervious surface (building and parking). Both sections have several stormwater inlets within a small area. While the transport component has a median contribution of 18% towards the total EP value, it has enough influence on heavily impervious areas of the watershed that it warrants inclusion in Equation 2 even though its maximum theoretical contributing score is 100 (versus 10,000 for the site component of the equation).

3. *Adaptations to Methodology*

In its current form, Equation 2 is purely theoretical in nature with equal weights applied to all parameters, which yields an unbalanced influence between the local and transport components as previously described. Adaptations may need to be made to the methodology when applying the method to a larger or smaller scale than the target watershed in this study. Because of the relative rankings used for the 2-yr runoff volume and distance to inlet, neighboring watersheds cannot be directly compared unless they use a common ranking for each of those parameters. For municipal planners who want to compare erosive potential across the community, absolute rankings must be established from aggregated data for runoff volume and distance to inlet, prior to creation of any risk maps.

To better represent erosion potential, further information should be gathered to determine if any of the six parameters or EP components need to be individually weighted. In this study, all parameters are equally weighted, as are the site and downstream transport components of EP. The current form of Equation 2 has the transport component delivering a maximum value of 100 towards the total EP, while the local component delivers a maximum value of 10,000. It is possible that this weight should be adjusted to represent the influence of transport on erosion potential through the contribution of sediment to receiving channels. In addition, within the site component, certain parameters, such as local slope or land cover, may have greater influence on surface erosion, and could be adjusted accordingly. No research in the literature was found to propose or justify any non-uniform weighting of the parameters used in this study; therefore, all parameter weightings remain equal. Because erosive risk cannot be quantified by field observation or measurement, absolute risk is unknown, which prevents use of a sensitivity analysis to determine potential non-equal weights of the parameters used in Equation 2.

f. CONCLUSIONS

This study proposes a process for estimating erosive potential in urban areas using commonly available geospatial layers and Python scripting. Many factors were determined to be influential in determining land surface erosion, with six major components selected as the basis for the proposed EP calculation. EP is broken up into site specific erosive potential and downstream transport potential components. Application of the methodology to the Central Stroubles watershed in Blacksburg, Virginia indicates low erosive potential across majority of the watershed. Of the two components, site specific erosion potential seems to have the most influence on total EP. Within the Central Stroubles watershed, transport potential had high contribution to total EP when impervious cover was high and distance to inlet shorter. Visual inspection of ten locations across the watershed confirm little to no visible signs of erosive damage, possibly due to maintenance by landowners which can curtail most signs of impending surface erosion; therefore, visual inspection by itself is an insufficient method for assessing or confirming EP.

Erosion potential risk maps provide a tool for municipal planners and engineers, giving them the ability to focus attention and resources on areas of an urban watershed that may be contributing to sediment concentrations in local channels. Particularly, it highlights areas of extreme erosive risk that may need to be managed with larger and more efficient erosion control measures during land disturbance. While traditional zoning restrictions have typically been limited to slope overlays to aid in controlling erosion, the methodology used within this study provides many additional contributing parameters beyond slope that can be used by future planners in the preparation of overlay mapping focused on preserving and improving the quality of the communities receiving waters.

4. CONCLUSION

a. IMPLICATIONS

“The nation that destroys its soil destroys itself” said Franklin D Roosevelt in 1937, while perhaps referencing the effects of the Dust Bowl on agricultural productivity there is also the imbedded implication of environment degradation caused by soil erosion. Soil erosion is an issue that is not limited to just rural areas but has extended into urban ones. Focus on soil conservation for agricultural purposes has driven current research and erosion estimation methods. Federal and state regulations regarding water quality and sediment as a pollutant have made erosion estimation in urban areas a priority. Development of erosion potential risk maps, as tools for municipal planners and engineers is crucial for the protection of the environment. These tools allow them the ability to focus attention and resources on areas of an urban watershed that may be contributing to sediment concentrations in local channels.

Commonly available geospatial layers, combined with Python scripting, were used to develop a process for estimating erosion potential in urban areas. A theoretical EP calculation was proposed that combines the effects of several important parameters to estimate land surface erosion. Application of the methodology to the Central Stroubles watershed in Blacksburg, Virginia indicates low erosive potential across the majority of the watershed. The study proposes other parameters that can be used in conjunction with traditional slope overlays by municipalities to highlight areas that may need to be managed with more efficient erosion control measures during land disturbance.

b. FUTURE WORK

As mentioned during the literature review, no conclusive research was found to propose or justify weighting of the parameters used in the study. Therefore, the equation presented has equal weights applied to all parameters, yielding an equation where the site component has a generally higher influence. However, when applied to an urban watershed of mixed land uses, the study indicated that the transport component does have a significant influence on EP in certain areas of the watershed. To better represent erosion potential, further information should be gathered to determine if any of the six parameters or EP components need to be individually weighted. With all parameters equally weighted, the transport component delivers a maximum value of 100 towards the total EP, while the local site component delivers a maximum value of 10,000. It is likely that this weight should be adjusted to represent the influence of transport on erosion potential through the contribution of sediment to receiving channels. The current form of the equation ranks all but two of the parameters on an absolute scale. The distance to inlet and 2-year runoff volume parameters are ranked relative to the values calculated for the watershed in question. For comparisons to be made between neighboring watersheds, an absolute ranking must be established prior to the creation of any risk maps.

The distance to inlet factor is currently estimated using a straight-line distance, rather than a real-world flow path. Modifications to the Python script could improve the estimation of this factor as effects of the DEM on water travel were ignored. Flow paths from the DEM were not used as the DEM is not infrastructure corrected and would not necessarily yield the correct flow path. Improvement in the existence and accuracy of DEMs and delineations of watersheds with urban infrastructure would provide correct flow paths and more accurate distance results. The incorporation of downstream land cover on the erosive potential of a travel path is another factor not considered in the current parameter. However, the land cover downstream of the cell could initiate sediment deposition prior to the runoff entering a stormwater network. Distance to inlet is considered an important parameter as stormwater infrastructure conveys runoff directly to receiving channels. Increased accuracy in the estimation of this distance value could improve the influence of downstream migration to a channel, where sediment becomes a pollutant.

REFERENCES

Balousek, J. D., Roa-Espinosa, A., and Bubenzer, G. S. (2000). “Predicting Erosion Rates on Construction Sites Using the Universal Soil Loss Equation in Dane County, Wisconsin.” *National Conference on Tools for Urban Water Resource Management & Protection*, 206–213.

Chang, T. J., Zhou, H., and Guan, Y. (2015). “Applications of Erosion Hotspots for Watershed Investigation in the Appalachian Hills of the United States.” *Journal of Irrigation and Drainage Engineering*, 142(3), 1–9.

Chesapeake Bay Program. (2017). “Bay Barometer: Health and Restoration in the Chesapeake Bay Watershed.” <https://www.chesapeakebay.net/documents/2015-2016_Bay_Barometer.pdf>.

Clarke, J. (2003). “Clean Water Act. Water: Science and Issues.” <http://www.encyclopedia.com/doc/1G2-3409400062.html> (Mar. 30, 2017).

Cooley, K. . (1980). “Erosivity Values for Individual Design Storms.” *Journal of the Irrigation and Drainage Division, American Society of Civil Engineers*, 106, 135–145.

DeRoo, A. P. J., Wesseling, C. G., Cremers, N. H. D. T., Offermans, R. J. E., Ritsema, C. J., and Van Oostindie, K. (1994). “LISEM: a new physical-based hydrological and soil erosion model in a GIS-environment, theory and implementation.” *Variability in stream erosion and sediment transport, Proc. symposium, Canberra, 1994*, 439–448.

Environmental Systems Research Institute (ESRI). (2016). “ArcGIS ArcMap 10.4.1.”

Foster, G. R., McCool, D. K., Renard, K. G., and Moldenhauer, W. C. (1981). “Conversion of the universal soil loss equation to SI metric units.” *Journal of Soil and Water Conservation*, 36(6), 355–359.

Fox, D. M., and Bryan, R. B. (2000). “The relationship of soil loss by interrill erosion to slope gradient.” *Catena*, 38(3), 211–222.

Fraser, R. H., Warren, M. V, and Barten, P. K. (1995). “Comparative Evaluation of Land Cover Data Sources for Erosion Prediction.” *Water Resources Bulletin*, 31(6), 991–1000.

Haan, Barfield, and Hayes. (1994). “Rill and Interrill Erosion Modeling: USLE/RUSLE Empirical Models.” *Design Hydrology and Sedimentology for Small Catchments*, Academic

Pres, Inc.

Hogarth, W. L., Rose, C. W., Parlange, J. Y., Sander, G. C., and Carey, G. (2004). “Soil erosion due to rainfall impact with no inflow: A numerical solution with spatial and temporal effects of sediment settling velocity characteristics.” *Journal of Hydrology*, 294(4), 229–240.

Jain, M. K., Kothyari, U. C., and Ranga Raju, K. G. (2004). “A GIS based distributed rainfall-runoff model.” *Journal of Hydrology*, 299(1–2), 107–135.

Jain, S. K., Kumar, S., and Varghese, J. (2001). “Estimation of Soil Erosion for a Himalayan Watershed Using GIS Technique.” *Water Resources Management*, 15, 41–54.

Karaburun, A. (2010). “Estimation of C factor for soil erosion modeling using NDVI in Buyukcekmece watershed.” *Ozean Journal of Applied Sciences*, 3(1), 77–85.

Knijff, J. M., Jones, R. J. A., and Montanarella, L. (2000). “Soil erosion risk assessment in Europe.” *European Comission*, (January 2000).

Krug, W. R., and Goddard, G. L. (1986). *Effects of urbanization on streamflow, sediment loads, and channel morphology in Pheasant Branch basin near Middleton, Wisconsin. Water-resources investigations report (USA)*.

Leh, M., Bajwa, S., and Chaubey, I. (2011). “Impact of Land Use Change on Erosion Risk: An Integrated Remote Sensing, Geographic Information System and Modeling Methodology.” *Land Degradation & Development*, 24(August 2011), 409–421.

Leopold, L. B. (1968). “Hydrology for- Urban Land Planning - Effects of Urban Land Use.” *Geological Survey Circular*, 554, 1–18.

Liu, X., Zhang, X., and Zhang, M. (2003). “Major factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis.” *Journal of Environmental Quality*, 37(5), 1667–1674.

Maryland Department of the Environment. (n.d.). “Erosion and Sediment Control in Maryland.” <http://mde.maryland.gov/programs/Water/StormwaterManagementProgram/Pages/erosionsedimentcontrol.aspx>.

Mattheus, C. R., and Norton, M. S. (2013). “Comparison of pond-sedimentation data with a GIS-based USLE model of sediment yield for a small forested urban watershed.” *Anthropocene*, Elsevier B.V., 2, 89–101.

Meijerink, A. M. ., Van Lieshout, A. M., and Mobareke, F. R. (1990). “Comparison of

Approaches for Erosion Modelling using Flow Accumulation with GIS." *HydroGIS 96: Application of Geographic Information Systems in Hydrology and Water Resources Management*, 25(5), 437–44.

Merritt, W. S., Letcher, R. A., and Jakeman, A. J. (2003). "A review of erosion and sediment transport models." *Environmental Modelling and Software*, 18(8–9), 761–799.

Moore, I. D., and Wilson, J. P. (1992). "Length-slope factors for the Revised Universal Soil Loss Equation: Simplified method of estimation." *J. Soil and Water Cons*, 4 7(5), 423–428.

Morgan, R. P. C., Morgan, D. D. V., and Finney, H. J. (1984). "A predictive model for the assessment of soil erosion risk." *Journal of Agricultural Engineering Research*, 30(April), 245–253.

Natural Resources Conservation Service. (n.d.). "More Than 80 Years Helping People Help the Land: A Brief History of NRCS."

Nearing, M. . (2001). "Potential changes in rainfall erosivity in the U.S. with climate change during the 21st century." *Journal of Soil and Water Conservation*, 56(3), 229–232.

Nearing, M. A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Le Bissonnais, Y., Nichols, M. H., Nunes, J. P., Renschler, C. S., Souchère, V., and Van Oost, K. (2005). "Modeling response of soil erosion and runoff to changes in precipitation and cover." *Catena*, 61(2–3 SPEC. ISS.), 131–154.

Onstad, C. A., and Foster, G. R. (1975). "Erosion Modeling on a Watershed." *Transactions of the ASAE*.

Pandey, A., Chowdary, V. M., and Mal, B. C. (2007). "Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing." *Water Resources Management*, 21(4), 729–746.

Park, S. W., and Mitchell, J. K. (1983). "Rainfall Characteristics and Their Relation to Splash Erosion." *Transactions of the ASAE*, 26(3), 795–804.

Paul, M. J., and Meyer, J. L. (2001). "Streams in the Urban Landscape." *Annual Review of Ecology and Systematics*, 32(1), 333–365.

Prasannakumar, V., Vijith, H., Abinod, S., and Geetha, N. (2012). "Estimation of soil erosion risk within a small mountainous sub-watershed in Kerala, India, using Revised Universal Soil Loss Equation (RUSLE) and geo-information technology." *Geoscience Frontiers*, Elsevier B.V., 3(2), 209–215.

Qichang, Z., Qige, Q., and Chunyan, G. (2000). “Quantitative analyses on the relationship between water erosion rate and underlying surface factors at regional scale.” *World Automation Congress proceedings*.

Quansah, C. (1981). “The Effect of Soil Type, Slope, Rain Intensity and Their Interactions on Splash Detachment and Transport.” *Journal of Soil Science*, 32, 215–224.

Renard, K. G., and Foster, G. R. (1991). “RUSLE: revised universal soil loss equation.” *Journal of Soil and Water Conservation*, 46(1), 30–33.

Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., and Yoder, D. C. (1997). “Chapter 3. soil erodibility factor.” *Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE)*, United States Department of Agriculture, 65–100.

Renard, K. G., and Freimund, J. R. (1994). “Using monthly precipitation data to estimate the R-factor in the revised USLE.” *Journal of Hydrology*, 157(1–4), 287–306.

Reshetiloff, K. (2004). *Chesapeake Bay: Introduction to an ecosystem*.

Römkens, M. J. M., Helming, K., and Prasad, S. N. (2002). “Soil erosion under different rainfall intensities, surface roughness, and soil water regimes.” *Catena*, 46(2–3), 103–123.

“Sediment.” (n.d.). *Chesapeake Bay Program,* <http://www.chesapeakebay.net/issues/issue/sediment#inline> (Mar. 29, 2017).

da Silva, R. M., Montenegro, S. M. G. L., and Santos, C. A. G. (2012). “Integration of GIS and remote sensing for estimation of soil loss and prioritization of critical sub-catchments: A case study of Tapacurá catchment.” *Natural Hazards,* 62(3), 953–970.

Šurda, P. ., Šimonides, I. ., and Antal, J. . (2007). “A determination of area of potential erosion by geographic information systems.” *Journal of Environmental Engineering and Landscape Management,* 15(June 2015), 144–152.

Virginia Department of Environmental Quality. (n.d.). “Module 3 : History of Erosion and Sediment Control and Stormwater Management Laws.” 1–10.

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Peter, M., Ii, R. P. M., and Ii, R. A. P. M. O. (2005). “The urban stream syndrome: current knowledge and the search for a cure.” *Journal of the North American Benthological Society*, 24(3), 706–723.

"Web Soil Survey." (2017). <https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>.

Williams, J. R. (1982). "Testing the Modified Universal Soil Loss Equation." *Proceedings of the Workshop on Estimating Erosion and Sediment Yield on Rangelands Tucson , Arizona*, 157–165.

Wischmeier, W. H., and Smith, D. D. (1978). "Predicting rainfall erosion losses." *Agriculture handbook no. 537*, (537), 285–291.

Young, R. A., and Wiersma, J. L. (1973). "The Role of Rainfall Impacts on Soil Detatchment and Transport." *Water Resources Research*, 9(6).

Zhang, G., Liu, B., Liu, G., He, X., and Nearing, M. a. (2003). "Detachment of Undisturbed Soil by Shallow Flow." *Soil Science Society of America Journal*, 67(3), 713–719.

Zhang, S., Li, Y., Fan, W., and Yi, Y. (2017). "Impacts of Rainfall, Soil Type, and Land-Use Change on Soil Erosion in the Liusha River Watershed." *Journal of Hydrologic Engineering*, 22(4), 746-.

Zhang, X., and Zhang, S. (2012). "Exploring effects of rainfall intensity on soil erosion at the catchment scale using modified SEMMED model at the Zuli River Basin, Western Loess Plateau, CHine." *IGARSS 2012*, 14, 2012.

Zhang, Y., Degroote, J., Wolter, C., and Sugumaran, R. (2009). "Integration of Modified Universal Soil Loss Equation (MUSLE) into a GIS Framework to Assess Soil Erosion Risk." *Land Degradation and Development*, 20, 84–91.

Ziegler, A. D., Sutherland, R. A., and Giambelluca, T. W. (2000). "Partitioning total erosion on unpaved roads into splash and hydraulic components: The roles of interstorm surface preparation and dynamic erodibility." *Water Resources Research*, 36(Compendex), 2787–2791.