STUDY OF RESERVOIR SEDIMENT AMOUNTS CONTRIBUTED TO WATERSHED EROSION

A Thesis Presented to
The Faculty of the
Fritz J. and Delores H. Russ
College of Engineering and Technology
Ohio University

In Partial Fulfillment
of the Requirement for the Degree
Master of Science

by
David M. Beekman
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<tbody>
<tr>
<td>(a_p)</td>
<td>Coefficient dependent on contour ridge height for P factor</td>
</tr>
<tr>
<td>(A)</td>
<td>Long term average soil loss per unit area (USLE, RUSLE)</td>
</tr>
<tr>
<td>(A_m)</td>
<td>Long term average soil loss (Musgrave Equation)</td>
</tr>
<tr>
<td>(A_r)</td>
<td>Long term average soil loss (Rational Method)</td>
</tr>
<tr>
<td>(A_{99%}, A_{95%}, A_{90%}, A_{75%}, A_{50%})</td>
<td>Soil erosion potential percentile markers</td>
</tr>
<tr>
<td>(b)</td>
<td>Empirical coefficient for surface cover factor</td>
</tr>
<tr>
<td>(b_p)</td>
<td>Coefficient dependent on contour ridge height for P factor</td>
</tr>
<tr>
<td>(B)</td>
<td>Amount of deposition considered to benefit the long term maintenance of the soil resource</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Rill erosion to interrill erosion ratio</td>
</tr>
<tr>
<td>(B_{ur})</td>
<td>Mass density of live and dead roots in upper soil layer</td>
</tr>
<tr>
<td>(B_{us})</td>
<td>Mass density of incorporated surface residue in upper soil layer</td>
</tr>
<tr>
<td>(c_p)</td>
<td>Coefficient dependent on contour ridge height for P factor</td>
</tr>
<tr>
<td>(C)</td>
<td>Cover management factor (USLE, RUSLE)</td>
</tr>
<tr>
<td>(CC)</td>
<td>Canopy cover subfactor</td>
</tr>
<tr>
<td>(C_b)</td>
<td>Relative effectiveness of subsurface residue in consolidation factor</td>
</tr>
<tr>
<td>(C_f)</td>
<td>Surface soil consolidation factor</td>
</tr>
<tr>
<td>(C_m)</td>
<td>Inherent soil erodibility (Musgrave Equation)</td>
</tr>
<tr>
<td>(C_r)</td>
<td>Rainfall factor (Rational Method)</td>
</tr>
<tr>
<td>(c_{uf})</td>
<td>Soil consolidation on effectiveness of incorporated residue factor</td>
</tr>
</tbody>
</table>
\( c_{ur} \) Subsurface residue calibration coefficient

\( c_{us} \) Subsurface residue calibration coefficient

\( d_p \) Coefficient dependent on contour ridge height for P factor

DA Drainage Area

DR Sediment Delivery Ratio

E Total storm energy

EI Storm erosivity

\( EI_i \) Percentage of annual EI occurring at time period i

\( EI_t \) Sum of EI percentages for entire time period

\( F_c \) Fraction of land surface covered by canopy

\( g_p \) Sediment load that would occur at the end of slope if the strips caused no deposition

\( G_s \) Specific gravity of soil

\( g_s \) Sediment load at end of slope

\( \gamma_d \) Dry specific weight of soil

\( \gamma_w \) Specific weight of water

H Distance raindrops fall after striking the canopy

\( I_{30} \) Maximum 30-minute storm intensity

K Soil erodibility factor (USLE, RUSLE)

\( K_r \) Soil erodibility (Rational Method)

L Slope length factor (USLE, RUSLE)

\( L_m \) Horizontal slope length (Musgrave Equation)

\( L_r \) Slope length (Rational Method)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\lambda$</td>
<td>Horizontal slope length</td>
</tr>
<tr>
<td>$m$</td>
<td>Slope length exponent</td>
</tr>
<tr>
<td>$M$</td>
<td>Product of primary particle size fractions</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of periods used in a summation</td>
</tr>
<tr>
<td>$n_w$</td>
<td>Number of criteria being considered</td>
</tr>
<tr>
<td>$N$</td>
<td>Year period over which storms occur</td>
</tr>
<tr>
<td>OM</td>
<td>Percentage of organic matter within soil</td>
</tr>
<tr>
<td>$p$</td>
<td>Profile permeability class</td>
</tr>
<tr>
<td>$p_w$</td>
<td>Specified weight of the most popular criterion</td>
</tr>
<tr>
<td>$P$</td>
<td>Support practice factor (USLE, RUSLE)</td>
</tr>
<tr>
<td>$P_b$</td>
<td>Base value of the $P$ factor for contouring</td>
</tr>
<tr>
<td>PLU</td>
<td>Prior land use subfactor</td>
</tr>
<tr>
<td>$P_m$</td>
<td>Minimum $P$ factor value</td>
</tr>
<tr>
<td>$P_{mb}$</td>
<td>Minimum $P$ factor for a given ridge height with base conditions</td>
</tr>
<tr>
<td>$P_{m30}$</td>
<td>2-year 30-minute rainfall</td>
</tr>
<tr>
<td>$P_r$</td>
<td>Support practice factor (Rational Method)</td>
</tr>
<tr>
<td>$P_y$</td>
<td>Sediment delivery ratio of a slope under strip cropping or terracing</td>
</tr>
<tr>
<td>$Q_k$</td>
<td>Computed runoff amount for soil and cover management condition</td>
</tr>
<tr>
<td>$r_i$</td>
<td>Rank position of the number of criteria being considered</td>
</tr>
<tr>
<td>$r_j$</td>
<td>Rank position of the criterion</td>
</tr>
<tr>
<td>$R$</td>
<td>Rainfall and runoff erosivity factor (USLE, RUSLE)</td>
</tr>
<tr>
<td>$R_m$</td>
<td>Soil-Cover factor (Musgrave Equation)</td>
</tr>
<tr>
<td>$R_u$</td>
<td>Surface roughness before tillage</td>
</tr>
</tbody>
</table>
\( s \)  
Soil structure code used in soil classification

\( S \)  
Slope steepness factor (USLE, RUSLE)

\( s_c \)  
Slope steepness for which a value of \( P_b \) is desired

\( SC \)  
Surface cover subfactor

\( s_e \)  
Slope steepness above which contouring is ineffective

\( s_g \)  
Percentage of terrace slope grade

\( S_g \)  
Slope gradient

\( SLR \)  
Soil loss ratio

\( SLR_i \)  
Soil loss ratio for time period I

\( s_m \)  
Slope steepness at which contouring is most effective

\( S_m \)  
Degree of slope in degrees (Musgrave Equation)

\( SM \)  
Soil moisture subfactor

\( S_p \)  
Percentage of land covered by surface cover

\( S_r \)  
Slope factor (Rational Method)

\( SR \)  
Surface roughness subfactor

\( \theta \)  
Average slope angle from horizontal

\( V \)  
Volume of soil

\( w_i \)  
Soil loss factor weights

\( w_j \)  
Normalized weight of the \( j^{th} \) criterion

\( W_s \)  
Weight of soil

\( w \)  
Soil moisture content
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>AM/FM</td>
<td>Automated Mapping and Facilities Management</td>
</tr>
<tr>
<td>ARS</td>
<td>Agricultural Research Service</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DLG</td>
<td>Digital Line Graph</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>ESRI</td>
<td>Environmental Systems Research Institute, Inc.</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IDF</td>
<td>Intensity Duration Frequency</td>
</tr>
<tr>
<td>IDW</td>
<td>Inverse Distance Weighted</td>
</tr>
<tr>
<td>MSL</td>
<td>Mean Sea Level</td>
</tr>
<tr>
<td>MWCD</td>
<td>Muskingum Watershed Conservancy District</td>
</tr>
<tr>
<td>NRCS</td>
<td>Natural Resource Conservation Service</td>
</tr>
<tr>
<td>NRSRLDC</td>
<td>National Runoff and Soil Loss Data Center</td>
</tr>
<tr>
<td>ODAS</td>
<td>Ohio Department of Administrative Services</td>
</tr>
<tr>
<td>ODNR</td>
<td>Ohio Department of Natural Resources</td>
</tr>
<tr>
<td>RS</td>
<td>Remote Sensing</td>
</tr>
<tr>
<td>RTK GPS</td>
<td>Real Time Kinematic Global Positioning System</td>
</tr>
<tr>
<td>RUSLE</td>
<td>Revised Universal Soil Loss Equation</td>
</tr>
<tr>
<td>SCS</td>
<td>Soil Conservation Service</td>
</tr>
<tr>
<td>SWCS</td>
<td>Soil and Water Conservation Society</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>USDA</td>
<td>United States Department of Agriculture</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>USLE</td>
<td>Universal Soil Loss Equation</td>
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CHAPTER I

INTRODUCTION

The process of weathering has contributed to the detachment of soil and rock particles, located on exposed surfaces, allowing them to travel from their origin. This detachment and transportation of surface particles due to weathering is better known as erosion. The forces of water, wind, ice, waves, and gravity are the major contributors to the erosion process. As these forces cause soil and rock to erode, the deposition of particles in streams, rivers, and lakes is termed sediment.

The process of transporting erosion materials from their original locations to settling destinations may result in unwanted effects. Erosion reduces the productivity of the land. Sediment degrades water quality and often carries pollutants absorbed in the soil. Deposition of sediment in natural streams, irrigation channels, estuaries, reservoirs, harbors, and water conveyance structures reduces their capacities to perform prime functions and often requires costly treatments. Of the total 0.9 billion metric tons of sediment carried by rivers from the continental United States, about 60 percent is estimated to be from agricultural lands (National Research Council, 1993). The cost of soil erosion from farms is estimated at $3 billion annually while total damage from soil erosion is estimated at tens of billions of dollars per year (Blackland Research Center Web Page, 2000). This chapter introduces background information used for erosion modeling and presents the objectives for this study.
1.1 The Importance of Soil

Before investigating soil erosion, it is essential to discuss the importance of soil in its natural state so that one has more justification to protect it from erosion. Soils are living systems that are vital for the production of food and fiber that humans need to survive. It is the food and fiber used in maintaining the ecosystems on which all life ultimately depends. Soil both directly and indirectly affects agricultural productivity, water quality, and climate through its functions of promoting plant growth, regulating water flow, and serving as an environmental buffer (Lal and Pierce, 1991).

Soils mediate the biological, chemical, and physical processes that supply nutrients and water to growing plants. The microorganisms in the soil convert nutrients into forms that plants can use. These nutrients and water are stored in the soils until the plant needs them to produce roots, stems, and leaves, which eventually become a source of food for humans and animals.

Soils regulate and partition the flow of water through the environment. This is seen as rainfall falls on the soil surface, where it either infiltrates the soil or moves across the soil surface into streams or lakes. The condition of the soil determines whether the rainfall is absorbed or runs off. If it is absorbed, it may be stored and later used by plants, move into groundwater, or move through the earth later appearing in springs or seeps. This partitioning of rainfall between infiltration and runoff determines whether a storm results in a replenishing rain or a damaging flood. The movement of water through the soils to streams, rivers, groundwater, and lakes is an important component in the hydrological cycle.
The biological, chemical, and physical processes that occur in soils buffer environmental changes in air quality, water quality, and climate (Johnson et al., 1992). Soil is a storage chamber for the decomposition of organic wastes including pesticides, sewage, solid wastes, and a variety of other wastes. The accumulation of these wastes may affect the safety and quality of food produced. Improper management may cause soils to become sinks for carbon dioxide and other gases that contribute to the greenhouse effect (Lal and Pierce, 1991).

1.2 Types of Erosion

Wind and water are the two major types of erosion. In wind erosion, the wind velocity, duration, and areas without obstacles all affect the amount of soil to be eroded. Wind erosion typically affects soil with low moisture content and fine to very fine particles. Wind is not as effective an erosional agent as water because of its lower density (Kehew, 1995).

Erosion by running water is the most important type of erosion in terms of the amount of sediment removed from the land surface. Erosion by water takes place in several different stages. This process begins as a raindrop falls from the sky. When the raindrop hits the ground’s surface, the force is sufficient to dislodge individual soil particles from the surface of the soil. The soil particles are dispersed both horizontally and vertically from their origin. If this splash occurs on a slope, over half of the soil particles are dispersed down the slope. As the number of raindrops increase, more soil
particles are displaced, potentially ending up downhill from their origin (Goldman et al., 1986).

In the early stages of a rainstorm, most of the precipitation infiltrates into the ground. If the duration and intensity of the precipitation are sufficient, a saturated zone develops just below the soil surface and water begins to pond. When the ponded water reaches a depth greater than the height of the surrounding surface, water begins to flow downhill in a thin, wide sheet as overland flow. On soil surfaces, this shallow flow of water can transport detached soil particles and is referred to as sheet erosion (Amimoto, 1978).

Sheet erosion is quickly replaced by rill erosion. Rill erosion is the channelized flow of water that has a higher velocity and greater ability to transport particles downhill. Over time, rill erosion is transformed to gully erosion. Gullies, larger channels gradually extending themselves upstream, may render the land unfit for agriculture (Haan et al., 1982).

Not all erosion takes place at the surface. When sediments with large quantities of swelling clays are exposed on valley slopes, intense erosion can take place below the surface, which is termed piping (Kehew, 1995). In piping, the exposed clay surfaces expand when wet, and crack as they shrink and dry. As time progresses, the cracks are enlarged into a network of tunnels just below the surface. These tunnels transport water and sediment to exit holes near the base of the slopes.

As water reaches a main channel, such as a river or stream, the erosion process continues as bank erosion. This typically occurs at locations where the channel tends to
bend or meander (Morris and Fan, 1998). Bank erosion is caused by the shear forces due to the velocity gradient.

Once the channel bed slope decreases, the velocity of the water decreases. This causes soil particles to begin to lose energy and start settling in reservoirs, lakes, deltas, and estuaries. The continuous settling of soil particles eventually results in the deposition of sediments.

1.3 Use of Geographical Information Systems

Geographic Information Systems (GIS) are computer systems capable of managing, manipulating, and analyzing spatial data (Theobald, 2000). Originally developed as a tool for cartographers, GIS has recently been used in engineering design and analysis, especially in the fields of water quality, hydrology, and hydraulics. Some examples are seen in surface water quality analysis (Hoover, 1997) and evaporation and transpiration evaluation (Chang et al., 1997).

GIS provides a mechanism to overlay data layers and perform spatial queries (Laurini and Thompson, 1992). This, in turn, allows new spatial data to be created. Results can be digitally mapped and tabulated, allowing for efficient analysis and decision making. It is accomplished in a computer environment that joins graphical elements (points, lines, and polygons) with associated tabular attribute descriptions (Tate, 1999). GIS systems have the ability to perform numerous tasks utilizing both the spatial and attribute data stored within them (Malczewski, 1999). These functions distinguish GIS from other information management systems. Although GIS is distinguished from
other systems, it is an integrated technology, which allows for the integration of a variety of geographical technologies such as remote sensing (RS), global positioning systems (GPS), computer aided design (CAD), and automated mapping and facilities management (AM/FM) (DeMers, 1997).

I.4 Nature of the Study

Bayes (2000) modeled soil erosion in the Charles Mill Lake Watershed using GIS. Prior to this, studies of soil erosion were limited to small plots of land because of large variation of soil types, slope, and land use. Several recommendations made by Bayes (2000) include additional research for various parameters, interpolation methods, and additional studies for verification of his model.

In an effort to verify the soil erosion model using GIS, this study retraced the procedures used for the Charles Mill Lake Watershed. In addition to reproducing the soil erosion model for the Charles Mill Lake Watershed, a similar soil erosion model was produced for the Piedmont Lake Watershed. The additional model would provide a means of comparison with which the existing model could be verified. In lieu of the fact that the Piedmont Lake Watershed is located in a different region of Ohio, the relationships of various landscape parameters could also be verified.

The data used for both studies were obtained from the same agencies. The digital topography contours and hydrography were downloaded from the Ohio Department of Administrative Services (ODAS) Geographic Information System Support Center page on the World Wide Web. The digital land use data was downloaded from the
Environmental Protection Agency’s (EPA) web page. The digital data was collected by the U.S. Geological Survey (USGS) and converted to ARC/INFO by the EPA. The digital soil attributes were downloaded from the Natural Resources Conservation Service’s (NRCS) web page. For the Charles Mill Lake Watershed, the digital geographic soil data was retrieved from the Ohio Department of Natural Resources (ODNR). This was also the case for the digital geographic soil data for Belmont County, Ohio in the Piedmont Lake Watershed. For the remaining counties located in the Piedmont Lake Watershed, Guernsey and Harrison Counties in Ohio, digital geographic soil data was not available. The soil surveys for these counties were obtained in paperback form from the respective Soil & Water Conservation Districts. This data then had to be converted to digital format using ARC/INFO digitizing techniques.

The digital hydrography data obtained from the ODAS does not include hydrography data below water surfaces, so other sources were sought. The topography for each proposed reservoir in 1934 was obtained from the Muskingum Watershed Conservancy District (MWCD) in paperback form. Like some of the soil data, the contours had to be converted into digital format using ARC/INFO digitizing techniques. The U.S. Army Corps of Engineers surveyed Charles Mill Lake in 1998 in cooperation with the MWCD. The MWCD then supplied the data in digital format. A similar survey was also conducted in 1998 for Piedmont Lake by the MWCD in digital format.
1.5 Objective of the Study

Based on the methods and procedures developed by Bayes (2000) for soil erosion estimation in the Charles Mill Lake Watershed, this study attempted to verify these methods and procedures for the estimation of soil erosion from the Piedmont Lake Watershed. By reproducing the results in the Charles Mill Lake Watershed and applying the methods to the Piedmont Lake Watershed, the results of each analysis could be compared.

Besides the comparison, there was a need to develop standards upon which the models were based. The sediment delivery ratio was used to determine whether the models were adequate. A dimensionless parameter defined by dividing the total mass of sediments in a reservoir by that of the watershed erosion, the sediment delivery ratio is the ratio between the amount of sediment delivered at a location to the amount of material that has eroded from the associated drainage area (Wischmeier and Smith, 1978). Values of sediment delivery ratio obtained by the Blackland Research Center (2000) at Texas A&M University using a mathematical relationship for the continental United States was used for further comparison.

Due to variations in the accuracy of the study results, an additional investigation was performed using weighting procedures. The procedures involved applying weighting coefficients to the erosion model factors. The weighting application was conducted to develop an alternative approach to the modeling process for use with any watershed.

The areas for this study consist of the watersheds of Charles Mill Lake and Piedmont Lake. Charles Mill Lake is located east of Mansfield, Ohio in the north-central
part of the state. Its watershed is situated throughout the Ohio counties of Ashland, Richland, and Crawford. Piedmont Lake is located northeast of Cambridge, Ohio in the eastern part of the state. The Piedmont Lake Watershed is situated within the Ohio counties of Guernsey, Harrison, and Belmont. Belmont County encompasses the majority of the lake. The lakes were built for the purposes of flood control and conservation. Charles Mill Lake was built in 1935, while Piedmont Lake was built in 1937. The dams for both lakes are owned and operated by the U.S. Army Corps of Engineers. The conservation and recreation of these lakes and surrounding lands are managed by the MWCD, which is the largest conservancy district in Ohio. Table I.5.1 and Table I.5.2 list physical features of each lake and its watershed. The locations of each watershed and surrounding areas are presented in Figure I.5.1 and Figure I.5.2.

Table I.5.1 Physical Features of Charles Mill Lake and Its Watershed

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Length</td>
<td>20,700 feet</td>
</tr>
<tr>
<td>Lake Breadth</td>
<td>6,200 feet</td>
</tr>
<tr>
<td>Maximum Depth</td>
<td>27 feet</td>
</tr>
<tr>
<td>Water Surface Area (normal pool)</td>
<td>1339.5 acres</td>
</tr>
<tr>
<td>Shoreline Length</td>
<td>34 miles</td>
</tr>
<tr>
<td>Lake Elevation (normal pool)</td>
<td>997.1 feet (MSL)</td>
</tr>
<tr>
<td>Lake Elevation (spillway)</td>
<td>1020.0 feet (MSL)</td>
</tr>
<tr>
<td>Watershed Area</td>
<td>217 mile²</td>
</tr>
</tbody>
</table>

Table I.5.2 Physical Features of Piedmont Lake and Its Watershed

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Length</td>
<td>20,700 feet</td>
</tr>
<tr>
<td>Lake Breadth</td>
<td>6,200 feet</td>
</tr>
<tr>
<td>Maximum Depth</td>
<td>27 feet</td>
</tr>
<tr>
<td>Water Surface Area (normal pool)</td>
<td>1339.5 acres</td>
</tr>
<tr>
<td>Shoreline Length</td>
<td>34 miles</td>
</tr>
<tr>
<td>Lake Elevation (normal pool)</td>
<td>997.1 feet (MSL)</td>
</tr>
<tr>
<td>Lake Elevation (spillway)</td>
<td>1020.0 feet (MSL)</td>
</tr>
<tr>
<td>Watershed Area</td>
<td>217 mile²</td>
</tr>
<tr>
<td>Feature</td>
<td>Feet</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Lake Length</td>
<td>53,800</td>
</tr>
<tr>
<td>Lake Breadth</td>
<td>8,200</td>
</tr>
<tr>
<td>Maximum Depth</td>
<td>30</td>
</tr>
<tr>
<td>Water Surface Area (normal pool)</td>
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<tr>
<td>Shoreline Length</td>
<td>35.3</td>
</tr>
<tr>
<td>Lake Elevation (normal pool)</td>
<td>913.0</td>
</tr>
<tr>
<td>Lake Elevation (spillway)</td>
<td>924.6</td>
</tr>
<tr>
<td>Watershed Area</td>
<td>85.5 mile²</td>
</tr>
</tbody>
</table>
Figure 1.5.1 Map of Charles Mill Lake Watershed and Surrounding Area
Figure 1.5.2 Map of Piedmont Lake Watershed and Surrounding Area
II.1 Efforts to Predict Soil Erosion

Prior to the mid-1930's, efforts to predict soil erosion were not a major concern. At about this time, it became evident that fertile agricultural soil was eroded in rather vast amounts nationwide. Researchers began to contemplate consequences of such erosion and attempted to estimate the amount of soil erosion from a defined area.

Cook (1936) became one of the pioneers in an effort for predicting soil erosion. Through his analyses, Cook recognized susceptibility of soil to erosion, potential erosivity of rainfall and runoff, and effects of plant covers to soil erosion. The first equation for calculating field soil loss, which mathematically expressed the effects of slope steepness and slope length on erosion, was developed only a few years later by Zingg (1940). Smith (1941) presented factors of cropping systems and support practices applied to the previous soil loss equation, by which he used to develop a graphic method for selecting conservation practices for various soils. Browning *et al.* (1947) added soil erodibility and management factors to the equation. By preparing extensive tables of soil erodibility and management factors, Renard *et al.* (1997) emphasized the evaluation of slope-length limits for different cropping systems on specific soils and slope steepness with and without contouring, terracing, or strip cropping.
After presenting a method for estimating soil loss from fields of claypan soils, Smith and Whitt (1948) presented the “rational” erosion equation for the principal soils of Missouri as follows:

\[ A_r = C_r \times S_r \times L_r \times K_r \times P_r \]  

(II.1.1)

where \( A_r \) is equal to the soil loss per year, \( C_r \) is the average annual soil loss from claypan soils for a specific crop rotation, slope length, slope steepness, and row direction. \( S_r \) is the slope steepness, \( L_r \) is the slope length, \( K_r \) is the soil erodibility, and \( P_r \) is the support practice. The last four factors are dimensionless multipliers used to adjust the value of \( C_r \) to other conditions. Because rainfall and runoff are not considered in the equation, the estimation could not be applied to other states.

Until about 1946, the majority of soil loss estimation equations developed were for areas located in the Corn Belt of the United States. Researchers began to seek a need for equations to predict soil loss in other agricultural regions of the United States. A national committee met in Ohio in 1946 to adapt the Corn Belt equations to cropland in other regions (Wischmeier and Smith, 1978). Soil loss data from all over the United States were reviewed. After the committee reappraised the factors that were previously used, a rainfall factor was added to the equation. This equation became widely known as the Musgrave equation, which included factors for rainfall surface runoff as affected by slope steepness and slope length, soil characteristics, and vegetal cover (Musgrave, 1947). The Musgrave equation is expressed as:
where $A_m$ is the long-term average soil loss from sheet and rill erosion in inches per year, $C_m$ is the soil erodibility factor, $R_m$ is the crop-management factor, $S_m$ is the percent degree of the slope, $L_m$ is the length of the slope, and $P_{m30}$ is the 2-year, 30-minute rainfall amount. To aid in solving the Musgrave equation, Lloyd and Eley (1952) developed graphs, which were tabulated for various conditions that the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) used in the northeastern United States.

As a result of the developed soil loss equations, leading conservation researchers recommended that a national soil loss equation should be adopted. This urged the USDA Agricultural Research Service (ARS) to establish the National Runoff and Soil Loss Data Center (NRSLDC) at Purdue University in 1954 (Renard et al., 1997). The responsibilities of the National Runoff and Soil Loss Data Center were to locate, assemble, and consolidate all available data from runoff and erosion studies throughout the United States for further analysis. Federal-State cooperative research projects at 49 locations contributed more than 10,000 plot-years of basic runoff and soil loss data to this center for summarizing overall statistical analysis (Wischmeier and Smith, 1978).

Based on the information assembled by the NRSLDC, along with conclusions from deliberations of joint soil loss conferences held at Purdue University in 1956, Wischmeier, Smith, and others developed the Universal Soil Loss Equation (USLE). The USLE is (Wischmeier and Smith, 1965, 1978):

$$A_m = C_m R_m^{0.0016} S_m^{1.35} L_m P_{m30}^{1.75}$$
\[ A = R \times K \times L \times S \times C \times P \]  

(II.1.3)

where \( A \) is the average soil loss per unit area in kilograms per square meter per year. \( R \) is the rainfall and runoff erosivity factor, \( K \) is the soil erodibility factor, \( L \) is the slope length factor, \( S \) is the slope steepness factor, \( C \) is the cover management factor, and \( P \) is the support practice factor.

The USLE was first introduced at a series of workshops on soil loss prediction (Renard et al., 1997). After several years of trial use by SCS and others, improved factor values and the evaluation of additional conditions were implemented. This led to the publication of the USLE in Agricultural Handbook No. 282 (Wischmeier and Smith, 1965). Although widespread acceptance of the USLE was not immediate, it has had a tremendous impact and has become the foremost soil conservation planning tool in the United States and abroad (Renard et al., 1997).

II.2 From USLE to RUSLE

After Wischmeier and Smith (1965) first published the USLE, research into its applications never ceased. This research led to important improvements that allowed the USLE to be more widely used by providing techniques for estimating site values of its factors for additional land uses, climatic conditions, and management practices. These improvements were incorporated into an updated version of the USLE that was published in Agricultural Handbook No. 537 (Wischmeier and Smith, 1978).
Following the second publication of the USLE, additional research was conducted and completed. At a 1985 workshop, government agencies and university erosion scientists decided it was time for a major overhaul of the USLE in order to incorporate the results of erosion research to increase the versatility for applications on various non-agricultural lands (Toy et al., 1999). It was aimed to offer the technology as an integrated computer program to facilitate calculations and the examination of several soil conservation alternatives. Some of these improvements include a time-varying approach to reflect freeze-thaw conditions and consolidation caused by extraction of moisture by growing crop for the soil erodibility factor, a sub factor approach for evaluating the cover-management factor for cropland, rangeland, and disturbed areas, a new equation to reflect the slope length and steepness factors, and new conservation-practice values for both cropland and rangeland practices (Renard et al., 1997). In addition to these improvements, the computation may now be implemented using an integrated computer program. The incorporation of these new improvements resulted in the Revised Universal Soil Loss Equation (RUSLE) that was published in Agricultural Handbook No. 703 (Renard et al., 1997).

The RUSLE uses the same equation as the USLE, Equation II.1.3, to compute the average annual erosion on field slopes. The difference between the USLE and RUSLE occurs in the determination and application of the factors in the equation. A detailed explanation for each factor is presented in the following.

Since the RUSLE is widely used as an integrated computer program, the software package is continuously upgraded to incorporate new and more accurate applications.
The Soil and Water Conservation Society (SWCS) first released the RUSLE for use in late 1992 as version 1.02. Improved versions of the RUSLE were periodically released to correct errors and to give the RUSLE increased capability such as version 1.03 in 1994. Version 1.04, released in 1994, was the last version of the RUSLE distributed by the SWCS. This version incorporated improvements identified by ARS, SCS, and others for no-till, pasture, land tilled after long periods without tillage, and manure applications. These improvements were developed from analysis of a large, comprehensive database on no-till cropping and data from several locations on the effect of incorporated manure on soil loss (Renard et al., 1994).

Version 1.05 of the RUSLE was the version produced by a copyright through a Cooperative Research and Development Agreement with ARS given to SCWS, which included all releases of the RUSLE until 1996 (National Sedimentation Laboratory Web Page, 2001). Although version 1.05 was released to the SWCS, it was never sold to the public.

Version 1.06 is the current version of the RUSLE released by the ARS at no charge. This version includes computation of deposition on concave slopes, in terrace channels, and in sediment basins as a function of sediment characteristics. It can compute deposition in terrace channels as a function of the incoming sediment load and the transport capacity in the terrace channel. It computes the values for the effectiveness of ground cover based on land use, slope steepness and length, and the ratio of rill to interrill erodibility. It incorporates the computation of the slope length factor from an estimate of the ratio of rill to interrill erosion, slope steepness, and land use. It also improves
computations of the effectiveness of ground cover on steep slopes at construction sites (National Sedimentation Laboratory Web Page, 2001). This version has the capability to compute sediment delivery ratios and sediment yields as well (Toy et al., 1999).

To better understand the capabilities and improvements to each of these versions, a detailed insight into each of the factors that make up the USLE and RUSLE is included in the following. Although the determination of these factors may be modified, it is still based on rainfall and runoff erosivity, soil erodibility, slope length, slope steepness, cover-management, and support practice to compute the average soil loss per unit area.

II.2.1 R Factor

The rainfall and runoff erosivity factor, R, represents the erosivity due to the climate at a particular location. An average annual value of R is determined from historical weather records and is the average annual sum of the erosivity of individual storms. The erosivity of individual storms is computed as the product of total storm energy (E) times the maximum 30-minute intensity (I_{30}). EI is an abbreviation for energy times intensity. The storm energy value indicates the volume of rainfall and runoff, but a long, steady rainfall may have the same E value as a shorter rainfall at a much higher intensity. The I_{30} component reflects the prolonged peak rates of detachment and runoff. The product term EI is a statistical interaction term that reflects how total energy and peak intensity are combined in each particular storm. It also indicates how particle
detachment is combined with transport capacity. Using this value, the rainfall and runoff factor can be determined as (Renard et al., 1997):

\[
R = \frac{\sum_{i=1}^{n} (E I_{30})_i}{N}
\]  

(II.2.1)

where \( R \) is the rainfall and runoff erosivity factor, \( E \) is the total storm energy, \( I_{30} \) is the maximum 30-minute intensity, and \( N \) is the number of years over which the storms occur.

In order to more easily calculate the rainfall and runoff erosivity factor, Wischmeier and Smith (1965) developed isoerodent maps, which were created from 22-year rainfall records. These maps allowed users to directly acquire or interpolate rainfall and runoff values for desired study areas. The plotted lines on the isoerodent maps are called isoerodents because they connect points of equal rainfall erosivity.

**II.2.2 K Factor**

The soil erodibility factor, \( K \), is an empirical measure of soil erodibility as affected by intrinsic soil properties. The determination of the \( K \) factor is based on a unit plot of 22.1 meters (72.6 feet) long, a 9 percent slope, and is in continuous fallow with tillage performed up and down the slope (Wischmeier and Smith, 1978). For this use, continuous fallow is land that has been tilled and kept free of vegetation for more than 2
years. The K factor is influenced by the detachability of the soil, infiltration and runoff, and the transportability of the eroded soil.

The main soil properties that affect the K factor are soil texture, organic matter, structure, and permeability of the soil profile (National Sedimentation Laboratory Web Page, 2001). In general, clay soils have a low K value because they are resistant to detachment. Sandy soils have a low K value because they have high infiltration rates, and sediment eroded from sandy soils is not easily transported. Silt loam soils have moderate to high K values because soil particles are fairly easily detached, infiltration is moderate to low producing moderate to high runoff, and the sediment is fairly easily transported. Finally, silt soils have the highest K values because they voluntarily crust, which produces high runoff rates and sediment amounts. They can be detached without much effort, and result in sediment that is easily transported.

Direct measurement of the erodibility factor is both costly and time consuming, due to the various soil properties and soil interactions that affect the K factor. Representative values of K for most of the soil types and texture classes can be obtained from tables prepared by soil scientists based on the most recent research information available (Wischmeier and Smith, 1978). Values for the exact soil conditions at a specific site can be computed by the use of a soil erodibility nomograph developed by Wischmeier and associates (1971). This nomograph has become the most widely used method for obtaining values of soil erodibility.

Wischmeier and Smith (1978) developed an algebraic approximation of the soil erodibility nomograph. This approximation is represented as:
\[ K = \frac{2.1 \times 10^{-4} (12 - OM) M^{1.14} + 3.25(s - 2) + 2.5(p - 3)}{100} \]  

where \( K \) is the soil erodibility factor, \( OM \) is defined as the percent organic matter in the soil, \( s \) is the soil structure code used in soil classification, and \( p \) is the profile permeability class, and \( M \) is the product of the primary particle size fractions calculated by:

\[ M = MS \times SS \]  

where \( MS \) is the percent modified silt or the percent of soil whose diameter is between 0.002 mm and 0.1 mm and \( SS \) is the percent of silt plus sand or the percent of soil whose diameter is between 0.1 mm and 2 mm.

**II.2.3 L Factor**

As the slope length factor, \( L \), increases, the amount of erosion increases. Slope length is not the distance from the highest point in a field to the lowest point. Instead, it is defined as the horizontal distance from the beginning of overland flow to the location where (1) the slope gradient decreases enough that deposition occurs, (2) the runoff becomes a concentrated flow, or (3) the runoff enters a well defined channel such as part of a natural drainage network or a constructed grass waterway or terrace channel (Walker, 1983). According to Renard *et al.* (1997), slope lengths are generally less than 121.92 meters (400 feet). Although slopes lengths of up to 304.8 meters (1,000 feet)
occasionally exist, they should be used in the RUSLE unless the surface has been carefully graded into ridges and furrows that maintain flow for long distances (Renard et al., 1997).

The effect of slope length on annual runoff per unit area of cropland may generally be assumed negligible (Wischmeier and Smith, 1978). However, the soil loss per unit area generally increases substantially as slope length increases. The greater accumulation of runoff on the longer slopes increases its detachment and transport capacities. The type of erosion taking place on these slopes, rill or interrill, also affects the amount of soil loss taking place. Rill erosion is primarily caused by surface runoff and increases in a down slope direction due to runoff increasing in a down slope direction. Interrill erosion is primarily caused by the impact of raindrops and occurs along a uniform slope. This is the reason that soil loss tends to be greater for rill erosion than interrill erosion.

Wischmeier and Smith (1965) originally expressed the slope length factor in English units. It can be expressed in metric units as:

\[ L = \left( \frac{\lambda}{22.13} \right)^m \]  

where \( \lambda \) is the horizontal length in meters from the top of the slope to a point of concentration of the runoff and \( m \) is the variable slope length exponent. Although the value for \( m \) was originally determined from field data (Wischmeier and Smith, 1965), Foster et al. (1977) developed an equation to represent the \( m \) value as:
where $\beta$ is the value for conditions when the soil is moderately susceptible to both rill and interrill erosion. McCool et al. (1989) determined the equation for $\beta$ to be:

$$
\beta = \frac{\sin \theta}{0.0896} \frac{3.0(\sin \theta)^0.8 + 0.56}{1}
$$

where $\theta$ is the average slope of the soil from horizontal specified in degrees.

II.2.4 S Factor

The slope steepness factor, $S$, reflects the influence of slope gradient on erosion. As the slope gradient increases, the amount of runoff generally increases leading to increased erosion. This relationship is influenced by such factors as type of crop, surface roughness, and profile saturation. The slope shape also influences the amount of erosion that occurs. Slope shape is a variation of slope steepness along the slope. Soil loss is the greatest for convex slopes. Convex slopes are steep near the toe of the slope, where the runoff rate is the greatest, and gentle near the head of the slope, where the runoff rate is relatively small. Contrary to convex slopes, concave slopes experience the least amount
of soil loss. These slopes are steep near the head of the slope and gentle near the toe of
the slope.

When the USLE was first published, Wischmeier and Smith (1965) used the
following equation to calculate the slope steepness factor:

\[
S = \frac{0.43 + 0.30S_g + 0.043S_g^2}{6.613}
\]

where \( S_g \) is the slope gradient expressed as a percent. After additional research and
applications of the USLE, Wischmeier and Smith (1978) later evaluated the slope
steepness factor by the equation:

\[
S = 65.41\sin^2 \theta + 4.56\sin \theta + 0.065
\]

where \( \theta \) is the average slope of the soil from horizontal specified in degrees. The most
recent equation to calculate the slope steepness factor was published by McCool et al.
(1987). This is the equation that is currently used for determining the slope steepness
factor and is represented as:

\[
S = \begin{cases} 
10.8\sin \theta + 0.03 & \text{if } \text{slope} < 9^\circ \\
16.8\sin \theta - 0.50 & \text{if } \text{slope} \geq 9^\circ 
\end{cases}
\]
where $\theta$ is the average slope of the soil from horizontal specified in degrees. Equation II.2.9 is not applicable to slopes shorter than 4.572 meters (15 feet), so McCool et al. (1987) developed an equation to estimate the slope steepness factor for this situation to be:

$$S = 3.0(\sin \theta)^{0.8} + 0.56$$

(II.2.10)

where $\theta$ is again the average slope of the soil from horizontal specified in degrees. A final equation to determine the slope steepness factor that McCool et al. (1987) published is for slopes that have recently tilled thawing soil, in a weakened state, and subjected primarily to surface flow. This equation is expressed as:

$$S = \begin{cases} 10.8\sin \theta + 0.03 & \text{if slope } < 9^\circ \\ \frac{\sin \theta}{(0.0896)^{0.6}} & \text{if slope } \geq 9^\circ \end{cases}$$

(II.2.11)

where $\theta$ is the average slope of the soil from horizontal specified in degrees.

II.2.5 C Factor

The cover management factor, C, reflects the reduction in soil erosion contributed to the effects of cropping and management practices. It is the most easily changed factor in the USLE and RUSLE. The C factor indicates how the conservation plan will affect
the average annual soil loss. For this reason, it is the factor most often considered in
developing a conservation plan. The C factor is influenced by canopy cover, ground
surface cover, surface roughness, prior land use, root mass plus incorporated residue, soil
moisture, and expected highly erosive rainfall.

The C factor is based on the concept of an area under clean-tilled continuous
fallow conditions. Using this as a standard, the soil loss ratio is estimated as the ratio of
soil loss from actual conditions to losses experienced from the standard at a given time.
By separating the soil loss ratio into a series of subfactors, Renard et al. (1997) state that
the important parameters to consider are the impacts of previous cropping and
management, the protection offered the soil surface by the vegetative canopy, the
reduction in erosion due to surface cover and surface roughness, and in some cases the
impact of low soil moisture on reduced runoff from low-intensity rainfall. By assigning
corresponding values, each of these factors may be multiplied together to determine a soil
loss ratio. This equation is expressed as (Renard et al., 1997):

$$SLR = PLU \times CC \times SC \times SR \times SM$$  \hspace{1cm} (II.2.12)

where SLR is the soil loss ratio, PLU is the prior land use subfactor, CC is the canopy
cover subfactor, and SC is the surface cover subfactor, SR is the surface roughness
subfactor, and SM is the soil moisture subfactor. The SM subfactor is included for
analysis conducted in areas where soil moisture during critical crop periods depends on
crop rotation and management such as the Northwestern Wheat and Range Region.
The PLU subfactor expresses the influence of subsurface residual effects from previous crops on soil erosion and the effect of previous tillage practices on soil consolidation. The equation for the PLU subfactor is (Renard et al., 1997):

\[ PLU = \left( C_f \ast C_b \right)^{\frac{\left(-c_{ur}B_{ur} + \frac{c_{us}B_{us}}{C_f^2C_b}\right)}{c_{ur} + c_{us}}} \]  

where \( C_f \) is a surface soil consolidation factor, \( C_b \) represents the relative effectiveness of subsurface residue in consolidation, \( B_{ur} \) is the mass density of live and dead roots found in the upper soil layer, \( B_{us} \) is the mass density of incorporated surface residue in the upper soil layer, \( c_{ur} \) is the impact of soil consolidation on the effectiveness of incorporated residue, and \( c_{ur} \) and \( c_{us} \) are calibration coefficients indicating the impacts of the subsurface residues.

The CC subfactor expresses the effectiveness of vegetative canopy in reducing the energy of rainfall striking the soil surface. The equation for the CC subfactor is (Renard et al., 1997):

\[ CC = 1 - F_c^{-0.1H} \]  

where \( F_c \) is the fraction of land surface covered by canopy and \( H \) is the distance that raindrops fall after striking the canopy.

The SC subfactor expresses the effects of erosion as the reduction in transport capacity of runoff water and decreased surface being susceptible to raindrop impact. It is
perhaps the single most important factor in determining SLR values (Renard et al., 1997).

The equation for the SC subfactor is given as:

\[
SC = -b \cdot S_p \cdot \left(\frac{0.24}{R_u}\right)^{0.08} \tag{II.2.15}
\]

where \( b \) is an empirical coefficient, \( S_p \) is the percentage of land area covered by surface cover, and \( R_u \) is the surface roughness before tillage.

The SR subfactor expresses the effects of soil erosion and the impact on residue effectiveness due to the quantity of depressions and barriers that surface runoff must overcome. Renard et al. (1997) express the SR subfactor as:

\[
SR = -0.66(R_u - 0.24) \tag{II.2.16}
\]

where \( R_u \) is previously defined as the surface roughness before tillage.

After the SLR is incorporated with corresponding runoff and erosivity and EI values, the crop management factor may be determined. An individual SLR value is thus calculated for each time period over which the subfactors are assumed to remain constant. Once each individual SLR value is multiplied by its corresponding percentage of annual EI and summed, these values can be divided by the total percentage of annual EI value for the entire period to yield the desired value for the cover management factor. Renard et al. (1997) expressed this equation as:
where $C$ is the cover management factor, $SLR_i$ is the value for time period $i$, $EI_i$ is the percentage of the annual $EI$ occurring during that time period, $n$ is the number of periods used in the summation, and $El_i$ is the sum of the $EI$ percentages for the entire time period.

### II.2.6 P Factor

The support practice factor, $P$, is the ratio of soil loss with a specific support practice to the corresponding loss with up slope and down slope tillage. It describes the effects of practices such as contouring, strip cropping, concave slopes, terraces, sediment basins, grass hedges, silt fences, straw bales, and subsurface drainage. These practices are applied to support the basic cultural practices used to control erosion such as vegetation, management systems, and mulch additions that are represented by the $C$ factor. Improved tillage practices such as no-till and other conservation tillage systems, sod-based crop rotations, fertility treatments, and crop-residue management are additional erosion control practices considered in the $C$ factor and supported by the $P$ factor.

On relatively smooth soil surfaces, the flow of water is determined by random, down slope natural topography. This flow eventually becomes channelized leading to soil loss by rill erosion. When tillage is performed, localized channels are involuntarily created within the furrows. By immediately channelizing water as it contacts the ground, rill erosion is accelerated leading to increased soil loss. This is especially the case if the
tillage occurs up slope and down slope. Support practices typically effect erosion by redirecting runoff around the slope so that it has less erosivity or slowing down the runoff to cause deposition, using destructions such as concave slopes or barriers like vegetative strips and terraces. The major factors to consider in estimating a P factor include runoff rate as a function of location, soil and management practice, erosivity and transport capacity of the runoff as affected by slope steepness and hydraulic roughness of the surface, sediment size, and sediment density (National Sedimentation Laboratory Web Page, 2001).

When Wischmeier and Smith (1965) first published the USLE, the support practice factors used were adopted from a 1956 ARS-SCS slope practice workshop at Purdue University. The P factors were derived from consideration of available data and observations. These support practice values were developed for three types of tillage practices: contouring, contour stripping, and terracing.

In the second publication of the USLE by Wischmeier and Smith (1978), similar P values were used. The only significant difference was that the more recent factors provided more accurate estimates, which were based on addition data and observations.

Renard et al. (1997) presented P factor values for the RUSLE based on erosion theory and analysis of experimental data. The data used in their experiments are from plots, small watersheds, and solutions of equations derived from erosion theory. Renard et al. (1997) also address support practice values developed for contouring, contour stripping, and terracing. In addition to providing detailed scenarios for each of these types of tillage practices, they include methods for estimating P values for subsurfaced
drained areas and rangelands. The P factors to be described are based on experiences by Renard et al. (1997) for the RUSLE.

The basic equation to estimate the support practice, P, for contouring is:

$$P = 1 - \frac{(1 - P_b)(1 - P_m)}{1 - P_{mb}}$$  \hspace{1cm} (II.2.18)

where $P_b$ is the base value of the P factor for contouring, $P_m$ is the minimum P factor value, and $P_{mb}$ is the minimum P factor for a given ridge height with base conditions. The value for $P_b$ is described by the following:

$$P_b = \begin{cases} 
    a_p (s_m - s_c)^{b_p} + P_{mb} & s_c < s_m \\
    c_p (s_c - s_m)^{d_p} + P_{mb} & s_c \geq s_m \\
    1.0 & s_c \geq s_e 
\end{cases}$$  \hspace{1cm} (II.2.19)

where $s_m$ is the slope at which contouring has its greatest effectiveness, $s_c$ is the slope for which a value of $P_b$ is desired, and $s_e$ is the slope steepness above which contouring is ineffective. The parameters $a_p$, $b_p$, $c_p$, and $d_p$ are coefficients dependent on contour ridge height. The equation for $P_m$ may be computed by:

$$P_m = P_{mb} \left( \frac{Q_{s}}{3.72} \right)$$  \hspace{1cm} (II.2.20)
where $Q_k$ is the computed runoff amount for soil and cover management conditions, and $P_{mb}$ is the minimum P factor for a given ridge height with base conditions.

The support practice for contour stripping may be estimated by:

$$P = \frac{(g_p - B)}{g_p}$$

where $g_p$ is the sediment load that would occur at the end of slope if the strips caused no deposition and B is the amount of deposition considered to benefit the long-term maintenance of the soil resource.

Although equations for additional scenarios have been developed to estimate the support practice, they are not as significant as contouring, contour stripping, and terracing. Therefore, the final support practice is the practice of terracing, which may be expressed as:

$$P = 1 - B(1 - P_y)$$

where B is again the amount of deposition considered to benefit the long-term maintenance of the soil resource and $P_y$ is the sediment delivery ratio. $P_y$ is determined from:
where \( s_g \) is the percentage of terrace slope grade.

**II.3 Comparison of the USLE to the RUSLE**

The RUSLE is an updated version of the USLE based on analysis of research results presented by Wischmeier and Smith (1978) in Agricultural Handbook No. 537. Although the original theory behind the USLE is retained in the RUSLE, the methods for evaluating factors have been modified and new data has been incorporated with which to evaluate the factors for specified conditions. It also includes the implementation of the RUSLE through computer software. Even though the USLE is the most widely used equation for estimating soil loss, the RUSLE is scientifically based (Renard et al., 1994). As the RUSLE continues to prove its better estimating ability, it will eventually be adopted as the principle soil loss equation.

The USLE erosivity calculations in the western U.S. were based on data from only a few weather stations to develop a value for the R factor. The RUSLE incorporates the analysis of data from over 1,000 weather stations (Renard et al., 1994). In addition to increased analysis in the western U.S., the maps for the eastern U.S. were re-contoured to yield a more accurate estimation. Although the RUSLE computes higher erosivity for high-intensity storms than the USLE, the RUSLE decreases the erosivity determined by
the impact of raindrops on flat surfaces of ponded water (Renard et al., 1997). The RUSLE also includes improved procedures to account for rainfall on frozen or partially frozen soil in the Northwest Wheat and Range Region (Toy et al., 1999).

The RUSLE has the ability to account for the presence of rock fragments in the soil profile and the consolidation of soil structure due to moisture extraction of a growing crop in the months and years following disturbance for determining the soil erodibility factor, which is not included in the USLE (Toy et al., 1999). The RUSLE has been made time varying to reflect freeze-thaw conditions (Renard et al., 1997). An alternative regression equation is also included in the RUSLE to compute soil erodibility for volcanic tropical soils (Toy et al., 1999).

The USLE equations used to compute the effect of slope length on soil loss is modified in the RUSLE to reflect the differential influence of slope length on rill and interrill erosion rates by means of a rill to interrill erosion ratio (Renard et al., 1997). The equations used to compute the effect of slope steepness on soil loss are based on much larger data sets in the RUSLE than those used in the USLE. Data for computing the S factor in the USLE was taken from not more than five locations, while the data for the RUSLE was taken from 15 locations, which yields increased accuracy of the factor estimation (Renard et al., 1994).

The cover management factor for the USLE is calculated as a regional value based on seasonal soil loss ratios developed from experimental data. The RUSLE computes site-specific C values using an equation that calculates the soil loss ratio by subfactors (Renard et al., 1997). The subfactors are based on prior land use, surface cover, crop
canopy, surface roughness, and soil moisture. Calculating the C factor with the RUSLE subfactor method makes it possible to compute soil loss using basic crop data that were not available when the USLE was originally developed. The major difference between the USLE and RUSLE is the computation of the cover management factor for conservation tillage systems, and especially for no-till (Renard et al., 1994). The USLE appears to over-estimate the C factor by almost 300 percent for conservation tillage. The RUSLE uses values that have been validated against data collected from more than sixty studies, while the values for conservation tillage used in the USLE are based on data from not more than five studies (Renard et al., 1994). The RUSLE data for contouring and strip cropping is also more reliable than that used for the USLE. The contouring and strip cropping data analysis for the RUSLE are based on more than fifteen studies, while the data for the USLE are only based on five studies (Renard et al., 1994). One final improvement in the RUSLE is that it includes both time-invariant and time-variant options in determining appropriate cover management values (Toy et al., 1999). The time-invariant option is used when surface conditions remain essentially the same through time, while the time-variant option is used when surface conditions change significantly through time.

Considerable attention was devoted to the determination of the support practice values in the development of the RUSLE (Toy et al., 1999). If the P values are incorrectly used in the RUSLE, runoff might become concentrated and accelerated to result in an increase in soil loss rates. The RUSLE has expanded the support practice to consider conditions for contouring, strip cropping, terracing, and rangelands (Renard et
The RUSLE also possesses the power to accommodate changes in support practices and their effectiveness through time.

II.4 Sediment Delivery Ratio

An important new feature added to the latest version of the RUSLE is the ability to calculate the sediment delivery ratio. Wischmeier and Smith (1978) defined the sediment delivery ratio as the ratio of sediment delivered at a given location in the stream to the gross erosion from the drainage area above that location. Bayes (2000) clearly stated this as the difference between the eroded material and the material that is transported downstream. This definition is represented by the equation:

\[
\text{Sediment Delivery Ratio (\%) =} \frac{\text{Sedimentation}}{\text{Erosion}} * 100\%
\]  

(TII.4.1)

Toy et al. (1999) stated that since the sediment delivery ratio represents the proportion of suspended sediment that escapes a lake or basin and is transported downstream, it is the inverse of the trap efficiency. The trap efficiency is thus the proportion of sediment that is retained within a lake. Because the sediment delivery ratio is significantly affected by the sediment particle size and density distributions, the RUSLE calculates the sediment delivery ratio based on the sediment load, the size and density of soil particles reaching the terrace channel, and the transport capacity of the flow in the channel (Toy et al., 1999). The sediment load is a measure of the amount of
sediment being transported down slope. The sediment load is used in the RUSLE to calculate the sediment yield, which is the sediment load at the end of the slope length, at the outlet of terrace diversion channels, or at sediment basins (National Sedimentation Laboratory Web Page, 2001). The transport capacity of the terrace channel is a function of the volume and velocity of the channel flow. If the sediment load exceeds the transport capacity, the rate of deposition depends upon the size and density of the particles in transport. If the sediment is very small, the deposition will be less than if the sediment is large.

In Wischmeier and Smith’s (1978) second publication of the USLE, they discussed that available watershed data at the time indicated that the sediment delivery ratio varied as the 0.2 power of drainage area size. It was also stated that values were observed for relationships where the sediment delivery ratio varied as the 0.1 power of the drainage area size for very large areas. Although these were values were based on observations, Wischmeier and Smith (1978) concluded that the sediment delivery ratio might vary substantially for any size of drainage area. Wischmeier and Smith (1978) also concluded that the sediment delivery ratio can be drastically affected by factors such as soil texture, obstructions, vegetation, relief, erosion type, sediment transport system, stream gradients, and areas of deposition within a watershed.

An alternative method for estimating the sediment delivery ratio was developed by the Blackland Research Center (2000) located at Texas A&M University. This method is based on observations of the amount of sediment delivered and the gross erosion calculated with the USLE for several major basins throughout the continental
United States. These observations were used to develop relationships relating sediment
delivery ratio to drainage area. The relationships between sediment delivery ratio and
drainage area for these basins were graphically represented to yield a better understanding
of their interaction. The Blackland Research Center (2000) derived a mathematical
relationship between the sediment delivery ratio and drainage area from the graphing
techniques. This relationship is represented as:

\[ DR = 0.267 \times DA^{-0.2237} \]  

where \( DR \) is the sediment delivery ratio and \( DA \) is the drainage area given in square
kilometers. Although the magnitude of the values the Blackland Research Center
obtained for the sediment delivery ratio may vary from the values of the relationship
described by Wischmeier and Smith (1978), both relationships represent that the sediment
delivery ratio usually decreases with increasing drainage area.

The computer application of the RUSLE estimates the sediment delivery ratio for
two situations. The first situation calculates the sediment delivery ratio for a slope under
strip cropping based on the equation (Renard et al., 1997):

\[ P_y = \frac{g_s}{g_p} \]  

where \( P_y \) is the sediment delivery ratio, \( g_s \) is the sediment load at the end of the slope, and
\( g_p \) is the sediment load that would occur at the end of slope if the strips caused no
deposition. The second situation calculates the sediment delivery ratio under terracing based on Equation II.2.23. Although the RUSLE computer applications may yield an accurate estimation for the sediment delivery ratio, it does not take into account changes in particle size resulting from deposition in the concave segment of a hill slope or behind sediment control barriers (Toy et al., 1999). The computer application also does not account for changes in sediment particle size resulting from deposition in a series of basins (Toy et al., 1999).
III.1 Lake Sedimentation Verification

An investigation on the Charles Mill Lake Watershed utilizing ArcView GIS and the RUSLE to estimate the quantity of soil eroded from the watershed was previously conducted by Bayes (2000). This study was performed to determine if the developed method could be applied to other watersheds with varied characteristics. The Piedmont Lake Watershed was selected for the purpose of the study.

The Piedmont Lake Watershed like the Charles Mill Lake Watershed is a subwatershed of the Muskingum River Watershed. The Charles Mill Lake Watershed is 61 percent larger than the watershed of Piedmont Lake. On the other hand, the surface of Piedmont Lake is 41 percent larger in area than that of Charles Mill Lake. The relationships between each lake and its corresponding watershed were another factor that was considered. This is due to the fact that Piedmont Lake encompasses more than 4 percent of its total watershed area, while Charles Mill Lake only covers approximately less than 1 percent of its watershed. Furthermore, the terrain of the Piedmont Lake Watershed contained slopes that were steeper than those of the Charles Mill Watershed. The terrain slope plays an important role in estimating the erosion potential of the watersheds.
As was previously stated, ArcView GIS, specifically ArcView GIS 3.2®, was used in conjunction with the RUSLE to conduct this study. The Environmental Systems Research Institute, Inc. (ESRI) developed ArcView GIS 3.2® in order for users to visualize, explore, query, and analyze data geographically (Environmental Systems Research Institute, Inc., 1996). ArcView GIS is a powerful desktop GIS capable of vector and raster analysis with the Spatial Analyst and 3D Analyst Extensions (Bayes, 2000). Thus, with the necessary geographically referenced data, ArcView GIS can analyze the RUSLE to estimate erosion potential.

The vector and raster analysis is dependent on the user’s desired outcome. Vector analysis is based on manipulations of lines that represent direction and elevation. Although vector analysis is useful largely for representative purposes, it is not as powerful or accurate as a raster analysis. Raster analysis is based on the concept of raster algebra, which manipulates numerous raster images or grids by mathematical expressions. These raster images can be described as a grid of cells similar to a matrix (Jones, 1997).

III.2 GIS Watershed Data Acquisition and Analysis

Prior to conducting any data analysis, the watershed data were acquired in a geographically referenced format. The Ohio Department of Administrative Services distributes the data, in the form of USGS 1:24,000 digital quadrangle maps, for hypsography, hydrography, boundaries, roads and trails, railroads, public land survey, and miscellaneous transportation. Data were downloaded in the form of Digital Line Graphs
Since ArcView rasters could not directly recognize the DLGs, a program was used to project the DLGs into georeferenced layers, which could then be identified by the software.

III.2.1 DEM Interpolation

In order to develop a Digital Elevation Model (DEM) for the watersheds, each watershed boundary was delineated. This was accomplished using the hydrography and hypsography DLGs, which contained stream and contour data, respectively. The contour data from the hypsography DLGs were at 3.048-meter intervals, which was a satisfactory scale for use in modeling a large watershed. By delineating the watershed, a polygon representing each watershed could be displayed.

Since the DLGs were in vector format, the hypsography data were converted into raster format to create the DEM. The line vertices of these vectors were converted into points using another program within the GIS software. By using the tension model of the spline interpolator within ArcView, the point elevations were interpolated to produce a grid for each watershed.

When conducting the interpolation, the software required a grid cell size to be specified. For the purpose of comparison with Bayes’ (2000) results for the Charles Mill Lake Watershed, a cell size for 625 square meters was selected, which was the value used in Bayes’ investigation. This value is based on square grid cells that have dimensions of 25 meters by 25 meters. Bayes (2000) based his selection on two criteria. The first was
the research by Molnár and Julien (1997) and Mitra et al. (1998) who discovered that large cell sizes, such as 6 km², would underestimate soil loss. The second was based on the research by Hoover (1997) who stated that the grid memory would increase four-fold compared to a decrease of cell size by one half. Bayes (2000) stated that using a cell size of 625 square meters would not allow the memory size to be too large in order to accomplish the goal of modeling the watershed elevation with acceptable error.

With the DEM for each watershed in place, a detailed analysis of the slopes of the watersheds could be conducted to investigate the slope length and slope steepness for each watershed. With the aid of raster algebra, ArcView enables users to derive the slope for each cell of a DEM.

Throughout the history of the USLE, researchers have often experienced difficulty in estimating a slope length factor (Wischmeier and Smith, 1978). As Bayes (2000) stated, previous studies often assumed an average value for the slope length factor. In his analysis, Bayes (2000) used a value of 22.13 meters for the \( \lambda \) factor in Equation II.2.4, which is the equation used to estimate the slope length factor. This is based on the value for the standard length for testing erosion parameters (Renard et al., 1997). The value of 22.13 meters for \( \lambda \) was also used in this analysis to be consistent with the investigation by Bayes (2000). In addition the \( m \) and \( \beta \) values used to calculate the slope length factor, were computed using Equation II.2.5 and Equation II.2.6, respectively.

From the slope values derived by ArcView, they could then be used to compute a slope steepness factor for the DEM cells based on Equation II.2.9. To estimate the slope steepness factor, Equation II.2.9 depends on whether the slope is less than nine degrees or
greater than or equal to nine degrees. For this reason, the slopes values were queried to separate the slopes that were less than nine degrees from those that were greater than or equal to nine degrees. The results of these queries for Charles Mill Lake are displayed in Figure III.2.1, while the query results for Piedmont Lake are displayed in Figure III.2.2.
Figure III.2.1 Results of Slope Query for the Charles Mill Lake Watershed
Figure III.2.2 Results of Slope Query for the Piedmont Lake Watershed
Using the original topographic maps of the lakes prior to their construction, which were supplied by the Muskingum Watershed Conservancy District, the contours of each lake were digitized into vector format. Once the contours were brought into ArcView as vectors, they were converted to points in the same manner as the contours for the DEM interpolation. The points were then interpolated to create a bathymetric image of each lake.

The interpolation of the bathymetric points consisted of three different methods in order to develop a raster image that most appropriately represented the original lake contours. The three methods are identified as the tension model spline interpolation, the regularized spline interpolation, and the inverse distance weighted (IDW) interpolation. The tension model spline was the interpolation method used in the DEM interpolation, by weighing and specifying the number of sample points in each cell, to produce accurate bathymetric images. The IDW method was chosen to best represent the interpolation of the original contour lines, which was also used by Bayes (2000) for his investigation of Charles Mill Lake. The method selection was due to locations of the sample points. The data points near the shore were extremely dense compared to the rest of the data points throughout the lake, in which situation that the IDW interpolation models can do best.

Once the bathymetric images of each lake’s original topography were created, the bathymetric images of each lake’s topography in 1998 were created. The Muskingum Watershed Conservancy District supplied the data for this analysis from a survey
conducted by the U.S. Army Corps of Engineers in 1998. As a result of the survey data being obtained at different times, the data for Charles Mill Lake was supplied in point format, while the data for Piedmont Lake was supplied in vector format. The three previous interpolation methods were applied for the 1998 bathymetric analysis of each lake.

For Bayes’ (2000) analysis, as well as this investigation, the tension model spline interpolation was selected to best represent the 1998 topography for Charles Mill Lake. The data points for the surface were uniformly distributed, which was an ideal case for this type of interpolation. Since the data points were very dense, there was not a lot to interpolate between points. Thus, all three interpolation methods resulted in somewhat similar images of the 1998 topography; however, the tension model spline interpolation was more representative.

Since the data for Charles Mill Lake was supplied in point format, no conversions were required prior to conducting the interpolation. The Piedmont Lake data needed to be converted from vector format to points, which was completed in the same manner as the DEM interpolation and the interpolations of the original lake contours. Since the vectors were converted to points, the data points for Piedmont Lake were as dense and uniformly distributed as those of Charles Mill Lake. Thus, the tension model spline interpolation did not yield a representative raster image for Piedmont Lake. The data point orientation closely resembled that of the original contour data points, which were extremely dense compared to those distributed throughout the lake. This explains why
the IDW interpolation resulted in the best raster image for the 1998 Piedmont Lake topography.

Like the DEM interpolation, the bathymetric interpolations required a grid cell size to be specified. Bayes' (2000) research used a ten-meter cell size, which was also adopted for the bathymetric analysis for each lake in this study. This cell size not only yielded an accurate representation of the topography, but also satisfied the memory requirement acceptable for the study.

III.2.3 Interpretation of Soil Erosion Properties

The soil data for the Charles Mill Lake Watershed and the section of the Piedmont Lake Watershed located in Belmont County of Ohio were downloaded in digital format from the ODNR as sets of polygons with the USDA soil type as the attribute. The remaining soil data for the Piedmont Lake Watershed, in Guernsey and Harrison Counties, were obtained from the respective Soil & Water Conservation Districts. Since these soil surveys were in paper form, the data was converted into sets of polygons in digital format using ARC/INFO digitizing techniques.

Although the digital soil data provided geographically referenced polygons for each type of soil located in the watersheds, it provided little information to be used in the erosion analysis. Additional data for these soils containing information such as soil erodibility factors, moisture content, permeability, organic matter content, sieve analysis,
and other soil properties data were downloaded from the NRCS to aid in the erosion analysis.

Because each set of soil alone data have limited use, various formats of the soils data were joined in ArcView to form a spatially based polygon theme for each watershed. By extracting certain attributes from the themes, additional themes, such as soil erodibility factors and land use / land cover, were developed for the erosion analysis. The soil erodibility factors were converted from their previous forms as vector polygons into a raster format, which was consistent with accompanying watershed grids used for the analysis. The land use / land cover themes were used in coordination with the procedures developed by Wischmeier and Smith (1978) and Renard et al. (1997) to establish values for the cover management factors, which were eventually converted to raster format.

The final properties to investigate prior to the watershed modeling were the values for the rainfall and runoff erosivity factor and the support practice factor. The rainfall and runoff erosivity factors were derived by interpolating values from isoerodescent maps (Renard et al., 1997) and georeferencing the values in ArcView. Because of little variation in rainfall and runoff erosivity values over each watershed, a single factor representing the average rainfall and runoff erosivity factor was estimated for each watershed analysis. Thus, the rainfall and runoff erosivity factor used for the Charles Mill Lake Watershed was 1,889.22 MJ*mm/ha*h*y, which was consistent with the one estimated by Bayes (2000), while a value of 2,025.38 MJ*mm/ha*h*y was used for Piedmont Lake. Since no evidence of support practice or erosion control in either
watershed could be found, the support practice factor for the analysis of each watershed was assumed to be one.

III.3 GIS Watershed Modeling

With the acquisition and necessary conversions of the watershed data in GIS, the raster algebra was implemented to estimate the amount of soil loss from each watershed. This model produced an image of the annual soil loss for each watershed based on the expression:

\[ [A] = R \times [K] \times [L] \times [S] \times [C] \times P \]  \hspace{1cm} (III.3.1)

where \( A \) is the grid for the average annual soil loss, \( R \) is the rainfall and runoff erosivity factor, \( K \) is the grid for the soil erosivity factor, \( L \) is the grid for the slope length factor, \( S \) is the grid for the slope steepness factor, \( C \) is the grid for the crop management factor, and \( P \) is the support practice factor.

Investigation into the model was performed to better understand the characteristics of the watersheds. The term “erosion hot spots”, was proposed by Bayes (2000) to describe locations that have high erosion potentials within a watershed. Cumulative histograms were produced from the erosion models for each watershed. Figure III.3.1 is the cumulative erosion histogram for Charles Mill Lake, while Figure III.3.2 shows the cumulative erosion histogram for Piedmont Lake. The histograms were
Percent of Cells in Erosion Model vs. Erosion Potential Histogram for Charles Mill Lake

Figure III.3.1 Cumulative Histogram of the Erosion Model for Charles Mill Lake.
Figure III.3.2 Cumulative Histogram of the Erosion Model for Piedmont Lake.
used to locate the 50th, 75th, 90th, 95th, and 99th percentile soil loss for the watersheds.

The soil loss percentiles were used to produce raster images that present locations where the soil loss is greater than the associated values. These images were used to identify the areas where “erosion hot spots” were located, i.e. 99th percentile soil loss.

III.4 Soil Loss Factor Weighting

As mentioned, one of the objectives in this study was to verify the results of the previous investigation for soil erosion estimation in the Charles Mill Lake Watershed to determine if the method is applicable for use in other watersheds. A further study was conducted to determine if modifications on the factors of the soil loss equation could yield a more realistic model.

Three different weighting procedures were used to analyze the significance of each erosion factor. The procedures include:

- Ranking
- Rating
- Pairwise Comparison

These procedures differ in terms of accuracy, degree of easiness to use, understanding on the part of the decision makers, and theoretical foundation. The derivation of weighting procedures is a main step in obtaining the decision maker’s preferences (Malczewski, 1999). A weight can be defined as a value assigned to a factor that indicates its importance relative to other factors considered. The larger the weight being applied, the
more important the factor is relative to other factors. The weights of all factors considered are typically to sum to a value of 1.

By assigning weights to evaluation criteria, the decision maker can account for changes in the range of variation for each evaluation criterion and different degrees of importance attached to these ranges of variation (Kirkwood, 1997). A weight is dependent on the range of the criterion values. Increasing or decreasing the range can make a weight larger or smaller (Malczewski, 1999). By adjusting the weights of the soil loss factors, the range for a more appropriate average soil loss value may be determined.

### III.4.1 Weighting Equation

The initial step in applying weights to the soil loss factors was to determine how the weights would be applied. Since the average soil loss is the product of the six factors, the weights could not be multiplied by each factor individually. This would lead to a summation of the weight coefficients not equal to 1. Hence, the most appropriate way for applying weighting factors was to take the natural logarithm of the equation. The average soil loss could then be obtained by solving for the natural antilogarithm of the following equation:

\[
\ln [A] = w_1 \ln(R) + w_2 \ln(K) + w_3 \ln[L] + w_4 \ln[S] + w_5 \ln[C] + w_6 [P] \quad (III.4.1)
\]
where $A$ is the grid for the average annual soil loss, $R$ is the rainfall and runoff erosivity factor, $K$ is the grid for the soil erosivity factor, $L$ is the grid for the slope length factor, $S$ is the grid for the slope steepness factor, $C$ is the grid for the crop management factor, $P$ is the support practice factor, and $w_i$ ($i = 1, 2, \ldots, 6$) are the weights applied to the erosion factors. Equation 111.4.1 can also be expressed as:

$$ [A] = R^{w_1} * [K]^{w_2} * [L]^{w_3} * [S]^{w_4} * [C]^{w_5} * [P]^{w_6} \quad (III.4.2) $$

where the terms are the same as in Equation 111.4.1. These equations provide an applicable weighting method where $w_1 + w_2 + w_3 + w_4 + w_5 + w_6 = 1$.

The significance of each soil erosion factor was determined using multiple iterations of varying weights. By comparison of percent differences of soil loss from these iterations and comparisons of sediment delivery ratios from these iterations, the significance of each factor was evaluated so that the best weighting equation could be obtained.

III.4.2 Weighting Methods

The ranking method is the simplest method for assessing the significance of weights. These methods require all considered factors to be ranked in the order of the decision maker’s preference. Three approaches for the ranking method were examined: rank sum, rank reciprocal, and rank exponent.
The rank sum approach calculates weights according to the following equation:

\[ w_j = \frac{n_w - r_j + 1}{\sum (n_w - r_i + 1)} \]  

(III.4.3)

where \( w_j \) is the normalized weight for the \( j \)th criterion, \( n_w \) is the number of criteria being considered, \( r_j \) is the rank position of the criteria, and \( r_i \) is the rank position of the number of criteria considered.

The rank reciprocal approach is derived from the normalized reciprocal of a criterion's rank. The rank reciprocal approach calculates weights according to the following equation:

\[ w_j = \frac{1}{r_j \sum \left( \frac{1}{r_i} \right)} \]  

(III.4.4)

where \( w_j \) and \( r_j \) are defined the same as in Equation III.4.3.

The final approach for the ranking method is the rank exponent method. For this method, the decision maker is required to specify the weight of the most popular criterion on a scale of 0 to 1. The criterion weight is entered into the following equation:

\[ w_j = \frac{(n_w - r_j + 1)^{\nu}}{\sum (n_w - r_i + 1)^{\nu}} \]  

(III.4.5)
where \( w_j \) and \( r_j \) are defined the same as in Equation III.4.3 and \( p_w \) is the specified weight of the most popular criterion. From this equation, \( p_w \) can be solved by iteration and then used to calculate the weights for the remaining criteria.

The rating method is an alternative for assessing the importance of weights. It requires decision makers to estimate weights on a predetermined scale. A scale from 0 to 100 is typically used. Two approaches for the rating method were examined: point allocation and ratio estimation.

The point allocation approach is based on allocating points ranging from 0 to 100. The more points a criterion receives, the greater its relative importance. The amount of points assigned to each criterion is divided by a value of 100 to yield a ratio, which serves as the weights for the criteria. This method is relatively inaccurate and basically just a guess of the weights by the decision maker.

The ratio estimation is a modification of the point allocation approach. It uses ranking to identify the significance of the criterion. The most important criterion is assigned a score of 100, while smaller weights are assigned to the criteria lower in the order. The score for the least important criteria is divided by the scores of the other criterion. This ratio expresses the relative significance of a change from the worst level of the criterion to its best value, which is compared to a change from the worst level to the best level of the other criterion. Once this procedure has been completed for each criterion, the normalized weights are obtained by dividing each of these weights by the total.
The pairwise comparison method was the weighting procedure developed by Saaty (1980) investigating multiattribute decision making concepts. It involves using pairwise comparisons to create a ratio matrix. The weights developed in this method are determined by normalizing the eigenvector associated with the maximum eigenvalue of the ratio matrix.

The pairwise comparison method is based on a scale with values ranging from 1 to 9 to rate the preferences between two criteria. The scale for these values is presented in Table III.4.1. The scores for the pairs of each criterion are placed in the upper right corner of the pairwise comparison matrix. This matrix consists of the factor criterion placed along the first column and first row so that each criterion may be compared with one another. The pairwise comparison matrix is assumed to be reciprocal. This means that the values listed in the lower left corner of the matrix are the reciprocal of those from the upper right corner. Since a factor compared to itself is of equal importance, the entries of the diagonal are all 1. An example of the pairwise comparison matrix is shown in Table III.4.2.

Once the pairwise comparison matrix was derived, the values in each column of the matrix were summed and each element in the matrix was divided by its column total. This resulted in the creation of the normalized pairwise comparison matrix. The elements in each row of the normalized matrix were averaged to create the weights for the criteria compared.

An important feature of the pairwise comparison method is that it takes into account the consistency of the comparisons performed. The eigenvector of the
normalized matrix is calculated and used in determining the consistency index, which is a measure of departure from consistency. The consistency index is divided by the random index, the consistency index of a randomly generated pairwise comparison matrix, to calculate the consistency ratio. The consistency ratio is designed so that if it is less than a value of 0.1, there is an allowable level of consistency in the pairwise comparison. If the consistency ratio is greater than or equal to 0.1, there is inconsistency in the weighting procedure and the intensity of importance values assigned in the original pairwise comparison matrix must be evaluated again.

Table III.4.1 Scale for Pairwise Comparison

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
</tr>
<tr>
<td>2</td>
<td>Equal to moderate importance</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
</tr>
<tr>
<td>4</td>
<td>Moderate to strong importance</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
</tr>
<tr>
<td>6</td>
<td>Strong to very strong importance</td>
</tr>
<tr>
<td>7</td>
<td>Very strong importance</td>
</tr>
<tr>
<td>8</td>
<td>Very to extremely strong importance</td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
</tr>
</tbody>
</table>
Table III.4.2 Pairwise Comparison Matrix

<table>
<thead>
<tr>
<th>Criterion</th>
<th>R</th>
<th>S</th>
<th>L</th>
<th>K</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>S</td>
<td>1/3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>L</td>
<td>1/4</td>
<td>1/2</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>K</td>
<td>1/5</td>
<td>1/3</td>
<td>1/2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>1/7</td>
<td>1/6</td>
<td>1/5</td>
<td>1/4</td>
<td>1</td>
</tr>
</tbody>
</table>
CHAPTER IV
APPLICATION AND RESULTS

IV.1 Lake Bathymetric Analysis

The bathymetric images of the lakes prior to construction were developed from digitized topographic maps of the surfaces in 1934. The contours were digitized into vector format, converted to points, and interpolated using the IDW method. The result of the original bathymetric image of Charles Mill Lake is presented in Figure IV.1.1, while the result for Piedmont Lake is presented in Figure IV.1.2.

The MWCD acquired the 1998 topographic information from lake surveys conducted by the U.S. Army Corps of Engineers during the summer of 1998. These surveys were performed using two real-time kinematic Global Positioning Systems, or RTK GPS, receivers and a sonar based depth gauge. Since the data for the lakes was obtained from the MWCD at different times, the format of the data was not consistent. The survey data for Charles Mill Lake was in point format, while the survey data for Piedmont Lake was in vector format. The 1998 bathymetric image of Charles Mill Lake was created from the point data using the tension model spline technique as shown in Figure IV.1.3. The Piedmont Lake data was converted to points and the IDW interpolation method was used to create the 1998 bathymetric image as displayed in Figure IV.1.4.

With the bathymetric surfaces of the lakes in 1998 and 1934 compiled, the amount of sediment deposited over the life of the lakes could be estimated. This was
accomplished by subtracting the 1934 surfaces from the 1998 surfaces of each respective lake. The depth of sediment deposited over the life of Charles Mill Lake is presented in Figure IV.1.5, while the depth of sediment deposited over the life of Piedmont Lake is presented in Figure IV.1.6. From these results the average volume of sediment for Charles Mill Lake was estimated to be $8.67 \times 10^4$ m$^3$, while the average volume of sediment for Piedmont Lake was estimated to be $6.26 \times 10^5$ m$^3$.

The range of sediment deposition varied throughout each lake. Generally, large amounts of sediment deposition occurred in and along the original stream channel. In many cases, the sediment deposits almost, if not completely, filled the original stream channel leaving a smooth surface. Significant amounts of sedimentation were also located near the inlets of feeder streams. In Charles Mill Lake, large amounts of sediment were trapped near the eastern side of the lake. These locations were natural lakes in place prior to construction of the Charles Mill Lake Dam. Since natural lakes have lower elevations, sediment becomes trapped and settles at the lower flow velocities. The soil loss occurring along and near the banks of the lake was overlooked by Bayes (2000) in his analysis of Charles Mill Lake. Bayes (2000) neglected this soil loss and assumed the sediment depth to be zero at these locations. Hence, an average sediment depth value obtained by Bayes (2000) was actually higher than the true average sediment depth for the lake. For the purposes of comparison, both sediment loss and deposition have been considered in this study. On the other hand, the sediment from bank erosion is also evident in the analysis of Piedmont Lake. Since the occurrence of in-lake soil erosion affects the average amount of sediment deposited, it was included to better
Figure IV.1.1 Bathymetric Map of Charles Mill Lake in 1934
1934 Bathymetric Map

Figure IV.1.2 Bathymetric Map of Piedmont Lake in 1934
Figure IV.1.3 Bathymetric Map of Charles Mill Lake in 1998
Figure IV.1.4 Bathymetric Map of Piedmont Lake in 1998
Figure IV.1.5 Sediment Depth in Charles Mill Lake in 1998
Figure IV.1.6 Sediment Depth in Piedmont Lake in 1998
understand the characteristics of sediment deposition within the lake. The bank erosion could be due to many reasons including wake of passing boats and flooding.

**IV.2 Watershed Erosion Modeling**

The erosion model was developed from the factors in the USLE and RUSLE. Before the factors could be applied to the soil loss equation, a background investigation of each of these was conducted to obtain applicable values for use in the erosion model. Elements investigated included the amount of rainfall, the use of the land, the steepness and length of the slope, the soil erodibility, and the erosion prevention practices.

The rainfall and runoff erosivity factor, R, was determined by using rainfall intensity duration frequency (IDF) data from the US Weather Bureau. The IDF data was used to plot points that were connected in ArcView GIS to create isoerodent maps. These plotted lines are called isoerodents because they connect points of equal rainfall erosivity. The points were interpolated to create grids that represent values for the rainfall and erosivity factor. The variation of the R-values was extremely small over each of the watersheds due to their small size. For this reason, an average value of rainfall and runoff erosivity was estimated for each watershed. The approach of using average values could not be applied to large watersheds because the variations of the R-values would be much more significant. The average value used for the rainfall and runoff erosivity factor for the Charles Mill Lake Watershed was 1889.22 MJ*mm/ha/hr/yr, while that for the Piedmont Lake Watershed was 2025.38 MJ*mm/ha/hr/yr.
Soil information attained from the NRCS, ODNR, and county soil and water districts was used for determining the soil erodibility factors. It included organic content, permeability, and grain size distributions that could be used in Equation II.2.2 and Equation II.2.3 to calculate the soil erodibility factor. The data also supplied soil erodibility factors for each soil type, which were predetermined by experimental analysis. This eased the burden of calculating $K$ values for individual soil types. The data for the soil parameters were in tabular format and not geographically referenced. Using the joining techniques in ArcView, these tables were merged with the geo-referenced soil attributes imported into ArcView. The soil erodibility factors were then converted from vector format into raster format as the remaining modeling parameters to be used in the erosion model.

The soil erodibility factors for the Charles Mill Lake Watershed are presented in Figure IV.2.1, while those for the Piedmont Lake Watershed are presented in Figure IV.2.2. The soil erodibility factor ranges from 0.00 to 0.43 for both watersheds; however, the average value for the Charles Mill Lake Watershed is 0.3687, while the average value for the Piedmont Lake Watershed is 0.3244. This indicates that, on average, the Charles Mill Lake Watershed is more susceptible to erosion than the Piedmont Lake Watershed. These figures also express how erosion significance varies between different soil types.

With the DEM created for each watershed, the slope for each 25 m grid cell was computed using raster algebra. This enabled the slope lengths to be calculated using Equations II.2.4 through II.2.6. As was the case with Bayes’ (2000) study, all the slope length parameters were determined according to these equations except $\lambda$. The horizontal slope distance was unknown and difficult to calculate within ArcView. For the purposes
of this study, it was assumed that the horizontal slope distance was 25 meters. This assumption was made because the normal experimental value for \( \lambda \) was 22.13 meters, which is close to the grid cell sizes of 25 meters used.

The slope length factors used for the Charles Mill Lake Watershed are shown in Figure IV.2.3, and those used for the Piedmont Lake Watershed are shown in Figure IV.2.4. These factors vary throughout each watershed. The slope length factor for the Charles Mill Lake Watershed ranges from 1.00 to 1.38 with an average value of 1.065, while the slope length factor for the Piedmont Lake Watershed ranges from 1.000 to 1.094 with an average value of 1.072. Although the slope lengths for the Charles Mill Lake Watershed are higher in some locations, the overall slope length average is higher for the Piedmont Lake Watershed. These longer slope lengths for the Charles Mill Lake Watershed are due to the flat slopes.

Once the slopes were calculated, queries were performed in ArcView to find locations that had slopes less than nine degrees and those with slopes greater than or equal to nine degrees. This information was used in conjunction with Equation II.2.9 to determine the slope steepness factors. The slope steepness factors for the Charles Mill Lake Watershed are shown in Figure IV.2.5, while those for the Piedmont Lake Watershed are shown in Figure IV.2.6. The slope steepness factors ranged from 0.03 to 10.85 with an average value of 1.065 for the Charles Mill Lake Watershed. The slope steepness factors ranged from 0.03 to 11.27 with an average value of 2.575 for the Piedmont Lake Watershed. These values and figures clearly show that the slopes of the Piedmont Lake Watershed are significantly steeper than those of the Charles Mill Lake Watershed.
The cover management factor, \( C \), was developed from land use and land cover data retrieved from the EPA. The data consisted of geographically referenced information in digital format. Methods from the USLE and the RUSLE were applied to the land use and land cover data to estimate values for the cover management factor. The land use / land cover data and corresponding cover management factors were merged with the acquired soil attributes in the same manner as the soil erodibility factors. The data was then converted from vector format into raster format for use in the erosion model.

The cover management factors for the watersheds varied from 0.001 to 0.1. The values for these factors are presented in Table IV.2.1 with their accompanying land use. The various land uses for calculating the cover management factor for the Charles Mill Lake Watershed are shown in Figure IV.2.7, while those for the Piedmont Lake Watershed are shown in Figure IV.2.8.

The support practice factor is generally included to represent methods to protect against soil erosion. These may include items such as silt fencing, straw bales in ditch lines, and contour farming. Since no methods were found to protect against soil erosion in either watershed, the support practice factor was assumed to be equal to one.

Using the soil loss factors, the erosion model was developed to estimate the erosion potential for each watershed. The erosion potential for the Charles Mill Lake Watershed is presented in Figure IV.2.9, and that for the Piedmont Lake Watershed is presented in Figure IV.2.10. The average soil loss for the Charles Mill Lake Watershed was about 0.168 kg/m\(^2\) per year. It is noted that the value of 0.154 kg/m\(^2\) per year was obtained by Bayes (2000) in his study of the Charles Mill Lake
Table IV.2.1 Land Uses and Associated Cover Management Values

<table>
<thead>
<tr>
<th>Land Use</th>
<th>C Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial and Services</td>
<td>0.003</td>
</tr>
<tr>
<td>Confined Feeding Operations</td>
<td>0.100</td>
</tr>
<tr>
<td>Cropland and Pasture</td>
<td>0.050</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>0.001</td>
</tr>
<tr>
<td>Evergreen Forest</td>
<td>0.005</td>
</tr>
<tr>
<td>Forested Wetland</td>
<td>0.001</td>
</tr>
<tr>
<td>Industrial</td>
<td>0.003</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>0.003</td>
</tr>
<tr>
<td>Nonforested Wetland</td>
<td>0.003</td>
</tr>
<tr>
<td>Orchards, Groves, Vineyards</td>
<td>0.042</td>
</tr>
<tr>
<td>Other Urban or Built-up</td>
<td>0.013</td>
</tr>
<tr>
<td>Reservoirs</td>
<td>0.000</td>
</tr>
<tr>
<td>Residential</td>
<td>0.013</td>
</tr>
<tr>
<td>Strip Mines, Quarries, Pits</td>
<td>0.100</td>
</tr>
<tr>
<td>Transportation, Comm., Utilities</td>
<td>0.013</td>
</tr>
<tr>
<td>Transitional Areas</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Watershed. The average soil loss for the Piedmont Lake Watershed was 0.648 kg/m² per year. The increased erosion potential in the Piedmont Lake Watershed was expected due to its larger rainfall intensities and steeper slopes. For both watersheds, the larger erosion potentials are located in the central part of the watershed near the feeder end of the lakes.
Figure IV.2.1 Charles Mill Lake Watershed Soil Erodibility (K) Factor
Figure IV.2.2 Piedmont Lake Watershed Soil Erodibility (K) Factor
Figure IV.2.3 Charles Mill Lake Watershed Slope Length (L) Factor
Figure IV.2.4 Piedmont Lake Watershed Slope Length (L) Factor
Figure IV.2.5 Charles Mill Lake Watershed Slope Steepness (S) Factor
Figure IV.2.6 Piedmont Lake Watershed Slope Steepness (S) Factor
Figure IV.2.7 Charles Mill Lake Watershed Land Use (C) Factor
Figure IV.2.8 Piedmont Lake Watershed Land Use (C) Factor
Figure IV.2.9 Charles Mill Lake Watershed Erosion Potential
Piedmont Lake Watershed

Figure IV.2.10 Piedmont Lake Watershed Erosion Potential
compared to other parts of the respective watersheds. The areas near the lakes have rather low erosion potential.

**IV.3 Relationship Between Erosion and Sediment**

With the bathymetric analysis and erosion model completed, an investigation was performed to establish the relationship between the watershed erosion and the lake sediment. The bathymetric analysis provided depths of sediment accumulated in each lake from their construction until 1998. These sediment depths were used to estimate average sediment volumes and mass of sediment accumulated in the lakes. The erosion model also provided locations of potential soil erosion. These locations were further investigated to locate areas with high erosion potentials or “hot spots”.

The analysis of the watershed erosion models resulted in an estimated average soil loss of 0.168 kg/m² per year for the Charles Mill Lake Watershed, and 0.648 kg/m² per year for the Piedmont Lake Watershed. This means $9.44 \times 10^7$ kg of soil eroded from the Charles Mill Lake Watershed per year, and $14.4 \times 10^7$ kg from the Piedmont Lake Watershed per year. For the 63-year life of the Charles Mill Lake, it results in $5.95 \times 10^9$ kg. On the other hand, $9.19 \times 10^9$ kg was estimated over the 61-year life of the Piedmont Lake.

The bathymetric analysis results showed that Charles Mill Lake had an average sediment depth of 0.016 meters in 1998, and Piedmont Lake had an average sediment depth of 0.068 meters in 1998. Based on these results, it was estimated that Charles Mill
Lake had an average sediment volume of $8.67 \times 10^4$ m$^3$ and Piedmont Lake had an average sediment volume of $62.6 \times 10^4$ m$^3$.

The average mass of sediment per year for the lakes was determined from the following relationship:

$$V = \frac{W_s}{\gamma_d} = \frac{W_s(1 + wG_s)}{G_s\gamma_w} \quad (IV.3.1)$$

where $V$ is the volume of soil, $W_s$ is the weight of the soil, $\gamma_d$ is the dry specific weight of the soil, $w$ is the moisture content of the soil, $G_s$ is the specific gravity of the soil, and $\gamma_w$ is the specific weight of water (Das, 1994). The soil parameters used were developed from sediment sample data obtained by Bayes (2000) for Charles Mill Lake. Based on the sample data, the average specific gravity of the soils was estimated to be 3.1. From this relationship the average mass of sediment per year was estimated to be $4.27 \times 10^6$ kg/yr for Charles Mill Lake and $31.8 \times 10^6$ kg/yr for Piedmont Lake. The mass of sediment accumulated over the life of each lake was $2.69 \times 10^8$ kg for Charles Mill Lake and $19.4 \times 10^8$ kg for Piedmont Lake.

Once the erosion and sediment values were calculated, a method of comparing the parameters was adopted to determine if the models were consistent with one another. Consistency between the models was important in order to prove that the GIS watershed model was valid for accurately estimating soil loss in various watersheds. The standard adopted to identify whether the models were consistent or inconsistent was the sediment delivery ratio.
As discussed in Chapter II.4, the sediment delivery ratio is the ratio of sediment delivered at a given location in the stream to the gross erosion from the drainage area above that location (Wischmeier and Smith, 1978). This expression is presented in Equation II.4.1. The sediment delivery ratio for the Charles Mill Lake Analysis was 4.5%, while the sediment delivery ratio for the Piedmont Lake Analysis was 22.2%.

Upon investigation of the sediment delivery ratio values, the result for Piedmont Lake was immediately observed to be rather large, while the result for Charles Mill Lake was more reasonable. Comparisons of these results against sediment delivery ratio values from other sources were necessary to verify the consistency of these models.

For the purpose of comparison, the method discussed in Chapter II by the Blackland Research Center (2000) at Texas A&M University for estimating sediment delivery ratios was introduced as an independent source. The results from the Texas A&M method yielded a sediment delivery ratio of 6.48% for Charles Mill Lake and 7.98% for Piedmont Lake. By comparison, the sediment delivery ratio of 4.5% derived from the erosion model and the bathymetric analysis for Charles Mill Lake was more reasonable than that of Piedmont Lake. The Texas A&M method shows that the sediment delivery ratio derived from the erosion model and bathymetric analysis for Piedmont Lake was relatively high.

IV.4 Weighting Analysis of Soil Loss Factors

As discussed in Chapter III, weighting procedures were applied to the factors of the soil loss equation in an effort to yield more reasonable erosion results. The weighting
analysis was encouraged by the large variation in the Piedmont Lake Sediment Delivery Ratio. The thought behind these procedures was based on the idea of applying weighting methods to erosion models of other watersheds with varying characteristics that may not yield results within expected ranges. Based on the results of the Charles Mill Lake Watershed Studies and the results of the Texas A&M methods, a reasonable sediment delivery ratio range was obtained for the Piedmont Lake Watershed. From this range, a target sediment delivery ratio of 6.99% was used for the Piedmont Lake Watershed. Various weighting methods were reviewed. Several methods were largely based on the decision maker alone with little to no scientific background. For instance, the rating methods use the point allocation approach and the ratio estimation procedure. According to Malczewski (1999), these procedures have no underlying theory and are not precise. Since these procedures were strictly based on the decision makers input, the results were widely varied and produced large sediment delivery ratio values. Therefore, the rating methods were eliminated from further analysis.

The ranking methods based on approximations were found to be more dependable than the rating methods. Although the rank sum and rank reciprocal methods yielded higher sediment delivery ratio values than anticipated, they were approaching the target. The rank sum method resulted in a sediment delivery ratio of 16.94%, while the rank reciprocal method resulted in a sediment delivery ratio of 11.43%.

Although the two previous ranking methods were not as applicable as expected, the rank exponent method was extremely useful and accurate in its approximations. By the process of iterations, a p value of 2 was determined. It yielded a sediment delivery ratio of 7.04%, which was close to the target value.
The pairwise comparison method is a more scientific approach than the other methods. According to Malczewski (1999), it is based on statistical and heuristic theory, which make it quite precise. This method resulted in the sediment delivery ratio of 7.57%. The weights and methods used are presented in Table IV.4.1. As discussed in Chapter III, the consistency ratio was calculated in the analysis to determine whether a reasonable level of consistency exists in the pairwise comparisons. The consistency ratio was 0.045, which is much less than the required value of 0.10.

Table IV.4.1 Weighting Methods and Associated Values

<table>
<thead>
<tr>
<th>Method</th>
<th>R</th>
<th>K</th>
<th>L</th>
<th>S</th>
<th>C</th>
<th>Sum</th>
<th>Sediment Delivery Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rank Sum</td>
<td>0.333</td>
<td>0.133</td>
<td>0.200</td>
<td>0.267</td>
<td>0.067</td>
<td>1.000</td>
<td>16.94%</td>
</tr>
<tr>
<td>Rank Reciprocal</td>
<td>0.438</td>
<td>0.109</td>
<td>0.146</td>
<td>0.219</td>
<td>0.088</td>
<td>1.000</td>
<td>11.43%</td>
</tr>
<tr>
<td>Rank Exponent</td>
<td>0.455</td>
<td>0.073</td>
<td>0.164</td>
<td>0.291</td>
<td>0.018</td>
<td>1.000</td>
<td>7.04%</td>
</tr>
<tr>
<td>Pairwise Comparison</td>
<td>0.477</td>
<td>0.100</td>
<td>0.151</td>
<td>0.232</td>
<td>0.040</td>
<td>1.000</td>
<td>7.57%</td>
</tr>
</tbody>
</table>

Target 6.99%
CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

V.1 Conclusions

As stated in the objectives of this study, this investigation was performed in an attempt to verify the methods and results of a previous GIS watershed erosion model for the Charles Mill Lake Watershed. Using similar modeling techniques, the erosion model for this watershed was successfully reproduced. In an effort to check that the method used for the Charles Mill Lake Watershed erosion model is applicable to other watersheds, another GIS watershed erosion model was developed for the Piedmont Lake Watershed. An important feature for the verification is that the characteristics and location of the Piedmont Lake Watershed vary from those of the Charles Mill Lake Watershed.

It was found that large sediment deposits were located in and along the original main channels of the lakes. Sedimentation was also noticeable in areas with lower elevations or where natural lakes were present. Another important aspect of the lake sedimentation analysis was the fact that many shoreline areas of both lakes were experiencing bank erosion. The developed erosion models determined the erosion potential for each watershed. The erosion potentials depict that there are significant soil loss variations throughout the watersheds. Through analysis of histograms and GIS queries, areas with high erosion potentials, “hot spots”, may be identified and used for
further analysis. These areas may be analyzed in more detail with smaller grid cell sizes to yield more accurate soil loss approximations.

Investigations between the relationships of sediment and erosion amounts were conducted on the lakes to obtain sediment delivery ratios. Based on alternative studies, the sediment delivery ratio for the Piedmont Lake Watershed revealed that the amount of soil loss calculated from the erosion model was underestimated. Procedures were developed to investigate weighting factors of the erosion model based on a targeted sediment delivery ratio.

Without the use of GIS, such a study of erosion analysis would be virtually impossible. Millions of grid cells were analyzed with each one having different values. The complexity of some of the calculations used would even be impossible to perform by hand for only one grid cell. GIS also made it possible for all the information to be spatially referenced with desired datums.

The information derived from this analysis may prove useful to lake and watershed management. The bathymetric analysis can be used to identify locations where dredging activities needed. The analysis could help determine where bank erosion may occur and lead to actions to prevent further erosion. The bathymetric analysis could also be used to investigate sediment accumulation for possible remedial actions. The erosion potential estimated may be used to identify locations that are suitable for building or appropriate land uses. By minor modifications of the developed erosion model, the erosion effects of proposed land uses may be investigated prior to creating possible unwanted soil loss.
Although the developed erosion model was centered specifically on watershed analysis, it could be applied to situations where there is a potential for soil erosion. Examples of other applications may include construction, mining, reclamation, landfill design, and transportation design.

V.2 Recommendations

Additional research into the application of weighting factors to the erosion model would be beneficial for verification. Since weighting factors can vary according to the decision maker, an alternate study of the Piedmont Lake Watershed by another decision maker may yield varied results. Hence, it is recommended that the method for weighting factors should be as objective as possible.

As stated in Chapter IV, the estimation of the slope length factor, \( L \), was based on the assumption of a 25-meter horizontal slope distance. The horizontal slope distance is represented by \( \lambda \), which is defined as the length of the slope from the origin of the designated slope to the location where the soil loss is being considered. A method to determine this specific value could not be established for each grid cell, but by developing a method to calculate this value in GIS would produce a more accurate slope length factor estimate.

Due to the inconsistent formats between the two lakes as evident in the 1998 lake topographic data, the analysis of the bathymetric surfaces have introduced inconsistency. Since the data for Charles Mill Lake was obtained in point format, it produced a more accurate surface than the vector data of Piedmont Lake. When vector data is converted to
points, a larger amount of interpolation is required than when converting a mass number of points. By obtaining similar data formats, a more consistent model can be produced.

Since the erosion model was modified through the application of weighting factors for the Piedmont Lake Watershed, additional studies should be done on other watersheds with both similar and different characteristics and locations. This would substantiate the relevance of the erosion model and weighting techniques for more watershed applications. Additional investigations into the presence of bank erosion and the significance of “hot spots” may provide more understanding of the erosion occurrences.
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