University of Redlands

Modeling Soil Loss on Yap, Federated States of Micronesia, Using GIS

A Major Individual Project submitted in partial satisfaction of the requirements
for the degree of Master of Science in Geographic Information Systems

by

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August 2014

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The report of Megan Elizabeth Klein is approved.

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August 2014

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Abstract

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by

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Some of the residents of Yap State, Federated States of Micronesia have proposed the construction of a golf resort on the western side of Dalipeninaw, one of Yap's municipalities. The coast of Dalipebinaw is lined with mangrove swamps and coral reefs which support a robust marine ecosystem, an integral part of social and economic traditions on Yap. Dr. Reed Perkins, a professor of Environmental Sciences at Queens University of Charlotte, NC was interested in devising a method which would allow planners of the golf resort to compare potential soil loss values between locations under consideration for the golf resort. With the ability to model this aspect of how their decisions might affect the environment, planners can implement conservation management strategies. To accomplish this task, a tool was developed in Python which uses the Revised Universal Soil Loss Equation to calculate potential average annual soil loss in tons, using parameters specified by the user based on plans for the resort. The tool can be rerun with different parameters to compare soil loss values. It generates a raster with soil loss values and a table containing total soil loss.

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List of Acronyms and Definitions

AOI	Area of interest
DEM	Digital elevation model
FSM	Federated States of Micronesia
GIS	Geographic Information System
NDVI	Normalized difference vegetation index
NIR	Near-infrared
NRCS	Natural Resources Conservation Service
RUSLE	Revised Universal Soil Loss Equation
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
WSS	Web Soil Survey

Chapter 1 – Introduction

The importance of this project stems from an interest in conserving the vibrant marine ecosystem surrounding the island of Yap (locally referred to as Wa'ab), one of four states comprising the Federated States of Micronesia (FSM) (Figure 1-1). It has been proposed that a 27-hole golf resort be constructed near the coast of one of Yap's municipalities, Dalipebinaw. The shoreline of Dalipebinaw is lined with mangrove swamps and coral reef which support the aquatic life that has been integrated into local social and economic traditions for centuries.

Figure 1-1: Map of FSM, Yap, Dalipebinaw.

The concern of the client, Dr. Reed Perkins, is that the addition of a golf resort will increase soil erosion and consequently, the transportation of sediment into the ocean. The process of sedimentation can have adverse effects on the health of the marine ecosystem. The marine ecosystem surrounding Yap is part of what makes it a beautiful and desirable place to be; it would defeat the purpose of investing so many resources in constructing a golf resort if its presence contributed to the demise of Yap's appeal. Another reason to consider the impacts of a golf resort is that the local economy is heavily dependent on the fishing that takes place in the reefs. This project is also important from a conservation

standpoint. Without considering how our actions affect the environment, a responsibility to carry out environmentally responsible planning is not upheld.

Many factors should be considered when assessing the feasibility of the proposed golf resort; however, the objective of this project was to predict how much runoff might be generated by a golf course depending on variables such as size, irrigation, and terrain. A geoprocessing tool was developed which uses spatial data to model how a golf resort might affect the amount of runoff being deposited into the ocean along Dalipebinaw. The model was adapted from an empirical model called the Revised Universal Soil Loss Equation (RUSLE).

1.1 Client

Dr. Reed Perkins, a professor in the Environmental Science Department at Queens University of Charlotte North Carolina, was the person who pitched the idea for this project. He has been working with the Yapese since 2001 to aid in their adaption to environmental changes caused by global climate change. His work for Yap is funded in part by a three-year grant of \$150,000 from the U.S. Forest Service. Dr. Perkins, along with his American and Yapese colleagues and many of his students, have travelled to and from Yap working on projects and creating spatial data, some of which were used in this project.

Throughout the time Dr. Perkins has spent working with the Yapese, he has witnessed how global climate change has put pressure on the local food supply. Yap is trying to adapt to an increased sea level which has reduced the amount of agriculturally developed land and total crop yield. Dr. Perkins and his colleagues have focused their research on using GIS and related technologies to combat these effects, and help the Yapese maintain their traditional style of life, farming, fishing, and living off the land. For example, they're looking at data they've collected to identify suitable areas for taro beds so as to remove existing beds from exposure to the rising sea. The project discussed in this paper was also intended to aid Dr. Perkins in his efforts to preserve the traditional lifestyle of Yap.

1.2 Problem Statement

While the Yapese are interested in constructing a 27-hole golf resort, changes in land use affect the hydrologic cycle which can lead to harmful interactions with the natural environment. In an effort to implement ecologically mindful land development, the client sought a way to model how the construction of a golf resort would affect soil loss on the western side of Dalipebinaw, Yap. More specifically, he wanted to compare soil losses between various sites in consideration for the golf resort. With the ability to rank potential build sites in terms of how much soil erosion each generates, developers can implement a management practice with minimal damage to the surrounding marine protected area.

1.3 Proposed Solution

The approach to solving this problem was to develop a geoprocessing tool that utilizes a series of ArcMap tools to calculate soil loss, as an indication of how much sedimentation

would be generated. The output of this tool provides a way for its user to compare how the construction of a golf resort in one area compares to others, as well as how it compares to pre-golf resort conditions. The differences between the tool created for this project and the plethora of other soil loss calculating tools and software extensions that already exist are that it does not require the Yapese to download anything from the Internet, and it is completely customized to their area of interest, thereby reducing the number of input parameters and making it simpler to use.

The tool was designed to be run in Esri's ArcMap. It incorporates topographic characteristics, delineated watersheds, climatologic statistics, land cover, and soil erosion data to model and quantify how much runoff a golf resort would generate. Model input parameters include the slope of the land, volume of irrigation, soil type, and land cover, all of which can be changed with each execution of the tool to compare how the variables impact soil loss.

1.3.1 Goals and Objectives

In a broad sense, the purpose of this project was to help the golf resort planners select a location for the proposed golf resort with minimal amounts of eroded soil being deposited into the ocean. This objective coincides with their goal to conserve the local marine ecosystem. Specific objectives met to attain this goal included implementing the Revised Universal Soil Loss Equation (RUSLE) for the calculation of soil loss, and the development of a tool in Python that is easy to use, intuitive to its user, and provides results that are easily interpreted. Another objective pertaining to the tool was that the user could rerun the tool using any combination of parameters to assess how varying parameters affect potential soil loss values. Therein lies the tool's power to help in the decision making process.

1.3.2 Scope

The scope of this project was to create a customized tool that calculates soil loss on Yap. The client was able to provide most of the data that were required to run the tool, and anything that he was unable to provide was obtained from the Internet at no additional cost. Metadata associated with data received from the client were not always thorough, thereby restricting the credibility of the results of this project. In some cases the method of collection was left out, or the source was not credited.

The study area consists of seven contiguous watersheds that lie either entirely or partially in Dalipebinaw, a municipality in the central region of Yap proper's west coast (Figure 1-2). The study area was determined by a set of criteria which was provided by the client regarding the potential location of the proposed golf resort:

- In the municipality of Dalipebinaw
- Approximately west or northwest of Colonia (the state capital)
- Upslope of the main road that lies along the west side
- Approximately 1 km² in total area

Figure 1-2: Project site in Dalipebinaw, Yap.

Because the client was interested in assessing how the golf resort was going to affect the marine environment, watersheds which met the aforementioned criteria were selected to comprise the study area for this project. That is not to say that the golf resort will not have harmful effects on other water systems on the island; however, the scope of this project was concerned with the impact of runoff on marine aquatic life. The study area is approximately 6.8 km².

1.3.3 Methods

The steps taken to complete this project can be classified into three categories: research and design, data procurement, and implementation. These stages were not carried out sequentially, and development in one area would often lead to revision of the others (Figure 1-3). The process began with the client providing all data to which he had access.

Data provided by the client included 556 MB of shapefiles and an orthorectified WorldView-2 satellite image of Yap.

Figure 1-3: Project phases.

The research and design phase consisted of a literature review of popular soil loss, erosion, and sediment yield models. Based on what data were obtained from the client and a survey of data available on the Web, it was determined that the Revised Universal Soil Loss Equation was best suited to make optimal use of available data.

Development of the tool was done using Esri's ArcMap. User input includes the feature class which represents the boundaries of the area of interest, and parameters such as volume of irrigation, type of soil, average slope of the land, and land cover, all of which can be changed with each execution of the tool in order to compare how the variables impact potential soil loss. The tool carries out a series of raster calculations to determine mean annual soil loss caused by the proposed golf course and the output include a raster with values representing mean annual soil loss and a table with the sum of all raster values, representing total predicted soil loss. The completed tool and all necessary data were packaged together into a project folder and delivered to the client. Specific information on how the tool calculates soil loss can be found in Chapter 4.

1.4 Audience

The intended audience for this project is the client, Dr. Reed Perkins, and the people on Yap who will be analyzing the suitability of golf resort locations in Dalipebinaw. This may include government representatives, conservationists, local residents, and developers. Yap has a small number of people who work with GIS data and related technologies. Dr. Perkins is the liaison who will be distributing this tool to those on Yap who need it.

1.5 Overview of the Rest of this Report

The following chapter provides a summary of relevant information gathered from the literature review conducted in preparation for this project. Chapter 3 features information regarding requirements and project planning. For detailed information about the data used, and the design of the database, refer to Chapter 4. It includes illustrations of the conceptual and logical data models, and an in-depth discussion of the attainment and preparation of the data. Chapter 5 addresses the project implementation, and includes

information and diagrams regarding the workflow. A discussion of the results can be found in Chapter 6, and conclusions and recommendations for future work in Chapter 7.

Chapter 2 – Background and Literature Review

In order to address the client's need to predict soil loss from a potential golf resort, a literature review was conducted which included a review of commonly used erosion models. The model decided upon for the purpose of this project was the Revised Universal Soil Loss Equation (RUSLE). This model is widely applied and is easily adapted to a GIS framework. It also made good use of the data available for this project, which is why it was selected. The following sections provide an introduction to the RUSLE and the methods it employs for calculating soil loss.

2.1 Revised Universal Soil Loss Equation

The Revised Universal Soil Loss Equation (RUSLE) is an empirical erosion model that was designed to calculate long-term average annual soil loss from rill and interill erosion caused by rainfall and overland flow for conservation and water management planning. The factors used in the calculation take into consideration climate, soil properties, topography, land cover, and land support practices. It is a revised version of the Universal Soil Loss Equation (USLE) that was published in the USDA Agricultural Handbook No. 537 in 1978 (Renard, Foster, Weesies, McCool, & Yoder, 1997). Some of the improvements made to the RUSLE from the USLE include the automation of calculations through the use of computers, accounting for seasonal variation in soil erodibility factors, new algorithms for calculating topographic factors, and a larger database from which factors are derived (Renard, Foster, Yoder, & McCool, 1994). While the USLE was originally designed for agricultural purposes within the contiguous United States, the handbook does state that it can be used for purposes other than agriculture (such as construction) and can be applied to any area for which the appropriate data is available (Wischmeier & Smith, 1978).

Millward & Mersey (1999) adapted the RUSLE to calculate potential soil loss in the Sierra de Manantlán Biosphere Reserve in Mexico for conservation planning purposes. Their study site was located in a mountainous region with tropical weather patterns. In order to facilitate the calculation, their data were integrated into a GIS. The results of their study were two rasters with soil loss classes ranging from minimal to extreme. One raster was calculated from data reflecting the project site wet season, and the other from the dry season. Results showed that extreme soil loss only occurs during the wet season. Land managers can use this information to plan accordingly. In a project conducted by Kouli, Souplos, and Vallianatos (2008), the RUSLE was used to predict soil loss on Chania, Northwestern Crete, an agriculturally developed island in Greece. The calculations were also carried out using GIS software. Their results indicate that the highest soil loss values are spatially correlated with high slope steepness factors. The authors of this report hoped the results of their study would attract the attention of local policy makers to attempt to reduce erosion.

2.2 RUSLE Factors

In order to model erosion, it is essential to have an understanding of the underlying processes. USDA Agricultural Handbook No. 703 includes the following equation to represent the processes involved in erosion and sedimentation by water, upon which the USLE is based:

$$E = f(C, S, T, SS, M)$$

where:

E = erosion

f = function of ( )

C = climate

S = soil properties

T = topography

SS = soil surface conditions

M = human activities

From this conceptual model of erosion processes, the USLE & RUSLE are expressed as:

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

where:

A = average soil loss per unit area based on units used for K and time period used for R.

R = rainfall-runoff erosivity factor (commonly referred to as rainfall erosivity factor), a rainfall erosion index plus a factor for any substantial runoff caused by snowmelt.

K = soil erodibility factor, the soil loss rate per erosion index unit for a particular soil type, as measured on a standard plot that is 22.13 meters long with a uniform 9% slope in continuous clean-tilled fallow.

L = slope length factor, ratio of soil loss from the project site slope length to soil loss from a 22.13 meter site under the same conditions.

S = slope steepness factor, ratio of soil loss from the project site's slope gradient to soil loss from a site with a 9% slope and otherwise identical conditions.

C = cover management factor, ratio of soil loss from an area with specified cover and management to soil loss from an identical site in continuous tilled fallow.

P = support practice factor, ratio of soil loss with a support practice to soil loss with straight-row farming up and down the slope.

These specifications of a standard plot are somewhat arbitrary; 9% was chosen because that is what many early models used, and 22.13 meters was chosen because that is one hundredth of an acre plot that is two rows (1.83 m) wide. The definitions of each of the RUSLE factors are summarized in Table 2-1 (Renard, Foster, Weesies, McCool, & Yoder, 1997).

Table 2-1. Summary of RUSLE factors.

RUSLE Factor	Summary	Dimensions
Soil loss (A)	Soil loss	$\frac{\text{mass}}{\text{area time}}$
Rainfall erosivity (R)	Rainfall erosion index	$\frac{\text{length force length}}{\text{area time time}}$
Soil erodibility (K)	Rate of soil loss per erosion index unit on 22.13 m site with 9% gradient	$\frac{\text{mass area time}}{\text{area length force length}}$
Slope length (L)	Soil loss from site : soil loss from 22.13 m of same site	$\frac{\text{length}}{\text{length}}$
Slope steepness (S)	Soil loss from site : soil loss from same site with a 9% gradient	none
Cover management (C)	Soil loss from site : soil loss from same site under tilled continuous fallow	none
Support practice (P)	Soil loss from site : soil loss from same site with straight-row farming	none

The following sections describe each factor in more detail, and the reasoning behind the methods used in this project to calculate each factor.

2.2.1 Rainfall Erosivity

The rainfall erosivity factor is based on the fact that if all variables are held constant except for rainfall, soil loss is directly proportional to the total energy of a storm (E) multiplied by its maximum intensity that occurred within a 30 minute period (I_{30}). Historically, it was believed that small and moderately sized storms did not significantly affect long-term soil loss; however, recent long-term studies have discredited this assumption. When calculating the rainfall erosivity factor, the relatively less intense storms are incorporated as well as the strongest ones (Renard et al., 1997). That is an important concept for this project, because, in order to account for the contribution of irrigation to soil loss, individual irrigation events were factored into the rainfall erosivity factor as small storms (Appendix C).

A number of equations have been developed to model the relationship between the energy and intensity of a storm for determining R factor; the version used to calculate rainfall erosivity on Yap is:

$$\text{Storm EI}_{30} = [\sum 1099 \times (1 - 0.72 \times e^{(-1.27 \times I_r)}) \times R_r] \times I_{30}$$

where:

Storm EI₃₀ = storm erosion index

I_r = intensity (in/hr)

R_r = rainfall amount during same time interval (in)

I₃₀ = maximum 30 minute intensity during storm

To calculate Storm EI₃₀, the storm intensity (I_r) and amount of rainfall (R_r) for a given interval are plugged into the following portion of the equation:

$$\text{Interval E} = [1099 \times (1 - 0.72 \times e^{(-1.27 \times I_r)}) \times R_r]$$

This calculates the energy associated with that time interval. The sum of all interval energies is equal to the total storm energy (E).

$$E = \sum \text{Interval E}$$

The total storm energy is then multiplied by the max 30 minute intensity (I₃₀) that occurred throughout the whole storm to calculate storm erosion index.

$$\text{Storm EI}_{30} = E \times I_{30}$$

The University of Guam Water and Environmental Research Institute (WERI) published a report in which they calculated an annual rainfall erosivity factor for Yap of 970.55 hundreds of foot-ton inches per acre-hour. This calculation was based on rainfall data collected from the Yap Weather Station Observatory from the years 1985 – 1999. Based on the data used, the estimated average annual rainfall on Yap is 122.74 inches (Khosrowpanah & Heitz, 2001).

There is a suggested method for correcting the R factor for topographic variation by accounting for the fact that rainfall causes less erosion on smaller slopes. In flat areas, pooled water absorbs the energy transferred from rainfall thereby reducing erosion. Due to a lack of data, this correction was not considered in this project. This correction is not commonly applied in other applications of the RUSLE. For more information on the correction, refer to Chapters 2 and 6 of USDA Agricultural Handbook No. 703 (Renard et al., 1997).

2.2.2 Soil Erodibility

The soil erodibility index measures how susceptible a particular type of soil is to being dislodged and transported by water, based on a number of characteristics. Mathematically, it represents the change in soil following the application of some amount of energy. There are three methods used to calculate soil erodibility, measurements taken directly from natural runoff plots, rainfall simulations, and predictive models. Direct measurements are the most accurate, and have the following three requirements in order to assure the most accuracy: a sufficient amount of records spanning a long period of time (20-22 years for the eastern US), a fallow plot that has been tilled just prior to and throughout the study (to remove post-cropping plant residue), and finally the test site

must be in accordance with the standardized topographic criteria of 22.13 meters long and a 9% gradient (Renard et al., 1997).

Methods for determining soil erodibility seek to incorporate properties and interactions that are very complex. Different methods have been developed to express erodibility; however, the most common method is through the use of a nomograph which plots the following five variables: percent modified silt, percent modified sand, percent organic matter, structure class, and permeability class. Lines on the nomograph are calculated using the following equation:

$$K = \frac{[2.1 \cdot 10^{-4}(12 - OM) M^{1.14} + 3.25(s - 2) + 2.5(p - 3)]}{100}$$

where:

OM = percent organic matter

M = product of primary particle size fractions: (percent modified silt) · (percent silt + percent sand)

s = structure class

p = permeability class

While this equation is used most frequently, it is not the only equation used to calculate erodibility and it is important to select the model which is best-suited for the soil type in question (Renard et al., 1997).

Another consideration for soil erodibility is the presence of rock fragments and biomass which reduce erosion by blocking soil from rainfall. This effect can be accounted for either in the cover management factor, or the soil erodibility factor (Renard et al., 1997). In this project, surface cover was not considered in the calculation of the cover management factor (see Section 2.2.4) so a K factor adjusted for surface cover by incorporating the whole soil (including all fragments) was used to account for the presence of rock fragments, and any other nonerodible material inhibiting soil erosion. Chapter 5, Section 5.2.2 provides an explanation of how K factors were obtained for this project.

2.2.3 Slope Length and Steepness

The effects of topography on erosion are accounted for in the slope length (L) and slope steepness (S) factors which are referred to in the literature collectively as the slope length (LS) factor. Slope length (L) is defined as the horizontal distance from the start of runoff to the point where either one of two things happens: either the location where soil particulate transportation has ended and deposition has begun, or where runoff has accumulated into a channel. When deriving slope length from a contour map, it is important to have enough detail to capture all places at which accumulation concentrates and slope length ends.

The equation for calculating slope length is:

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

where:

L = slope length factor

= horizontal distance of slope length in meters

m = the ratio of rill erosion to interrill erosion ( ) plugged into the following equation (Renard et al., 1997):

$$m = \frac{\beta}{1 + \beta}$$

A version of this slope length equation which was adapted for use in a GIS was selected for use in this project. That equation is:

$$L = \left(\frac{A \cdot \text{cell size}}{22.13} \right)^{0.4}$$

where A is equal to flow accumulation (Lim, Sagong, Engel, Tang, Choi, & Kim, 2005, Moore, & Wilson, 1992). ArcMap provides a tool which calculates flow accumulation from a digital elevation model, and the output is a raster whose cell values are the number of cells that flow into that cell. Chapter 5, Section 5.2.3 details how slope length factor was calculated for this project.

The next component in the LS factor is slope steepness (S) which has been documented as having a greater impact on soil loss than slope length. The S factor is a ratio of soil loss from the project site to soil loss from the exact same site with a uniform 9% grade. It is calculated using the following formulas:

$$\begin{aligned} S &= 10.8 \sin\theta + 0.03 && \text{if slope} < 9\% \\ S &= 16.8 \sin\theta - 0.5 && \text{if slope} \geq 9\% \end{aligned}$$

However, if the slope length is less than 15 feet, the following equation is used instead (Renard et al., 1997):

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

Similarly to the equation used to calculate slope length (L), slope steepness (S) was calculated based on a simplified version that was adapted for use in a GIS. The equation used was:

$$S = \left(\frac{\sin\theta}{0.0896} \right)^{1.3}$$

where θ is equal to slope angle, in degrees (Lim et al., 2005).

2.2.4 Cover Management

The cover management factor was included in the RUSLE to account for the effect of cropping management on soil loss potential. It is a ratio of soil loss under a certain crop management system to the same site under clean-tilled unsown conditions. The C factor is comprised of five subfactors: previous land use (PLU), vegetative cover (CC), surface cover (SC), surface roughness (SR), and in some cases, the effect of soil moisture on runoff from low-intensity rainfall (SM). It is expressed as the following:

$$C = \text{PLU} \cdot \text{CC} \cdot \text{SC} \cdot \text{SR} \cdot \text{SM}$$

Depending on how frequently the cover management conditions change, the C factor may need to be calculated on a varying temporal scale (i.e. with every seasonal crop rotation). However, if the conditions are not changing in short periods of time, it is

sufficient to use an average annual C factor (Renard et al., 1997). For this project, average annual C factors were used due to insufficient data to allow otherwise.

The method used to calculate the cover-management factor is a more recently developed technique than the series of calculations described in the Agricultural Handbook No. 703. It involves a remote sensing technique using satellite images to calculate a vegetation index called the normalized difference vegetation index (NDVI) which is rescaled into C factor values. NDVI measures the density and intensity of greenness of an area. Plant material contains pigments which absorb wavelengths in the red band and reflect those in the near-infrared band. Values range from -1 to 1 where the lower the value, the less green present (indicating the absence of biomass) and the higher the value, the more green in an area. Uncovered soil exhibits values around 0 while water exhibits values closer to -1 (Karaburun, 2010). The equation used to calculate NDVI:

$$NDVI = \frac{RR_{NIR} - RR_{Red}}{RR_{NIR} + RR_{Red}}$$

where:

RR_{NIR} = relative reflectance of the near-infrared band

RR_{Red} = relative reflectance of the red band

After calculating NDVI, a rescaling method was applied which has been specifically recommended for generating C factor values in tropical areas which experience heavy rainfall (Durigon, Carvalho, Antunes, Oliveira, & Fernandes, 2014). The equation used to rescale NDVI is:

$$C = \left(\frac{-NDVI + 1}{2} \right)$$

This method accounts for the effect of the vegetative canopy on potential rainfall. The canopy acts as a barrier through which rainfall does not have access to the soil thereby reducing erosion (Durigon et al., 2014). It accounts for the vegetative cover subfactor described above in calculating C factors. In this project surface cover was accounted for in the soil erodibility factor by using a whole soil K factor which is adjusted for the presence of rock fragments covering the soil. Surface cover and roughness reduce erosion by shielding soil from rainfall, creating absorptive pools, and inhibiting transport capacity (Renard et al., 1997). Insufficient data regarding prior land use, surface roughness, and soil moisture meant they were not considered in the generation of C factors.

2.2.5 Support Practice

The support practice factor measures the effect of modifications made by humans to the terrain. Typically this refers to modifications made for agricultural purposes with the intent on reducing erosion. Examples of support practices include contouring, stripcropping, terracing, and subsurface draining (Renard et al., 1997). In applications of the RUSLE for which support practices are either unknown, or not taking place, it suffices to set the support practice factor equal to 1 (Kouli, Souplos, & Vallianatos, 2008, Millward & Mersey, 1999). That approach was taken for this project due to a lack of information regarding support practices in the project site.

2.3 Summary

The Revised Universal Soil Loss Equation is a well-supported scientific measure of soil loss caused by rainfall and overland flow. According to this model, soil loss is the product of six factors, rainfall erosivity, soil erodibility, slope length and slope steepness, cover management, and support practices. While it does have its limitations such as inability to account for temporal variation, new methods for integrating the model into a GIS framework have emerged, making it a simple to use, and convenient tool for estimating soil loss for conservation planning.

Chapter 3 – Systems Analysis and Design

This chapter addresses the initiation and design of the project. It outlines the series of steps taken in order to assure the needs of the client were met and the problem was solved. These steps included a careful analysis of both functional and non-functional project requirements (Section 3.2), a system design that was appropriate for the end user (Section 3.3), and a project plan that was suitable for the client (3.4). Section 3.4 also includes a review of deviations from the initial plan that occurred throughout the project lifecycle.

3.1 Problem Statement

The residents of Yap have proposed the construction of a 27-hole golf resort on the western side of Dalipebinaw, one of Yap's municipalities; however there is concern that the resort will contribute a harmful amount of runoff into the coral reef and mangrove ecosystems that exist along the coast. There is concern that deposition might lead to degradation of the coral reefs, or other detrimental effects on aquatic life. The planners responsible for deciding where to build the golf resort need a way to compare potential soil loss between locations under consideration so that its presence has as little impact on the marine life as possible.

3.2 Requirements Analysis

Table 3-1 summarizes the functional and non-functional requirements for the project. The most important functional requirement for this project, per the client's specification, was to provide a way for developers to compare soil losses between sites in consideration for the golf resort. Based on the decisions to create a tool and employ the RUSLE within a GIS framework, additional requirements were that rasters containing RUSLE variables would need to be created and used to calculate the RUSLE. In order for the tool to be useful, an additional requirement was that the results needed to be presented in an easily interpreted format. Therefore, the output of the tool should provide the user with both a raster quantifying soil loss and a table which lists average annual soil loss for the whole area, based on user-specified parameters.

Table 3-1. Project functional and non-functional requirements.

Functional Requirements	Non-Functional Requirements
Provide a metric by which potential soil loss can be evaluated	Esri's ArcMap
Be able to handle unspecified parameters	Spatial Analyst extension
Generate raster based on hypothetical user-specified variables	Revised Universal Soil Loss Equation
Multiply all rasters involved in RUSLE to calculate average soil loss	User-defined golf resort boundaries
Display results in a way that is meaningful and intuitive	User-specified variables of the RUSLE

The non-functional requirements (those that were not carried out by the tool itself) include the software required to execute the tool (Esri's ArcMap), implementation of the RUSLE, and user-defined variables pertaining to the AOI. Such variables include the boundaries of the AOI, how much water will be used to irrigate the land, what the average slope will be, and what type of soil and vegetation will be in the area.

3.3 System Design

A system was designed to address the specific needs of the client as shown in Figure 3-1. There are seven components in the system. The core component is the soil loss tool that uses information input by the user about a potential build site for a golf resort and calculates how much soil would be lost as a result of its presence with respect to rill and interrill erosion. In order to complete the calculation, all variables of the RUSLE erosion model should be prepared in a raster format for use as default input data.

Figure 3-1: System architecture.

All of the data needed to calculate the RUSLE should be bundled and delivered in a file package along with the tool so that the least amount of input is required of the user to generate results. In order for the user to run the tool, they need ArcMap installed on their local machine, the file package containing the tool and a raster for each of the RUSLE variables, and data regarding the potential location of the golf resort. The output of the tool includes a raster with values representing soil loss, and a table containing the sum of all raster values, representing total potential soil loss.

3.4 Project Plan

The life cycle of this project was managed using the agile methodology, which consisted of numerous iterations of meetings with the client and advisor followed by modifications to the project plan. An example of when this turned out to be a beneficial approach to managing this project was after the client updated the scope of the project. Initially, the client had proposed that this project consist of a site suitability analysis for the relocation of crop fields to areas of relatively high elevation so as to avoid salinization and erosion from an increasing sea level. The rising sea is causing a reduction in Yap's crop yield and needs to be addressed; however there is concern that runoff from relocated agriculturally developed land will harm the surrounding marine environment. The client was interested in identifying locations on the island which were suitable for farming and would not generate a harmful amount of runoff into the ocean. However, upon hearing that the Yapese had proposed the construction of a golf resort in Dalipebinaw, the scope of the project was updated to modeling soil loss for potential build sites.

In the initial project plan, less time was budgeted for research than was actually required. Because of the complicated nature of describing hydrologic systems, the lack of data available for Yap, and the difficulty associated with applying RUSLE variables derived from farmland to tropical environments, it took much longer to adapt an empirical model to Dalipebinaw than what had been anticipated. In order to mitigate the risk of having a poorly designed model, a lot more time was spent studying examples of implementation of the RUSLE in climates similar to that of the project site. Unlike the research and design phase of the project plan, data procurement and implementation did not waiver from the amount of time that was projected during project planning.

The project plan was designed to follow the workflow shown in Figure 3-3. After the necessary data were collected and prepared, the analysis and construction of the tool began. The project site was established based on the information provided by the client regarding the location of the golf resort, the RUSLE factors were derived (except for support practice which was considered equal to 1 for this project) a script was written in Python which was imported into ArcMap and configured into the Calculate Soil Loss tool. The finished tool underwent a series of tests, after which was delivered to the client.

Figure 3-3: Project implementation process.

3.5 Summary

The client wanted a way to compare soil losses between potential golf resort build sites. The solution needed to be operable in ArcMap, and use specifications of the planned golf resort to quantify how much soil would be lost in the event that the golf resort is constructed accordingly. The tool uses the Revised Universal Soil Loss Equation to compute soil loss and generates both a raster displaying soil loss intensity as well as a table which lists the average annual soil lost in tons, based on the planned specifications. The system requires that the user have Esri's ArcMap installed on their local machine, as well as the file package containing the tool and all necessary data. The user then inputs the boundaries of their area of interest along with variables used to calculate soil loss, from which the tool creates the outputs and stores them to a location specified by the user.

This project was conducted in an agile management style with consistent input from the client and advisor. Revision of the methodology was fairly frequent due to complications that arose, mostly having to do with generating appropriate variables for the RUSLE. While the equation itself is straightforward and there are an abundance of examples of uses of the RUSLE available in academic literature, it is imperative to use the correct data for the calculation, and obtaining these data was not as easy as originally thought. Therefore, more time was spent deriving RUSLE variables than had been budgeted in the initial project plan.

Chapter 4 – Database Design

In order to implement the system architecture, a sound database design was required. Database design choices made were based on project requirements, and the methods used during project implementation. Section 4.1 shows the conceptual data model and how the data are related with respect to this project. The logical data model is discussed in Section 4.2 and shows how data were organized and in what format it was used during implementation. Section 4.3 details from where and how data were obtained, and 4.4 discusses preparation of data for implementation.

4.1 Conceptual Data Model

The conceptual data model for this project reflects the objects that are related to soil loss, and the relationships between featured objects with respect to the scope of this project (Figure 4-1). Based on the RUSLE, the objects influencing soil loss include land cover, topography, and precipitation. Vegetation is a unique subclass of land cover that makes up the majority of land cover in the project site and prevents soil loss by shielding the soil from precipitation. Watersheds delineate a network of channels atop topography through which precipitation transports dislodged soil particulates toward the coast. Precipitation promotes vegetation since plants are dependent on water for survival.

Figure 4-1: Conceptual Data Model.

4.2 Logical Data Model

Based on the conceptual model, an Esri file geodatabase was chosen to store all data (Figure 4-2). As shown in Table 4-1, there are four raster datasets included in the geodatabase, a soil erodibility factor (K factor) raster, a slope length and steepness (LS factor) raster, a slope length (L factor) raster, and a cover management (C factor) raster which includes the locations of present vegetation types. Table 4-2 lists the two tables that are included in the geodatabase, one containing the K factor values and another containing the C factor values.

Figure 4-2: Raster and tabular data in project geodatabase.

Each raster in the geodatabase stores values which are used in the computation of potential soil loss by the Soil Loss Calculation tool created for the client. The four rasters were projected into the Universal Transverse Mercator coordinate system in zone 54 North based on the World Geodetic System 1984. The unit used in this coordinate system is meters, which coincides with the data.

Table 4-1. Raster datasets contained in project geodatabase.

Raster Datasets			
Name	Pixel Type	Cell Size (m)	Spatial Reference
K Factor	Floating point	5 x 5	UTM, Zone 54N, WGS84
LS Factor	Floating point	10 x 10	UTM, Zone 54N, WGS84
L Factor	Floating point	10 x 10	UTM, Zone 54N, WGS84
C Factor	Floating point	2 x 2	UTM, Zone 54N, WGS84

The tables in the geodatabase are the soil erodibility and cover management values. The reason for including these tables is so that the tool can retrieve the RUSLE factor value associated with user-specified soil type and land cover parameters. The values stored in the tables can be accessed by the user should they ever desire to append the data to include new categories.

Table 4-2. Tables contained in project geodatabase.

Tabular Data		
Name	Fields	Data Type
K Factor	SoilType	Text
	Kfactor	Double
C Factor	VegType	Text
	Cfactor	Double

4.3 Data Sources & Collection Methods

Table 4-3 summarizes the data used in the project and the sources from which they were collected. Data needed to determine the project site were provided entirely by the client. Of the 36 shapefiles transferred, municipal boundaries, watershed boundaries, roads, and villages were used to determine the site. The municipal boundaries, roads, and villages shapefiles were originally created by manual digitization based on a 1983 USGS Quad Map. Municipal boundaries and roads have since been verified in the field using differential GPS. The watershed boundaries were drawn by Dr. Perkins using ArcView 8.3 based on a 30 meter USGS DEM and were intended to be “useful approximations” as per the author. Other data provided by the client used for analysis were the eight band WorldView-2 satellite image, one meter elevation contour lines, and vegetative cover. The contour lines were from a 30 meter USGS DEM and were created in ArcView 3.2. The vegetation layer was based on a US Forest Service vegetation classification map, and was created by unnamed people working on behalf of Queens University of Charlotte, NC. All other data used were obtained from sources other than the client.

Table 4-3. Data Sources.

Component	Data Name	Obtained From	Original Source(s)
Project Site	Municipality boundaries Watershed boundaries Roads Villages	Client	Vector layers digitized from USGS DEMs and Quad Maps
Rainfall Erosivity	Rainfall erosivity value	Internet	WERI University of Guam
Soil Erodibility	Soils K factor values	Internet	USDA NRCS WSS
Slope Length	1 m contours	Client	USGS DEMs & Quad Maps
Cover Management	Satellite containing red & NIR bands	Client	WV-2 Satellite Image
	Vegetation		USFS vegetation map

Soil data were acquired using an online tool called the Web Soil Survey (WSS), maintained by the USDA's Natural Resources Conservation Service. The WSS provides both the vector data representing the classification and location of each type of soil present in the project site. It also generates a report featuring the whole soil K factor value for each type of soil. The average annual rainfall erosivity factor and the equation from which it was derived were obtained from a report published by the Water and Environmental Research Institute at the University of Guam.

4.4 Data Scrubbing and Loading

Fortunately, the data used in this project did not require a particularly large amount of time for preparation. Aside from needing to be clipped to the project site and projected into the appropriate coordinate system, there was little else required to prepare the data. According to Tomlinson (2011), there are four types of error associated with geographic data: referential, topological, relative, and absolute. The type of error most likely associated with the data used for this project is absolute, which refers to error in something's true position in the world. The source of this type of error is most likely either due to human error that occurred during the digitizing process, or caused by inaccuracies associated with GPS equipment used to map features on Yap.

Unfortunately, aside from a subjective visual comparison between the data and the satellite imagery, there was no accurate way to identify the absolute errors that may be involved in the input data. The process of comparing data to the imagery was only

applicable to the roads layer since it is clearly discernible in the image. Data such as soil type, vegetation type, watershed boundaries, etc. cannot be corrected for using that method since an examination of the satellite image does not indicate the precise location of such features. The project proceeded under the assumption that all geographic data were representing their correct locations since there was no evidence to indicate otherwise.

4.5 Summary

The conceptual data model for this project reflects the interconnectivity of the natural processes that contribute to soil loss. These processes are considered in the soil loss equation used in this project and determine which data are needed. The data were stored in an Esri file geodatabase and include four raster datasets and two tables. Many of the data were provided by the client, additional required data were obtained from various online sources. Data manipulation was minimal since there was no reason to assume any errors with the information, and because of a lack of reference information with which to compare the data.

Chapter 5 – Implementation

The implementation of this project began by determining the project site based on criteria provided by the client. The criteria are listed in Section 5.1. The next step was to represent the factors used in the RUSLE as geographically referenced and/or tabular data for the tool to call upon when calculating potential soil loss. Diagrams showing the procedures used to create the RUSLE factors are shown in Section 5.2. Once the data were created, the tool was scripted in Python. Details regarding the creation of the tool can be found in Section 5.3. Once the tool was finished, it was tested and deployed to the client.

5.1 Determining the Project Site

To begin the analysis, boundaries for the project site were established based on a set of criteria pertaining to the potential golf resort location. The criteria were provided by the client, per the interested parties on Yap with whom he works. The criteria were that the golf resort be:

- In the municipality of Dalipebinaw
- Approximately west or northwest of Colonia (the state capital)
- Upslope of the main road that lies along the west side
- Approximately 1 km² in total area

Because the RUSLE measures erosion by water transport, the project site boundaries were based on boundaries of existing watersheds. Watersheds selected were those which met the aforementioned criteria and had some portion of the boundary coincident with the coast. This was important because the interest in this project was in the impact of the proposed golf resort on sedimentation into the marine ecosystem. If a watershed does not share a boundary with the coast, then water within its boundary is hydrologically isolated from the ocean, with respect to final accumulation point. This resulted in the selection of seven watersheds as the project site as shown in Figure 5-1.

Figure 5-1: Determining the project site based on site selection criteria.

A selection was performed to extract the desired watersheds from the layer containing watershed boundaries for the whole island into a new feature class. The outer most boundary of these seven watersheds is the project site. All subsequent data created were clipped to this area.

5.2 Representing RUSLE Factors in a GIS

The next step in the analysis phase of the project was to convert the data that were obtained from either the client or the Internet into a format that can be used in ArcGIS. This process is diagramed in Figure 5-2.

Figure 5-2: Data conversion for RUSLE factors.

The processes involved in generating each of these factors from the initial data is explained in more detail in the following sections.

5.2.1 Rainfall Erosivity

The rainfall erosivity factor (R factor) was taken from a report published by the Water and Environmental Research Institute (WERI) of the Western Pacific University of Guam (Khosrowpanah & Heitz, 2001). The report states that Yap has an average annual rainfall erosivity factor of 970.55 hundreds of foot-ton inches per acre-hour which the tool converts into $16,518 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ y}^{-1}$. Although it would have been preferable to have the rainfall erosivity factor vary spatially as opposed to being represented as a single point, the rainfall data were only available from a single weather station in the WERI study. Therefore, one value is used to represent the entire project site. Given that the weather station is located in the municipality immediately south of the municipality containing the study site, this value can still be reasonably applied to the entire study site.

5.2.2 Soil Erodibility

The process for deriving the soil erodibility factor (K factor) has been diagrammed in Figure 5-3.

Figure 5-3: Workflow for creating K factor raster and table.

The soil erodibility factor was derived from two items, the soil type vector layer and the K factor report, which were downloaded from the USDA NRCS Web Soil Survey (WSS) (websoilsurvey.sc.egov.usda.gov). The WSS is a convenient tool hosted online from which a plethora of soil data can be retrieved. It allows its user to specify an area of interest either by drawing it onto a map embedded in the tool interface or by uploading a shapefile. For this project, the project site described in Section 5.1 was uploaded to specify the area for which soil data was needed.

From the WSS, a soil layer and a K factor report were generated based on the project site boundaries. The soil layer was downloaded as a shapefile and was imported into the geodatabase as a feature class. A new field was created within the soil type feature class (data type float) for the K factor values, which were retrieved from the table downloaded from the WSS. In order to match a soil type to the appropriate K factor, the WSS tool assigns a unique number, called a map unit symbol, to each soil. The downloaded shapefile has a field containing this number, and the K factor report also references this number, making it easy to manually enter the correct K factor for each soil type. After the K factors were added to the soil type attribute table, the polygon layer was converted into a raster, classified by the K factors (Figure 5-4).

Figure 5-4: Soil erodibility map.

The K factor values are provided by the WSS in U.S. customary units of ton acre hour per hundreds of acre⁻¹ foot⁻¹ tonf⁻¹ inch⁻¹ which the tool converts into S.I. units of metric ton hectare hour per hectare⁻¹ megajoule⁻¹ millimeter⁻¹ before calculating total soil loss. The values were not converted prior to being added to the soil type attribute table in order to keep the convention used by the WSS.

In addition to the K factor raster, a K factor table was created and added to the project geodatabase (Figure 5-5). It contains fields for the soil types and their associated K factors. This table was necessary for the tool because it will be called when the user specifies a new soil type for the golf resort. More information about the tool and its parameters is provided in Section 5.3.

Table	
K_Factors	
SoilType	Kfactor
Dechel mucky silt loam, 0-2 percent slopes	0.15
Dublon variant sandy clay loam, 0-4 percent slopes	0.1
Gitam very gravelly silty clay loam, 2-6 percent slopes	0.1
Gitam very gravelly silty clay loam, 6-12 percent slopes	0.1
Ilachetomei peat, 0-1 percent slopes	0.05
Ngersuul variant silty clay loam, 2-8 percent slopes	0.1
Rumung-Weloy complex, 12-30 percent slopes	0.1
Rumung-Weloy complex, 30-50 percent slopes	0.1
Rumung-Weloy complex, 50-75 percent slopes	0.1
Sonahnpil variant extremely gravelly silt loam, 0-4 percent slopes	0.05
Weloy-Rumung complex, 2-12 percent slopes	0.1
Yap silty clay loam, 2-6 percent slopes	0.1

Figure 5-5: K factor table.

5.2.3 Slope Length and Steepness

The slope length and steepness factor, or LS factor, was derived from one meter elevation contour lines that were provided by the client. Using a series of steps outlined in many scholarly articles, the contour lines were used to generate the topographic factors, slope length and slope steepness. The workflow used to derive the LS factor is depicted in Figure 5-6.

Figure 5-6: Workflow for creating L and LS factor rasters

Before the slope length and steepness (LS factor) could be calculated, slope length (L factor) and slope steepness (S factor) were calculated individually. The first step in creating these rasters was clipping the contour lines to the project site. Following that step, a series of ArcMap tools provided as part of the Spatial Analyst extension were utilized as shown in Figure 5-6. Using the clipped contours, a digital elevation model (DEM) was created using the Topo to Raster tool. The DEM was then used in two different series of steps to calculate the slope length factor and the slope steepness factor.

To calculate slope length, a tool called Fill was applied to the DEM which produced a hydrologically correct raster by filling sinks and removing peaks in the elevation data. Then a tool called Flow Direction was used which determined the direction of flow within each cell. From the output of the Flow Direction tool, Flow Accumulation was run which counts the number of cells from which any cell is receiving flow. The output of Flow Accumulation was then applied to an equation which calculated the slope length factor.

$$\text{Slope length} = \left(\frac{\text{accumulation} \cdot \text{cell size}}{22.13} \right)^{0.4}$$

This calculation was done using a model assembled in ArcMap's ModelBuilder so that it could be easily repeated (Figure 5-7).

Figure 5-7: Model built to generate slope length raster.

The output of the model shown in Figure 5-7 is the raster shown in Figure 5-8, the L factor raster. Figure 5-8 shows the distribution of L factors for the project site. The values represent a ratio of soil loss from the project site to soil loss from a site with a slope length of 22.13 m and otherwise identical conditions. The values stored do not have units.

Figure 5-8: Slope length map.

To calculate slope steepness the DEM was used in a tool called Slope which generated a raster containing slope values in degrees. The slope steepness factor was then calculated by applying the slope raster to the following equation:

$$\text{Slope steepness} = \left(\frac{\sin \text{slope}}{0.0896} \right)^{1.3}$$

This calculation was also implemented using a model created in ModelBuilder (Figure 5-9). The output of the model was a raster containing the slope steepness factors.

Figure 5-9: Model built to generate slope steepness raster.

Once the L factor and S factor rasters were prepared, they were multiplied to generate LS factor (Figure 5-10). The values represent a ratio of soil loss from the project site to soil loss from a site with a slope length of 22.13 m, a uniformly distributed grade of 9%, and otherwise identical conditions. The values stored do not have units. A value of

zero means that the topographic features slope length and slope steepness do not contribute to potential soil loss from rill and interrill erosion. It represents the factor by which the area of interest contributes soil loss when compared to a standard area.

Figure 5-10: Slope length and steepness map.

The slope length and steepness (LS factor) and slope length (L factor) rasters are included in the final geodatabase; however, the slope steepness (S factor) raster is not included because it is never called in the tool. It was only needed insofar as to calculate slope length (LS factor). The tool features slope as one of the parameters which the user can either specify, or leave blank. If the user specifies a slope, the tool plugs that value into the slope steepness equation and multiplies that by the L factor raster to produce a new LS factor raster. If the user does not specify a new slope, the tool calls the LS factor raster from the geodatabase (Figure 5-17). This is explained in more detail in Section 5.3.1, which outlines the tool procedures.

5.2.4 Cover Management

The cover management (C factor) raster was derived from a satellite image and a feature class representing land cover. The process is outlined in Figure 5-11.

Figure 5-12: Model built to calculate NDVI.

Once a raster representing NDVI was created, that raster was then applied to another equation which rescaled the NDVI values into cover management factors. The equation to rescale NDVI is as follows:

$$C = \frac{(-NDVI + 1)}{2}$$

This portion of the C factor calculation was also executed in ModelBuilder with the model shown in Figure 5-13.

Figure 5-13: Model built to rescale NDVI and produce C factor raster.

The final C factor raster for the project site is shown in Figure 5-14. Its values were derived from normalized difference vegetation index values ranging from -0.84 – 0.35 to C factor values which fit the RUSLE. The higher the value, the less vegetative cover, and the more susceptible an area is to erosion. There are no units associated with the C factor.

Figure 5-14: Cover management map.

In addition to the C factor raster, the C values of different types of land cover were derived as the tool allows the user to specify a particular type of land cover for their area of interest. In order to derive a C factor value for each type of land cover, a land cover feature class was used as a “mask” for the C factor raster, from which an average cell value was extracted and assigned as the C factor for each type of land cover. This was accomplished by creating a new feature class for each land cover type present, clipping the C factor raster to the new feature class, and using the Get Raster Properties function to extract the average value, and repeating the process for all other land cover types. The model built to carry out this process can be found in Appendix A.

Finally, a table was created with two fields, a text field containing the land cover types, and a field (data type double) with the average C factor value for that land cover type. This table is shown in Figure 5-15.

LandCover	Cfactors
Agroforest	0.504
Barren	0.508
Cropland	0.583
Grassland	0.519
Mangrove	0.532
Marsh	0.487
Secondary Vegetation	0.524
Upland Forest	0.477
Urban	0.512

Figure 5-15: C factor table.

Within the project site, the land cover data used included nine types of land covers with derived C factor values ranging from 0.468 – 0.594. The small variation observed between C factors may be due to having averaged all cells that intersected a particular type of land cover. This indicates that the image classification of land cover did not fully coincide with the available land cover feature class used for this project.

All models pictured in this chapter were included in the project geodatabase for the convenience of repeating the process if necessary.

5.3 Developing the Soil Loss Tool

The next step in the analysis phase of the project was to create a script for a tool that would allow the user to specify values for the RUSLE factors based on plans for the golf resort, and recalculate soil loss based on those planned values. This was done using PyScripter for Python 2.7. It was designed so that the user may specify an area of interest (AOI) to which all the RUSLE variables are constrained. The AOI must be a feature class. From there, the script follows a systematic course of action as outlined in Figure 5-16. Essentially, the tool assigns all the RUSLE factors based on user input, uses those values to generate a soil loss raster, sums all the values of the raster to yield total soil loss, then creates a table containing the summed total soil loss. The outputs of the tool that are written to disk are a soil loss raster, and a table.

Figure 5-16: General workflow of Python script.

5.3.1 Scripting the Tool

The first step in the script as shown in Figure 5-16 is to determine the values for the RUSLE factors. These values vary depending on the location of the user-specified area of interest, and the user inputs as parameters. For each factor in the RUSLE, the tool provides one or more variables which the user can either choose to specify or leave blank. For any parameter left blank by the user, the script will default to the raster created reflecting “current” conditions, current being as of the date the source data were created (Section 5.2). Figure 5-17 illustrates how the tool “decides” how it is going to derive each RUSLE factor based on the presence or absence of user input. For a more detailed look at the script, see Appendix B.

Figure 5-17: Tool decision map.

In order to calculate the R factor, the tool provides the user a number of parameters pertaining to the presence of water. These parameters are based on how much irrigation the AOI is anticipated to receive. The WERI report, which calculated the rainfall erosivity factor for Yap, provides an equation for calculating storm erosivity. That equation is:

$$\text{Storm EI}_{30} = [\sum 1099 \times (1 - 0.72 \times e^{(-1.27 \times I_r)}) \times R_r] \times I_{30}$$

Where I_r represents a storm intensity value (in/hr) for a given amount of time, R_r represents the amount of rainfall (in) that fell during that same period of time, and I_{30} is the maximum intensity that occurred during a 30 minute interval throughout the storm (Khosrowpanah & Heitz, 2001). The R factor for an amount of time is equal to Storm EI_{30} values for that time frame (Renard et al., 1997).

In order to account for any irrigation of the golf resort that might occur, it was assumed that an “irrigation event” would have the same effect as rainfall on the soil erosion potential. Under this assumption, an updated R factor can be calculated by combining the average annual R factor of 970.55 hundreds of foot-ton inches per acre-hour (which will be converted by the tool into units of $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{y}^{-1}$) with an R factor calculated from “irrigation event” values. These values, which are based on the variables present in the Storm EI_{30} equation, are listed in the tool as:

- Inches of irrigated water in one hour
- Duration of irrigation in hours per day
- Number of days for irrigation in one year.

From these values, a Storm EI_{30} can be calculated for each “irrigation event”, assuming the irrigation intensity remains constant. The calculated Storm EI_{30} value can then be multiplied by the number of irrigation events that are predicted to occur in one year, the product of which equals the annual R factor with respect to irrigation. Weighting this value by the number of days in a year on which irrigation takes place allows it to be averaged with the WERI-calculated R factor, yielding a final R factor which takes into account both rainfall, and irrigation.

The soil erodibility and cover management factors follow a very similar process as one another, which does not include as many assumptions as does the rainfall erosivity factor. For both K/C factor, the user has the option to either select a category of soil/land cover from a drop-down menu, or leave the parameter unspecified. In the case that the user makes a selection, the tool will then refer to the corresponding K/C factor table and retrieve its value through the use of a search cursor. When the tool matches the user-selected category to an entry in the table, it stores the associated K/C value for later use in the final calculation. If the user does not make a selection, the tool performs an Extract by Mask (requires Spatial Analyst) on the K/C factor raster, which essentially “clips” the raster reflecting current conditions to the AOI. The clipped raster is then used later on for calculation of soil loss.

The parameter which pertains to the topographic factor is average slope; the user is given the opportunity to specify an average slope of the proposed golf resort if that information is known. In the case that the user does specify a slope, that value is plugged into the slope steepness equation, and the resulting value is multiplied by a portion of the L factor raster (which has been clipped to the AOI) to produce an LS factor raster reflecting the new slope. If the user does not specify a slope, then the script executes an

Extract by Mask which clips the LS raster to the AOI, and uses that in subsequent steps to calculate soil loss.

Once the script has successfully assigned the RUSLE variables, it proceeds to calculate soil loss according to the RUSLE equation:

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

It is at this point that units are converted into the metric system if they are not already and all factors are multiplied together. The resulting A raster represents the soil loss in tons per hectare per year. Since the raster is in 10m by 10m, another conversion between hectares and square meters takes place. Once the conversions are complete, the raster is saved, and the tool executes a tool called Zonal Statistics as Table. Sum, representing the total soil loss in tons from the AOI, is specified as the desired statistic, written into the table, and the table is written to disk along with the raster.

The script was designed to provide a relatively user-friendly experience which will make calculating soil loss simple for someone who does not know anything about erosion. The Python script was imported into ArcMap as a script tool, and the tool properties were adjusted to create a user-friendly interface. The following section details how this was accomplished.

5.3.2 Importing the Script into ArcMap

A new script was added into a toolbox housed within the project geodatabase, and named Calculate Soil Loss. From there, the script properties were configured such as the file path of the script written to calculate soil loss, a description of the tool, the parameters and their properties. The tool properties window is shown in Figure 5-18.

Figure 5-18: Configuring tool parameters in properties window.

The properties were configured according to Table 5-1. The inputs are the folder containing the geodatabase, the user's area of interest, and six variables that are used in the script to determine RUSLE factor values. The last two parameters are tool outputs, the soil loss raster and total soil loss table. As was stated in the previous section, for any of the six variables used to determine RUSLE factor values, the user can either specify a value or leave it blank if perhaps, it is not part of the plan to change, or if it is unknown.

Table 5-1. Configuration of tool parameters.

Parameter	Data Type	Direction	Optional	Default	Filter
Folder containing geodatabase	Folder	Input	Required	None	None
Area of interest	Feature Class	Input	Required	None	Polygon Feature Class
Inches of irrigated water per hour	Double	Input	Yes	None	Range 0 - 999
Hours of irrigation per day	Double	Input	Yes	None	Range 0 - 24
Days of irrigation in one year	Long	Input	Yes	243	Range 0 - 365
Type of soil	String	Input	Yes	None	Value List
Land cover	String	Input	Yes	None	Value List
Average slope in degrees	Double	Input	Yes	None	Range 0 - 90
Output raster	Raster Layer	Output	Required	None	None
Output table	Table	Output	Required	None	None

After the parameter configuration was complete, the tool user interface appeared as it does in Figure 5-19. There is no way to customize the appearance of the tool within ArcMap, so its aesthetics do not differ from the suite of tools included with ArcMap.

Figure 5-19: Tool interface.

The next step was to edit the tool help documentation. This was accomplished by editing the tool description in ArcCatalog. From the editing window, the tool description can be written including links and images. A description of each parameter was written, which serves as a set of instructions for the user as they go through each parameter. Figure 5-20 shows an example of one of the parameters which has a list value filter and documented instructions including a link to the original data source.

Figure 5-20: Soil type parameter with predefined list of values

After the help documentation was completed, the tool was ready for deployment as a fully functional ArcMap tool.

5.4 Deployment

The first step in preparing the tool for deployment was testing. The tool was tested over 20 times with varying combinations of parameter specifications. It was tested on multiple machines by multiple users, all of whom had used ArcMap in the past. After a satisfactory amount of successful testing, the tool was packaged into a folder along with the Python script file, four raster datasets, and two tables, all of which are called by the tool. With all of the necessary components organized into one folder, the information product deliverables were deployed to the client to be used for helpful spatial decision making on Yap.

5.5 Summary

After all the data were prepared and the database organized, the implementation began by establishing project site boundaries. RUSLE variables were determined for the project site data obtained from a tool called the Web Soil Survey (WSS) and various techniques

adopted from the literature review. Techniques included the use of remote sensing to calculate a normalized difference vegetation index, and implementation of various ArcMap tools in models created in ModelBuilder. Final data included four rasters and two tables. A tool was developed in Python which used the final data to calculate potential soil loss based on a set of input parameters. The parameters indicate to the tool what values and/or data to assign the RUSLE variables. The script was imported into ArcMap and configured to make the interface intuitive and easy to follow.

Chapter 6 – Results and Analysis

In this chapter the results of the project implementation are discussed. In Section 6.1, soil loss for the whole project site is shown based on the RUSLE factor data generated during project implementation. It also features a comparison between the resulting soil loss values to values generated from similar projects which used the RUSLE to calculate soil loss. Following Section 6.1 is a use case for the tool in which the tool is run with a set of test parameters. The results of the use case are verified in Section 6.3 which manually calculates soil loss for a single pixel and compares that to the tool output value.

6.1 Soil Loss in Project Site

Multiplying the rainfall erosivity factor, soil erodibility raster, slope length raster, and cover management raster, yields the soil loss in tons per hectare per year of the project site by rill and interrill erosion. A raster representing the amount of soil loss per cell can be obtained by converting this unit into tons per 100 m² per year because each cell is 10m x 10m (Figure 6-1).

Figure 6-1: RUSLE factor rasters and total soil loss raster (t/100m²).

Although the rainfall erosivity factor has the greatest value in the equation, it does not affect the spatial variation of soil loss because it is a constant value in this study. The spatially varied variables including, soil erodibility, slope length and steepness, and cover management, determine the variation of soil loss in the project site. The slope length and steepness factor has the greatest affect on the spatial distribution of soil loss; therefore, the largest soil loss values occur where the LS factor is largest.

In order to qualify whether or not the results of this project seem feasible, the soil loss obtained in this project was compared to values from similar projects (Table 6-1). Because the quantities of soil loss vary from one location to another, depending on climate, topographic profiles, soil type, vegetation, and support practices, the comparison only serves the purpose of identifying suspicious quantities. Ranges of values rather than averages were included in the table to demonstrate all possible values for a project's location.

Table 6-1. RUSLE factor values reported in similar studies.

Author	Project Location	R	K	LS	C	P	Soil Loss
		$\frac{\text{MJ} \cdot \text{mm}}{\text{ha} \cdot \text{h} \cdot \text{y}}$	$\frac{\text{t} \cdot \text{ha} \cdot \text{h}}{\text{ha} \cdot \text{MJ} \cdot \text{mm}}$	$\frac{\text{t}}{\text{ha} \cdot \text{y}}$			$\frac{\text{t}}{\text{ha} \cdot \text{yy}}$
Klein	Yap, FSM	16,518	.01-.02	0-43	.32-.92	1	0-7,600
Kouli et al.	Northwestern Crete, Greece	676-2,163	.02-.04	0-118	.13-.79	1	0-4,156
Millward & Mersey	Sierra Madre del Sur, Mexico	4,000-9,000 (wet season)	0-.03	0-300	0-.37	1	0-100+
Pandey et al.	Hazaribagh, India	1,062-2,014	.19-.3	0-8.5	0-1	.28-1	0-80+
Sheikh et al.	Lower Himalayas	851-1,458	.09-.48	0-55	0-.37	0-.9	0-61

Table 6-1 compares the soil loss calculated for the project area with four similar studies (Sheikh, Palria, & Alam, 2011, Pandey, Chowdary, & Mal, 2006, Kouli, Soupios, & Vallianatos, 2008, Millward & Mersey, 1999). Of the projects included in this assessment, Yap has the highest range of soil loss values. Yap's tropical climate produce the highest rainfall erosivity factor by almost twice the next highest value. Millward & Mersey (1999) calculated a rainfall erosivity factor range of 4,000 – 9,000 during the wet season of a mountainous tropical watershed in the Sierra de Manantlan Biosphere Reserve in Mexico. Yap's slope length factor range is relatively small compared to all but one of the projects listed. While this factor is derived from a digital elevation model, it does not suffice to compare elevations because this factor is a reflection of steepness and lengths of slope. This makes it difficult to interpret differences in slope length factor without more detailed analysis. The soil erodibility factor and cover management factor are more straight forward than the R and LS factors because they can be categorized and adapted from tables that have been published in previous studies. It is important to note that while the Yap study has the highest maximum soil loss value, the average value was

only 350 t ha⁻¹ so for a large percentage of the site, the most extreme conditions were not met.

6.2 Soil Loss Use Case

To demonstrate how the tool can be used by the client, the following section provides an example implementation of the tool with hypothetical parameters. Suppose that a golf resort has been proposed in the area shown in Figure 6-2 and the local government wants to evaluate the impact of the new development on soil loss. First, the user needs to digitize the proposed site and have it available as a feature class.

Figure 6-2: Test golf resort boundaries for use case.

Second, the user launches the tool and fills out the parameters based on proposed values shown in Figure 6-3.

Figure 6-3: Sample tool parameters.

The folder containing the geodatabase is selected along with the feature class containing the area of interest. The irrigation specifications are indicated along with a change in land cover to grassland and an average slope of 3.9° . No new type of soil was selected. After the tool runs the analysis, the resulting raster shown in Figure 6-4 indicates that the range of soil loss intensities in the area of interest is from 0 to 38 tons per 100 m^2 (0 to $3,800 \text{ t ha}^{-1} \text{ yr}^{-1}$). In this example, the greatest soil loss intensities are found in areas with the greatest slope length.

Figure 6-4: Output raster from sample parameters.

In addition to the soil loss intensity map shown in Figure 6-4, the table shown in Figure 6-5 is generated and saved to disk. The field titled SUM contains the total soil loss for the AOI in tons per year. In this example total soil loss for the AOI equals 1,078 tons per year.

Table				
SampleTable				
	OBJECTID *	COUNT	AREA	SUM
	1	12346	123460	1078

Figure 6-5: Output table from sample parameters.

Meanwhile, if a comparison between “before” and “after” scenarios is required, the user can rerun the tool with default values for the parameters. Figure 6-6 shows the soil loss intensities before and after the golf resort is developed.

Figure 6-6: Before and after comparison.

Based on the default rasters, 2,375 tons of soil are lost annually from the AOI compared to 1,078 tons lost from the AOI after a golf resort is built according to the specified parameters. In this case, average annual soil loss would decrease with the addition of the golf resort. Situations which can contribute to a decrease are, choosing a

more erodible soil, leveling the land (low average slope), and reducing vegetation density. If these conditions are typical in the event of golf resort construction, then it may be more useful to compare soil losses between two planned sites rather than a before and after scenario.

6.3 Tool Validation

In order to confirm whether or not the tool followed the intended procedure for calculating soil loss, a method was designed to compare the calculated value of one pixel to its expected value based on the input data. Figure 6-7 shows how the Identify tool was used to see what some of the RUSLE factor values should have been for a selected pixel.

Figure 6-7: Checking results using Identify tool.

In ArcMap, the input rasters and the output soil intensity raster of the AOI were added to a blank map document. Then, the Identify tool was used to select one pixel from the AOI output raster. The Identify tool produces a list of values for every raster at that pixel location thus providing a convenient list of default values for each RUSLE variable. Referring to the user-specified parameters (Figure 6-3) indicates whether a RUSLE variable should have been the one listed in the Identify window, or a different value. For example, since no new soil type was specified, the K factor value at that pixel location which should have been used by the tool is the one seen in the Identify window, 0.10. The tool converts K factors from U.S. customary units (used by the WSS) into S.I. units by a factor of 0.1317; therefore, the K factor at that pixel location used to calculate soil loss is 0.01317. An average slope of 3.9° was specified which, when plugged into the slope steepness equation, yields a slope steepness (S factor) of 0.6988. According to the Identify window, the slope length (L factor) for that pixel is 12.303. The product of the L and S factors is 8.597. Because a land cover was specified, the C factor table is used to

retrieve the value rather than the raster. According to the C factor table, Grassland within the project site has an average C factor of 0.519 (Figure 5-15). Based on the method for calculating the rainfall erosivity factor described in Section 5.2.1, the annual R factor for Yap which accounts for rainfall is 970.55 hundreds of foot-ton inches per acre-hour, or 16,518 MJ mm ha⁻¹ h⁻¹ y⁻¹. The amount added to the default rainfall factor as a result of the specified irrigation schedule is 4.4 which totals to an R factor of 16,522.4 MJ mm ha⁻¹ h⁻¹ y⁻¹.

The product of all the RUSLE factors in their correct units at the location of this pixel yields a value of 961.2 tons ha⁻¹; however, each pixel represents 100 m² so the volume lost in that 10 x 10 m area is 9.7 tons. In the tool, the rasters are reported in integer form (necessary for the Zonal Statistics as Table tool which calculates the raster sum) by removing any decimals; therefore, our expected value for the selected pixel is 9, which is exactly what was reported in the output raster. This demonstrates that tool works as it is intended. For more information on the calculations, see Appendix C.

6.4 Summary

Chapter 6 showed the results of the tool developed during this project. The RUSLE factor data created during implementation was used to calculate soil loss for the entire project site which ranged in values from 0 to 76 tons per 100 m². These values were compared with the results of similar projects which showed that the results did not seem unusual. A case study for the tool was conducted to demonstrate how it is used. A test area with hypothetical parameters generated a soil loss raster with values ranging from 0 to 38 tons per 100 m² and an average annual soil loss of 1,078 tons. These results were verified by manually calculating the soil loss value expected at one pixel location and comparing that value to the value calculated by the tool. The expected and tool-produced values were the same.

Chapter 7 – Conclusion and Future Work

The purpose of this project was to provide a metric by which potential golf resort sites can be compared with respect to runoff that might threaten the productivity of the coastal ecosystem of Dalipebinaw, Yap. The Revised Universal Soil Loss Equation (RUSLE) considers rainfall erosivity, soil erodibility, topographic factors, land cover, and support practices to calculate soil loss caused by rill and interrill erosion. In order to produce the desired comparative metric, a tool was scripted in Python which integrates the empirical model with spatial data used for its calculation. With this tool, the user can specify values used to calculate soil loss based on plans for the golf resort, and the tool generates a raster showing the spatial distribution of soil loss as well as a table containing total soil loss based on the planned parameters. Running the tool multiple times using different criteria allows the user to compare sites when deciding which potential site is best suited for the construction of a golf resort.

While the requirements of this project were met, more can be done to build upon the application of this tool. Three suggestions are posed for anyone interested in further development, for conservation strategies or otherwise. One limitation to this tool is that the user cannot specify more than one value for any parameter. In reality, there will likely be more than one type of soil, land cover, and variation in terrain and irrigation across space. This tool does not accommodate that reality. It would not be difficult to modify the tool to allow the user to make more than one selection for each RUSLE variable; however, if the boundaries are not specified as well, then its comparing power would not be much stronger than it is currently. To illustrate this concept, Figure 7-1 shows an example of how the tool would work if it were to account for spatial variation amongst variables.

Figure 7-1: Improvements for future work.

In order to achieve this modification, new strategies would be required for indicating RUSLE parameters. Implementing a different combination of ArcPy modules could make this possible.

Another suggestion for future work to further the usefulness of this project is to model the movement of water within the project site to predict the pathway of runoff and where it will end up. The tool produced for this project calculates a soil volume; however, it does not model the spatial distribution of runoff. If the Yapese are concerned with the health of the marine environment, it would be beneficial for conservationists to know where pour points are located, or, where runoff is depositing into the ocean. With this knowledge, management strategies could be devised to diffuse high concentrations of

runoff, or bolster the ability of that area to combat the effects of sedimentation. The RUSLE calculates erosion from rainfall and runoff, not sediment yield (net eroded soil based on all erosion processes). Another next step for marine conservation might be to evaluate other forms of erosion, to get an idea of exactly how much deposition could occur in the project site.

As time continues, the data used for this project becomes more out dated. Eventually, depending on the error tolerance afforded by the golf resort planning committee, the data called upon by the tool will not suffice for soil loss calculations. In order to continue using the tool, the raster datasets and tables used in this project will need to be updated with more current data. The other possibility for future work is to apply the methodology used during this project for another location. If the raster datasets and tables were to be replaced with those representing another area, the tool could be used to calculate soil loss for that location rather than exclusively for Yap.

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Appendix A. C Factor Model

Appendix B. Python Script

```
1.  #-----
2.  # Name:          Calculate Soil Loss
3.  # Purpose: Uses the principles of the Revised Universal Soil
    Loss Equation to calculate soil loss using data for an area
    of interest on Yap, FSM.
4.  #
5.  # Author:       Megan Elizabeth Klein
6.  #
7.  # Created:      09 June, 2014
8.  # Copyright:    (c) Megan Elizabeth Klein 2014
9.  #-----
10. # This tool will not function properly if the name of the
    geodatabase, or files contained within the geodatabase are
    changed without those changes being reflected in the code.
11.
12. #_____Imports_____
13. import math
14. import arcpy
15. from arcpy.sa import *
16. arcpy.env.overwriteOutput = True
17. arcpy.CheckOutExtension("Spatial")
18.
19. #_____Set Factors_____
20. arcpy.AddMessage("\nCalculating soil loss parameters...")
21.
22. gdbFolder = arcpy.GetParameterAsText(0)
23. areaInterest = arcpy.GetParameterAsText(1)
24.
25. #R Factor
26. waterIntensity = arcpy.GetParameterAsText(2)
27. # waterIntensity is inches of water per hour
28. waterHours = arcpy.GetParameterAsText(3)
29. # waterHours is number of hours per day of irrigation
30. if not waterIntensity:
31.     factorR = 16518.76
32. # 16518.76 is 970.55 (obtained from University of Guam WERI
    report) times a unit conversion factor of 17.02
33. elif not waterHours:
34.     factorR = 16518.76
35. # If either waterIntensity OR waterHours model parameter are
    left blank then factorR is 16518.76
```

```

36. else:
37.     waterIntensity = float(waterIntensity)
38.     waterHours = float(waterHours)
39.     waterDays = arcpy.GetParameterAsText(4)
40.     waterDays = float(waterDays)
41. # waterDays is number of days in a year area is irrigated
42.     halfWI = waterIntensity/2
43. # waterIntensity is halved because it's reported in in/hr and
    equation uses in/30 min
44.     irrigationEI30 = (((((1099*(1-.72*math.exp(-
        1.27*halfWI))*halfWI)*(waterHours*2))*halfWI)*waterDays)*
        .1702
45. # Equation obtained from University of Guam WERI report.
    waterHours is doubled because it's the number of 30 min
    increments of irrigation. Number is multiplied by unit
    conversion factor.
46.     factorR = 16518.76 + irrigationEI30
47. # Add annual R factors from rainfall and irrigation for total
    annual R factor
48. arcpy.AddMessage("\nRainfall erosivity factor calculated...")

49.
50. #LS Factor
51. slopeAvg = arcpy.GetParameterAsText(7)
52. if not slopeAvg:
53.     parentLS = gdbFolder + "\CalculateSoilLoss.gdb\LS_Factor"

54.     factorLS = ExtractByMask(parentLS, areaInterest)
55. # If slope is unspecified, clip LS raster to AOI and use
    values in remaining cells
56. else:
57.     parentL = gdbFolder + "\CalculateSoilLoss.gdb\L_Factor"
58.     factorL = ExtractByMask(parentL, areaInterest)
59.     slopeAvg = float(slopeAvg)
60.     factorS = (math.sin(slopeAvg*.01745)/0.0896)**1.3
61. # Convert from degrees to radians
62.     factorLS = factorL*factorS
63. # If slope is specified, use value to calculate S factor and
    multiply value by L factor values from raster clipped to AOI

64. arcpy.AddMessage("\nSlope length and steepness factor
    calculated...")
65.
66. #K Factor
67. soilType = arcpy.GetParameterAsText(5)
68. if not soilType:

```

```

69.     parentK = gdbFolder + "\CalculateSoilLoss.gdb\K_Factor"
70.     factorK = ExtractByMask(parentK, areaInterest)
71. # If soil type is unspecified clip K factor raster to AOI and
    use values from remaining cells
72. else:
73.     tableK = gdbFolder + "\CalculateSoilLoss.gdb\K_Factors"
74.     cursorK = arcpy.da.SearchCursor(tableK, ["Kfactors",
        "SoilTypes"])
75.     for row in cursorK:
76.         if soilType == row[1]:
77.             factorK = row[0]
78.             break
79. # If soil type is specified obtain corresponding K factor
    value from table containing K factor values
80. arcpy.AddMessage("\nSoil erodibility factor calculated...")
81.
82. #C Factor
83. vegType = arcpy.GetParameterAsText(6)
84. if not vegType:
85.     parentC = gdbFolder + "\CalculateSoilLoss.gdb\C_Factor"
86.     factorC = ExtractByMask(parentC, areaInterest)
87. # If vegetation type is unspecified clip C factor raster to
    AOI and use values from remaining cells
88. else:
89.     tableC = gdbFolder + "\CalculateSoilLoss.gdb\C_Factors"
90.     cursorC = arcpy.da.SearchCursor(tableC, ["Cfactors",
        "VegTypes"])
91.     for row in cursorC:
92.         if vegType == row[1]:
93.             factorC = row[0]
94.             break
95. # If vegetation type is specified obtain corresponding C
    factor value from table containing C factor values
96. arcpy.AddMessage("\nCover management factor calculated...")
97.
98. #_____Generate Soil Loss Raster_____
99. outRaster = arcpy.GetParameterAsText(8)
100. finalRaster = ((factorR*(factorK*0.1317)*factorLS*factorC)/
    100)
101. # Multiply K factor by unit conversion factor. This was not
    done earlier so as to keep the convention used by the WSS.
102. # Divide by 100 to convert t/ha --> t/100 sq m
103. finalRaster.save(outRaster)
104. arcpy.AddMessage("\nOutput raster saved...")
105.
106. #_____Calculate Total Soil Loss_____

```

```
107. arcpy.AddMessage("\nCalculating total soil loss...")
108. finalRaster = Int(finalRaster)
109. # finalRaster converted into integer format for use by
    ZonalStatisticsAsTable function
110. outTable = arcpy.GetParameterAsText(9)
111. rasterSum = ZonalStatisticsAsTable(areaInterest, "OBJECTID",
    finalRaster, outTable, "DATA", "SUM")
```


Appendix C. Sample Calculation of Soil Loss for Selected Pixel

Rainfall erosivity factor

R factor from precipitation:

$$970.55 \frac{\text{hundreds of foot} \cdot \text{tonf} \cdot \text{inch}}{\text{acre} \cdot \text{hour}} \times 17.02 = 16,518 \frac{\text{megajoule} \cdot \text{millimeter}}{\text{hectare} \cdot \text{hour}}$$

R factor from irrigation:

$$\text{Storm EI}_{30} = [\sum 1099 \times (1 - 0.72 \times e^{(-1.27 \times I_r)}) \times R_r] \times I_{30}$$

<u>Parameter Value</u>	<u>Variable in equation</u>
Intensity = 0.4 in/hr	$I_r = 0.2$ in/half hour (intensity)
Duration = 1 hr/day	$R_r = 0.2$ in (amount rainfall)
Frequency = 243 days/yr	$I_{30} = 0.2$ in/half hour (intensity, assumed constant)

Where:

$$1099 \times (1 - 0.72 \times e^{(-1.27 \times 0.2)}) \times 0.2 = 97.04$$

Multiply by number of half hour cycles to get energy of irrigation event:

$$97.04 \times 2 = 194.08$$

Multiply by I_{30} which is assumed equal to I_r to get total energy per day:

$$194.08 \times 0.2 = 38.82$$

Times a fraction of the year based on irrigated days:

$$38.82 \times \frac{243}{365} = 25.84$$

Convert units:

$$25.84 \frac{\text{hundreds of ft} \cdot \text{tonf} \cdot \text{in}}{\text{ac} \cdot \text{h}} \times 0.1702 = 4.4 \frac{\text{MJ} \cdot \text{mm}}{\text{ha} \cdot \text{h}}$$

Add erosivity factor from precipitation to erosivity factor from irrigation:

$$16,518 + 4.4 = 16,522.4 \frac{\text{MJ} \cdot \text{mm}}{\text{ha} \cdot \text{h}}$$

Soil erodibility factor

from Identify window: 0.1

Convert units:

$$0.1 \frac{\text{t} \cdot \text{ac} \cdot \text{h}}{\text{hundreds of ac} \cdot \text{ft} \cdot \text{tonf} \cdot \text{in}} \times 0.1317 = 0.01317 \frac{\text{metric ton} \cdot \text{ha} \cdot \text{h}}{\text{ha} \cdot \text{MJ} \cdot \text{mm}}$$

Slope length factor

From Identify window: 12.303

Slope steepness factor

$$\text{Slope steepness} = \left(\frac{\sin \theta}{0.0896} \right)^{1.3}$$

Parameter value: 3.9°

$$\left(\frac{\sin 3.9^\circ}{0.0896} \right)^{1.3} = 0.6988$$

Slope length and steepness factor

$$12.303 \times 0.6988 = 8.597$$

Cover management factor

Parameter selection: Grassland

From C factor table: 0.519

Support Practice

Set equal to 1, due to lack of information

Average annual soil loss

$$R \times K \times LS \times C \times P = A$$

$$16,522.4 \frac{\text{MJ} \cdot \text{mm}}{\text{ha} \cdot \text{h}} \times 0.01317 \frac{\text{metric t} \cdot \text{ha} \cdot \text{h}}{\text{ha} \cdot \text{MJ} \cdot \text{mm}} \times 8.597 \times 0.519 \times 1 = 970.89 \frac{\text{metric t}}{\text{ha}}$$

Converted to t/100 m²:

$$970.89 \frac{\text{metric t}}{\text{ha}} \div 100 = 9.7 \frac{\text{metric tons}}{100 \text{ m}^2}$$

Integer form used by ArcMap:

$$9.7 \frac{\text{metric t}}{100 \text{ m}^2} \rightarrow 9 \frac{\text{metric tons}}{100 \text{ m}^2}$$