Application of Geographic Information Systems and Unmanned Aerial Vehicles (UAV) for the Use of a Site-Specific Soil Erosion Model

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Abstract *— The use of geographical information systems (GIS) and aerial imagery analysis has long been used to determine resource concerns within different habitats yet with new developments in spatial technology we can narrow our scope to detect these concerns with greater precision. Soil erosion is one of the greatest concerns in natural resource conservation because its impacts can affect entire ecosystems. Large scale construction, heavy agricultural production and deforestation contribute to most of the world's soil erosion problems. Implementing Unmanned Aerial Vehicles (UAV) to scout areas of concerns can provided an economic and efficient solution to the costly satellite imagery currently used. The study of high resolution aerial imagery captured by UAV can provide researchers with data of greater quality. This investigation intends on using a UAV and GIS software to collect high resolution aerial imagery and Model the potential for soil erosion at a specific site. The equation used to model soil erosion is the Revised Universal Soil Loss Equation (RUSLE). The use of a UAV for this type of investigation is expected to narrow the focus to a specific area and extract data with higher precision.*

Key Terms *— Geographical Information System, RUSLE, Soil Erosion, Unmanned Aerial Vehicle.*

INTRODUCTION

Soil is one of the most important resources in nature because it not only forms part of every terrestrial ecosystem on the planet but it serves as a medium that supports a complex ecosystem in which a vast number of organisms, from large plant roots to viruses, coexist and interact [1]. Soil erosion has become more and more predominate in the past years due to intense construction, overworked agricultural fields and deforestation. The term soil erosion involves detachment and transport of soil particles from top soil layer, degrading soil quality and reducing the productivity of affected lands [2]. During the 1930's extreme soil erosion brought about one of the worst natural disasters known as "The Dust Bowl".

The Dust Bowl generated storms winds that carried layers of topsoil across the nation, all the way to the Atlantic. This disaster was product of intense agricultural production and lack of conservation activities. In 1935 congress signed into law the creation of the Soil Conservation Service (SCS) [3]. The Soil Conservation Service (currently known as the "Natural Resources Conservation Service") developed many conservation practices and incorporated various methods to identify resource concerns.

In 1965 in the United States Department of Agriculture (USDA) published the Universal Soil Loss Equation (USLE) in the 282 USDA Agriculture Handbook. This equation was designed to use five main variables to help define annual soil loss. By 1978 a revised version of the USLE known as the Revised Universal Soil Loss Equation (RUSLE) was proposed by Agriculture Research Service (ARS) scientist and adopted by the SCS the USDA in. Such equations as the Universal Soil Loss Equation (USLE), Revised Soil Loss Equation (RUSLE), and the Soil Erodibility Index (SEI) are still used by the agency today.

Using equations such as these allow the quantification of annual soil loss based on rainfall-runoff erosivity, slope properties, soil erosivity, land cover and conservation practices. The results of such calculations allow researcher to develop models that predict areas of concern, thus providing insight to areas that need conservation efforts. Researchers have also combined these equations with tools such geographical information systems (GIS) which has allow them to create soil loss models with spatial resolution.

GIS is a computer system for capturing, storing, checking, and displaying data related to position on Earth's surface [4]. Within GIS users can study the spatial resolution of natural occurring phenomena such as the effects of soil erosion on its surrounding habitats. When working in GIS users compile layers of data relevant to their interest of study in order to create a visual representation. GIS can also serve as a platform to develop spatial models of natural phenomena by introducing soil erosion equations into systems resulting in a map that pin points exactly what regions will be affected. In order to run equations such as the soil erodibility index in GIS it is important to have the highest quality data. Most datasets can be mined from federal resources such as the United States Geological Survey (USGS) or Natural Recourses Conservation Service (NRCS), but other dataset may have to be collected from the field. An example of this is the LS factor within the Soil Erodibility Index requires a digital elevation map (DEM) in order to determine slope and slope length. Federal resources only have 10 – 30 meter resolution DEMs which may not provide the most accurate results. This is where the use of aerial imagery and photogrammetry may provide better quality data.

Now in days we can create higher resolution DEM using Unmanned Aerial Vehicle (UAV) Technology and photogrammetric software. Aerial Imagery taken by UAV in unison with photogrammetric software has the ability to provide high resolution aerial imagery of areas that are inaccessible by foot. These platforms can proved aerial images with resolutions in centimeters versus the 10 meter resolutions available from satellite platforms. The analysis of high resolution images collected by UAV with additional in-situ measurements can compete with traditional field surveying of complex vegetation communities considering cost and time-effectiveness [5]. This investigation seeks to demonstrate how the use of high resolution aerial imagery collected by UAV and in conjunction with photogrammetric software can provide a high resolution DEM which in turn will help provide greater precision in a Soil Erodibility Index model for the Rio Grande watershed in Añasco, Puerto Rico.

Objectives

- Use GIS to create a soil erosion model based on the RUSLE equation to target a specific site.
- Use UAV to obtain recent aerial imagery to validate erosion risk of site with limited accessibility.

Study Area

The area of study is located within the Rio Grande watershed in Añasco, Puerto Rico. Elevation within the watershed varies from 1 to 1180 meters above sea level and stretches out to over 5,656,906.83 acres of mainly prime agricultural land. Using a soil erodibility map (K Factor) four zone where determined to provide good examples of the use of the RUSLE. The following soil properties were used to identify and map potential test sites:

Table 1

Soil Erodibility Properties of Potential Test Sites

Zones	Predominate Soils	Soil Erodibility	Area (ac)
Alfa	Dique Silt Loam	0.37	48.34
Bravo	Toa Silty Clay Loam	0.32	105.44
Charlie	Dique Silt Loam	0.37	144.58
Delta	Toa Silty Clay Loam	0.32	184.87

The four zones identified contained the soils with the highest probability for soil erosion on the banks of the Rio Grande River. Two of the zones identified contain similar erodibility properties which makes them stand out. Even though these soils represent the higher erodibility potential in their regions they are not considered to be highly erodible lands. This means if they demonstrate to be eroding it will most likely be because of the enviroment in which they are located. Figure 1 is a map that points out the location of all four zones within the watershed:

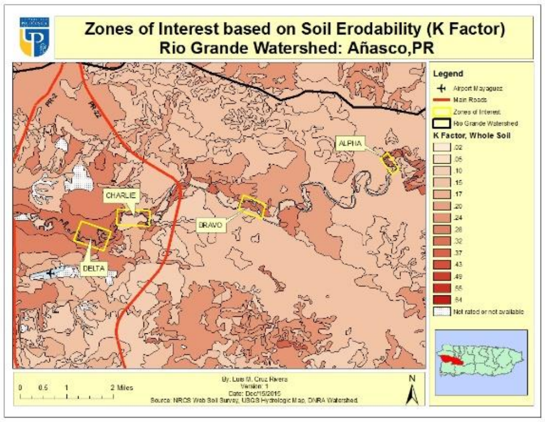

Figure 1

Map of Zones of Interest Based on Soil Erodibility

After analyzing the zones it was determined that for the purpose of this investigation it would only be necessary to select one zone. Zone Alpha and Charlie both demonstrated to have the greater potential for soil erosion based on the K factor of their soils yet zone Alpha's hydrological topography presents a greater threat for soil erosion. Zone Alpha can be seen below in figure 2.

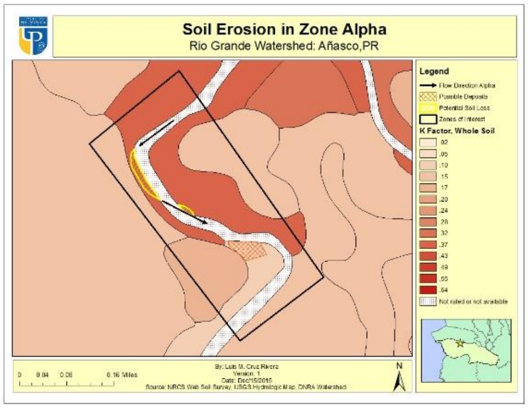

Figure 2

Map of Possible Erosion Scenario in Zone Alpha

The Rio Grande River assumes a meandering course which is known to gradually erode the outside backs of the river and deposit the sediment on the inside forming dunes on the inside corners of the stream. The deposition of this soil is due to a helical flow which carves into the bank. The more energy the stream carries the greater the effect of the helical flow on the bank. After analyzing aerial imagery take by UAV, zone Alpha demonstrated to be the greatest risk for this. Zone Alpha's higher elevation demonstrated to have greater influence on amount of flow energy that impacts the rivers banks. It was determined that zone Alpha would be the most suitable site to study. Also, part of this investigation depends on the authorization of the Federal Aviation Administration's fly zones for UAV, Zone Alpha was determined to be the best option for study.

METHODOLOGY

It was determined that the best way to study soil loss for the Rio Grande watershed was to target a region that contains the greatest potential for soil erosion within the watershed. Using K factor map four areas were determined to be suitable for study yet after taking into considerate hydrology, elevation and distance from airport it was determined that a single area would fit the purpose of this study. Zone Alpha presented the necessary soil and environmental conditions for the purpose of this study. It was decided that the RUSLE equation would best demonstrate annual soil loss potential for the Rio Grande watershed and because of its simplicity it would be easier to calculate within map algebra. The final product is intended to be model that will predict areas with higher annual soil loss potentials. A recent aerial image of the area of interest was captured by UAV in order to compare the results of the RUSLE model. Each layer was obtained from different sources. P factor was excluded from the final product because of the area of interest didn't have any active conservation practices. All raster layers were modified to not surpass a 30 meter pixel resolution in order to facilitate calculations made with the 30 meter digital elevation model used.

Materials

Hardware:

- Lenovo Thinkpad E540 laptop: 2.2 Ghz i7 core, 8 RAM.

- Dell Precision T3500 desktop: 3.07 Ghz Intel Xeon, 6 RAM.
- 3DRobotics Iris Quadcopter
- GoPro Hero 3+: 64 gbs, 10mp

Software:

- Image Mosaicking: Microsoft Research: Image Composite Editor (ICE): Version 2.0.3.0
- Ground Control Station: Mavlink Mission Planner: Version 1.3.34
- Geographical Information System: ESRI ArcGIS: Version 10.3.1

Soil Erosion Model (RUSLE)

The Revised Universal Soil Loss Equation (RUSLE) is an algorithm that was developed to model annual sheet and rill erosion potential in tons per hectare per year. RUSLE is a modified version of the universal soil loss equation (USLE) first published in 1965 in the USDA Agriculture Handbook 282 by W. Wischmeier and D. Smith. The RUSLE equation came to be was published later in 1978 in Agriculture Handbook 537. Like the USLE, RUSLE uses the soil erodibility (K Factor), slope length and steepness (LS factor), land cover (C Factor), and conservation practices (P Factor) to determine the annual soil loss potential in a given location [2]. USLE and RUSLE differ in the calculation of the rainfall-runoff (R factor). In the revised universal soil loss equation it was determined that the numerical value used for R in the soil loss equation must quantify the raindrop impact effect and must also provide relative information on the amount and rate of runoff likely to be associated with the rain [6]. With this in mind W. Wishchmeier derived a new R factor known as the "rainfall erosion index" which is now used in RUSLE. The RUSLE equation is calculated as follows (1):

$$A = R * K * LS * C * P \tag{1}$$

Where:
A = Annual Soil Loss (Tons/Hectare/Year)
R = Rainfall-Runoff Erosivity
K = Soil Erodibility
LS = Slope Length and Steepness
C = Cover & Management
P = Conservation Practices

Rainfall-Runoff Erosivity (R-Factor)

The rainfall-runoff erosivity factor for any given period is obtained by summing for each rainstorm the product of total storm energy I and the maximum 30-minute intensity (I30) [2]. Unfortunately these figures are rarely available at standard weather stations other methods have been developed and have proven to correlate with this data such as the Modified Fourneirs Index (MFI). Modified Fourniers Index developed by Arnoldus (1980) as seen in equation 2 was used to identify R factor [7].

$$MFI = \frac{\sum_{i=1}^{12} pi^2}{P} \tag{2}$$

$$Latter, R = (417 * MFI) - 152$$

Where:
pi = Average Monthly Precipitation (mm)
P = Average Annual Total Rainfall Rate (mm)
MFI = Modified Fourniers Index

During the revision of the USLE, the USDA created contours of the spatial variation of the R factor throughout the continental US [8]. The raster used for this investigation was created by NOAA's Coastal Management Administration in 2014 (see figure 4) and is based on the isoerodent maps published in the Runoff Estimates for Small Rural Watersheds and Development of a Sound Design method Volume II [9]. Figure 3 is an example of an isoerodent map.

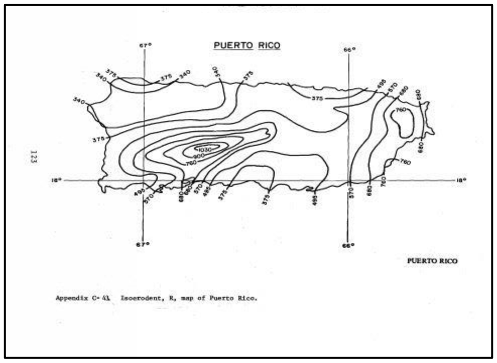

Figure 3
Isoerodent Map of Puerto Rico [9]

The isoerodent map created for Puerto Rico by Fletcher in the publication of the Runoff Estimates for Small Rural Watersheds and Development of a Sound Design method Volume II was intended to demonstrate the amount of energy released in a thirty minute intensity rainfall over Puerto Rico derived by using the following (3):

$$EI = \frac{\sum_{0}^{12}(916+331\ \log I)(I_{30\ max})}{100} \qquad (3)$$

Where:

I = Intensity of each constant intensity period of time multiplied by its volume in inches

I30 = Maximum 30 minute intensity for period of record.

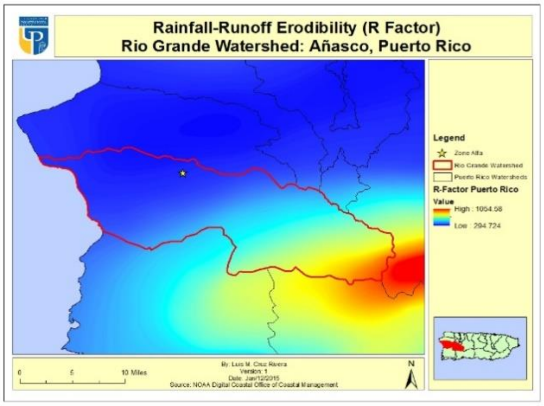

Figure 4
R-Factor Raster Layer [10]

Soil Erodibility (K-Factor)

The soil erodibility is determined based on different soil properties which define the susceptibility of a unit of soil to erode and the amount and rate and runoff. Soil texture, organic matter, structure and permeability determine the erodibility of a particular soil [2]. The K factor used was obtained by downloading the SSURGO digital soil database from the USDA-NRCS web soil survey website. This database was setup within a Microsoft Access database template included in the download and later viewed in ArcGIS via the "Soil Data Viewer" extension. The SSURGO database downloaded contains all the properties and qualities of the soil survey at study. The maps that are generated via "Soil Data Viewer" where then converted from a vector layer to a 30 meter resolution raster layer (seen in figure 5). The Rio Grande watershed lies within the Mayaguez soil survey, the Ponce soil survey and the San German soil survey which mean it was necessary to merge them to obtain the K factor for the entire watershed.

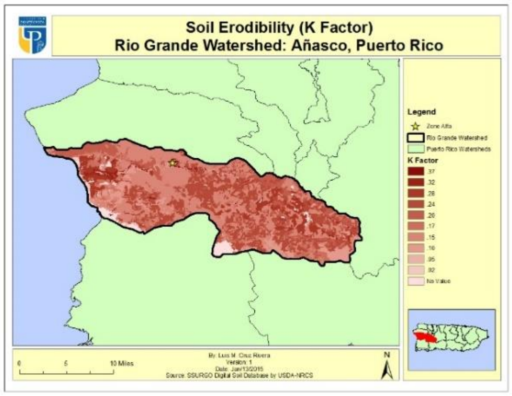

Figure 5
K-Factor of Rio Grande Watershed in Añasco, Puerto Rico

Slope Length and Steepness (LS-Factor)

The LS Factor is a combination of the slope steepness and slope length in such a way that allows the convenient calculation. The product of this calculation represent the potential soil erosion based on topographic conditions. Slope length (L) is defined as the distance from the source of runoff to the point where deposition begins, or runoff becomes focused into a defined channel [11]. Slope steepness represents the influence of slope gradient on soil erosion. The magnitude of soil erosion can be directly correlated with the length and angle of its surrounding topography. The greater accumulation of runoff on the longer slopes increases its detachment and transport capabilities [6]. This in combination with rainfall-runoff erosivity and soil erodibility one can clearly can identify highly erodible lands (HEL). The original equation used to derive the LS factor is seen below (4).

$$LS = \left(\frac{\lambda}{72.6}\right)^{m} * \ (65.41\sin\theta^{2} + 4.56\sin\theta + 0.065) \qquad (4)$$

Where:

λ = Slope length in feet

θ = Angle of slope

m = 0.5 if slopes >5

0.4 if slopes 3.5 to 4.5
0.3 if slopes 1 to 3
0.2 if slopes <1

This investigation adopted a LS factor equation which was designed for GIS applications (as seen in equation 5) with a digital elevation model. The equation used was published by the International Journal of Remote Sensing and Geoscience in 2013 by George Ashiagbor as the GIS equivalent to the LS factor equation by Wishchmeier & Smith [2].

$$LS = Pow\left([Flow\ Accumulation] * \frac{DEM\ Resolution}{22.1{,}0.4}\right) * Pow\left(\sin\frac{[Slope\ of\ DEM]}{0.09{,}1.4}\right) * 1.4 \qquad (5)$$

Where,
Pow = power

A 30 meter Digital elevation model of Puerto Rico (DEM) generated by the United States Geological Survey was used to determine the flow accumulation and slopes. All calculations where done within the map algebra tool in ArcGIS. The product of this equation can be seen in figure 6.

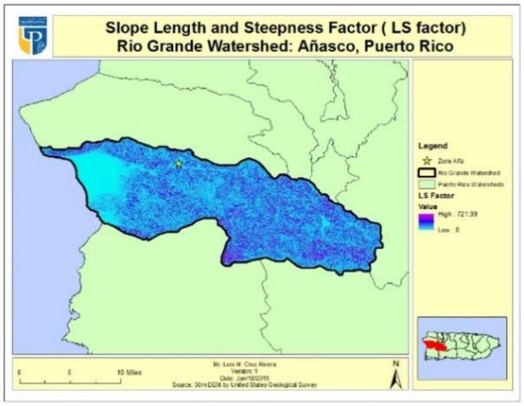

Figure 6
LS Factor using 30m DEM

Cover & Management Factor (C-Factor)

The C-Factor is a ratio of soil loss from land with specific vegetative densities to a correspond loss from fallow or bare soil conditions. The type and amount of vegetative cover reduces the effect of rainfall erosivity on soil and contributes to the reduction in runoff thus promoting infiltration. The C-Factor measures the combined effect of all interrelated cover and management variables, and it is the factor that is most readily changed by human activities [2].

In this study we obtained a 12 spectral bands of a Landsat 8 image of Puerto Rico (Path: 5, Row 47) on January 02 2016. Spectral bands 3, 4, and 5 where used to generate a false color image of the Rio Grande watershed. This Image was used to create a maximum likelihood supervised classification where five training groups where established based on C-Factor descriptions. The C-Factor description and values where adopted from Alejandra's M. Rojas study on soil erosion calculation of the Rio Grande watershed in Arecibo, Puerto Rico. C-Factors are directly related to the rainfall erosivity and since the rainfall runoff erosivity varies from location to location the C-Factor will also depend on its location. Alejandra's Rojas C-Factors were determined for the Arecibo watershed which shares similar rainfall runoff erosivity values to Añascos territory, this is why we proceeded to use the same C-Factor values (Table 2).

Table 2
Adopted C-Factor Values [12]

Training Group	**C-Factor Value**
Water	0
Dense Vegetation	0.002
Grass	0.12
Soil Without Vegetation	0.44
City	0.85

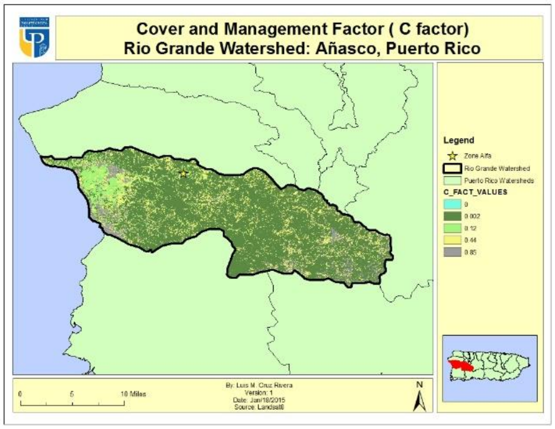

Figure 7
C-Factor Map

A C-Factor of 0.02% means that 0.02% of the amount of erosion will occur compared to continuous fallow conditions [2]. Using a sample of 44 randomly selected points within the watershed an error matrix was also created to validate the accuracy of the supervised classification, this matrix determined an overall accuracy of 75%. The C-Factor raster generated can be seen in figure 7.

Conservation Practices (P Factor)

The soil conservation practice factor outlines all of the practices that are actual being implemented in the area of interest to mitigate the eroding process. Such practices like strip cropping, cover crops, grassed waterways, terraces and more play an important role in reducing soil erosion. USDA-NRCS offers many different programs that assist land owners to implement these practices.

The area of interest of this investigation did not have any conservation practice implemented on nor around the test site. Nor could there be any other practice be located within the watershed so for the purpose of this model the P factor will not be influencing the final results. To do this, a P factor raster was created with pixels equivalent to 1. As seen in figure 8.

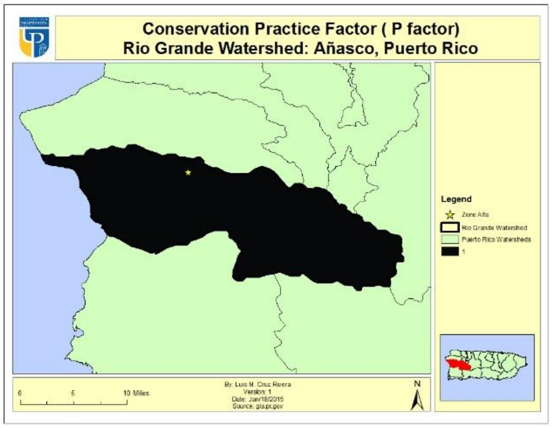

Figure 8
P-Factor Map

Collecting Aerial Images using Unmanned Aerial Vehicles to Validate Soil Erosion Model

In order to demonstrate the practicality of the soil erosion model created it was necessary to compare the results of the model with an image of the actual conditions of zone alpha. Since our area of interest was in a rural environment difficult to access by foot, we found it very prudent to use alternate means to access our area of interest. Images where collected via use of UAV.

Unmanned Aerial Vehicle (UAV)

During the past decades the use of UAV technology has become more and more predominate in environmental studies, this is due to the cost-effectiveness and efficient nature of these vehicles. UAV can not only venture to areas that would be difficult to reach on foot but they are capable of providing a broad spatial view of area of interest. They have also become less expensive than traditional platforms used for the same purposes. These platforms are complementary to traditional airborne or space borne platforms, and the can operate in circumstances where traditional platforms cannot, due to cost, lack of flexibility or danger [13].

Zone Alpha was located in area with dense vegetation and deep pools of water which made it difficult to access by foot. The UAV used was a quad copter model UAV which can move in various directions and hover to gather images of our area of interest unlike a fixed wing UAV. Quad copter UAV's provide more flexibility to collect data where elevations can shift drastically and present obstacles. The greatest flaw of using a quad copter UAV is the battery life which limits the flight time to a fraction of that of a fixed wing UAV. The UAV used was programmed using mission planner flight software (figure 9) under the following conditions (Table 3):

Table 3
UAV Flight Parameters

Condition	Parameters
UAV Flight Altitude	300 ft
Flight Speed	16.25 ft/s
Amount of Images Taken	98 @ 2 pic/s
Flight Duration	aprox 4 mins

Figure 9
UAV Flight Plan using Mavlink Mission Planner

Ninety eight images where taken over the full extent of zone Alpha, most of those images captured areas under very secluded conditions. Those ninety eight images where then stitched together using an open source software called Image Composite Editor by Microsoft. The final product provides insight to the current status of zone Alpha even though the image demonstrates some distortion because the lens used to collect the images was a wide angle lends from a GoPro Hero 3 plus (figure 10). The overall image shows a moving steam. The images collected show that the area predicted to be most affected by soil erosion is presently exposed bedrock. This demonstrates how the environmental conditions in zone Alpha influenced soil loss.

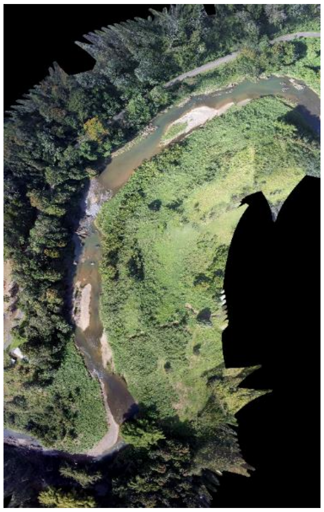

Figure 10
P-Factor Map

RESULTS

After obtaining the raster layers for each Factor we proceeded to calculate the annual soil loss potential for the Rio Grande watershed in Añasco, Puerto Rico (figure 11).

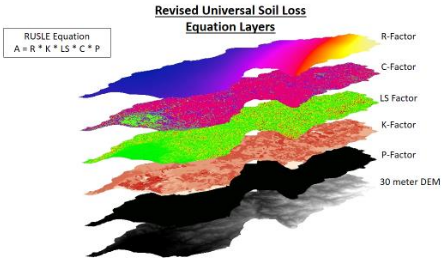

Figure 11
Layers Used to Run Soil Erosion Model

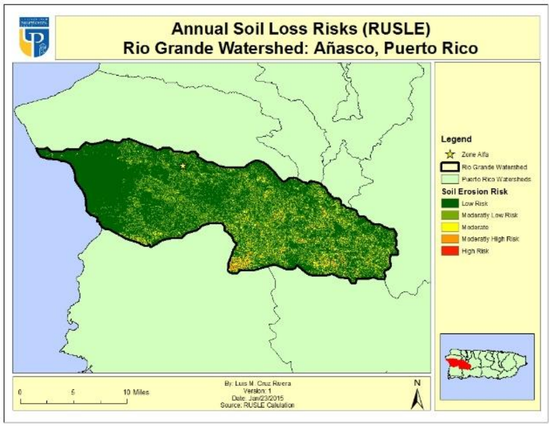

Figure 12
Final Product of the Soil Erosion Model Demonstrating the Annual Soil Loss

The annual soil loss layer (figure 12) was then used to identify the erosion potential in zone Alpha. The soil loss values within the zone Alpha were reclassified into five natural breaks to demonstrate differences in soil erosion potential within the area of interest and set the values apart from the rest of the watershed. Since the resolution of the DEM used was too low (30m) for site specific analysis, the close up on the final product was pixelated. To solve this we extracted the value of 97 points within the site and proceeded to use the kriging interpolation method to create a smooth image that represents the areas with greater erosion risks in zone alpha (figure 14). The final map demonstrates that the soil erosion potential identified using RUSLE is proportional to that hypothesized at the beginning of this investigation (figure 2).

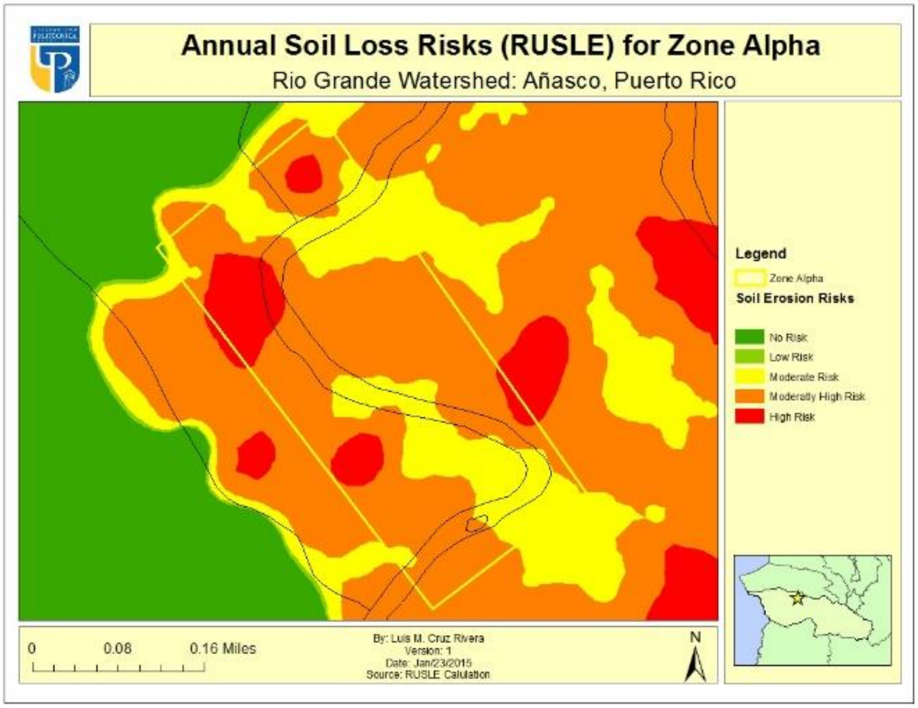

Figure 13
Areas within Zone Alpha that are affected by Soil Erosion based on Soil Erosion Model

Figure 14
Aerial Image Taken by UAV demonstrating that the Area Predicted to be Susceptible to Soil Erosion is Actually Eroded down to the Bedrock

CONCLUSION

Creating a soil erosion model within GIS has proven to be an effective method to identify areas of high risk of erosion. This investigation figured that in order to run a site specific erosion model it would be necessary to have a high resolution DEM. Since the DEM used had a 30 meter resolution it wasn't ideal to run the erosion model for zone Alpha creating a pixelated image with a broad scope. The soils data used to calculate RUSLE was created in the 1960's which means that they may or may not be up to date with what is actual happening in a given region. This is why it is important to have platforms such as UAV's to collect actual data. The UAV images taken served as a complement to demonstrate that the prediction of the erosion model was accurate. In the aerial image one can clearly identify the areas that have eroded down to the bedrock (figure 14). New methods developed are using UAV's and Photogrammetry to create high resolution DEM's but access to this technology was limited during this investigation. By using GIS and UAV technology in this investigation it was possible to locate the area with greatest soil erosion risk in zone Alpha and determine its current state.

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