

DEVELOPMENT OF A TROPICAL GEOGRAPHIC UNIT HYDROGRAPH IN THE LUQUILLO MOUNTAINS OF EASTERN PUERTO RICO: A NOVEL APPROACH

by

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(Under the Direction of Jason Christian)

ABSTRACT

Synthetic unit hydrographs (SUHs) are useful numeric models developed to predict empirical unit hydrograph parameters as a function of watershed characteristics. These statistical equations usually relate peak flow and timing to watershed characteristics. Once produced, a SUH estimates a storm hydrograph at the outlet of a watershed for a given excess precipitation amount. A sub class of SUHs is the Geographic Unit Hydrographs (GUH), which is informed by the geographic properties of basins (i.e. average slope, average land use, annual precipitation). Recent GUH models use geographic information systems (GIS) allow scientist and engineers to model the flow path and velocity to calculate the runoff response of that basin. This Tropical Geographic Unit Hydrograph (tGUH) model is developed for a specific tropical island environment, and includes an analytical methodology to derive required empirical coefficients directly from observed geographic characteristics, which in turn can provide a more consistent runoff estimate between users. Additionally, with the tGUH described here, unit hydrograph parameters are found to be sensitive to non-stationary parameters including land use (attributable to anthropogenic change) and annual precipitation change (attributable to climate change).

INDEX WORDS: Unit Hydrograph, Synthetic Unit Hydrographs, GIS, Tropical Hydrology

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CHAPTER 1

BACKGROUND

Introduction

Scientists and engineers monitor and collect streamflow data in rivers all around the world for purposes of flood prediction, structural specifications, water resource and ecological management. Entities such as the United States Geological Survey (USGS) maintain streamflow gauging stations and data throughout the nation and Puerto Rico. These stations provide critical information in water related disciplines but are not available for all watershed basins. Basins without available stream flow data are referred to as ungauged basins. These basins use synthetic unit hydrographs to express the rainfall-runoff response. Synthetic unit hydrographs (SUHs) are numeric models developed to predict unit hydrograph parameters as a function of watershed characteristics. These equations are usually theoretical or empirical methods relating peak flow and timing to watershed characteristics. Once developed for a basin area, an SUH can produce a storm hydrograph at the outlet (Bedient 2013).

Synthetic Unit Hydrographs

The unit hydrograph (UH) theory, which was originally advanced by Sherman (1932), can be described as “basin outflow resulting from 1.0 unit of direct runoff generated uniformly over the drainage area at a uniform rainfall rate during a specified period of rainfall duration.” Traditional methods, including Snyder, Clark, and the SCS method are widely used for the derivation of SUHs but contain several challenges for implementation such as manually fitting ordinances and adjusting the area under the SUH curve to match excess rainfall (Singh 2014).

Clark's and Nash's methods define the shape of the hydrograph with the minimum number of parameters. In these semi-distributed and data driven hydrological models, the parameters have to be calibrated against observed streamflow which would not be available in ungauged basins. The Geographic Instantaneous Unit Hydrograph (GIUH) method allows for the derivation of important parameters of ungauged basins to compute the entire SUH shape. Using GIS to derive a SUH allows for high resolution representation of hydrological parameters. The advances facilitating the extraction of hydrological parameters using GIS contribute to limiting the role of calibration parameters in new hydrologic models (Singh 2014).

There have been many different SUHs developed throughout the years that have been used in predicting streamflow and flood frequency in ungauged basins. SUH methods assume that the unit hydrograph is representative of the combined effects of the area, shape, slope and storage within a watershed (Bedient 2013). Some synthetic unit hydrograph methods use lag time (t_p) or time to rise (T_R) to help describe the length of the main channel and shape of the basin. Other SUH methods use the relationship of timing and the inverse of the channel slope, which infers that if the watershed were longer and the slope smaller, there would be a greater time to rise. Other common parameters used include the peak flow (Q_p) and basin area relationships showing that a larger area would produce a higher peak flow (Bedient 2013).

Clark (1945) was the first to develop a fully time distributed SUH model by using a time-area relationship through a linear reservoir to generate a hydrograph for a watershed. These time-area relations can be derived from geographic information. A linear reservoir is used to represent the storage within the watershed (Cleveland 2008). The Clark model uses two parameters to derive the SUH: time of concentration (T_C) in hours, and storage coefficient (S) in hours of a single linear reservoir. The Clark IUH model can be expressed as:

Eq. (1)
$$U_i = C1 A_i + C2 U_i - 1$$

where U_i is the i -th ordinate of the IUH and A_i the i -th ordinate of the time–area diagram; $C1$ and $C2$ Clarks routing coefficients and can be calculated by:

Eq. (2)
$$C1 = \Delta t(S + 0.5\Delta t)$$

Eq. (3)
$$C2 = 1 - C1$$

where Δt is the computational interval in hours. To derive a UH of desired duration (D) use the equation:

Eq. (4)
$$U_i = 1/N(0.5i - N + U_i - N + 1 + \dots + U_i - 1 + 0.5 U_i)$$

where U_i is the i th ordinate of the UH of D -hour duration and computational interval Δt hours and N is the number of computational intervals in D -hours, $D/\Delta t$. Because Clark's model uses T_c and S , parameters which can only be derived from detailed knowledge of the basin, it can be difficult to estimate these parameters in ungauged basin (Singh 2014).

Snyder's method was an SUH developed from data originating in watersheds in the Appalachian Highlands. Snyder's method uses time to peak (t_p) in hours, peak discharge (Q_p) in cubic feet per second, and base time (t_b) in days to describe the shape of the hydrograph. The equations can be expressed as

$$\text{Eq. (5)} \quad t_p = C_T (L L_{CA})^{0.03}$$

$$\text{Eq. (6)} \quad Q_p = 640 C_p A / t_L$$

$$\text{Eq. (7)} \quad t_b = 3 + 3(t_L/24)$$

where C_T and C_p are dimensionless coefficients; A is area of watershed (mi^2); L is length of main channel (mi); L_{CA} is length of channel (mi) from the basin outlet to the point on the stream nearest to the outlet (Bedient 2013; Bhunya 2005). The Snyder method, in practical applications, is tedious and incorporates subjectivity by the manual fitting of points (Singh 2014). Bhunya *et al.* (2003) suggest a two-parameter gamma distribution that uses scaling parameters to derive the shape of the unit-less hydrograph so that no manual fitting of points is needed.

The SCS method developed by the Soil Conservation Service in 1957, calculates volume of runoff (V) and peak discharge (q_p) as described by

$$\text{Eq. (8)} \quad V = \frac{1}{2} q_p t_B = \frac{1}{2} q_p (t_P + t_e)$$

$$\text{Eq. (9)} \quad q_p = \frac{3}{4} V / t_p$$

where q_p has units in mm/hr and t_e is time from peak to end of hydrograph. To determine the shape of SUH from nondimensional q/q_p versus t / t_p hydrograph, the time to peak (t_p) and peak discharge (q_p) are computed as

$$\text{Eq. (10)} \quad t_p = D/2 + t_L$$

$$\text{Eq. (11)} \quad q_p = 484 A / t_P$$

where (D) duration of rainfall (hrs); q_p is in cfs; (A) is area (mi^2); t_p is in hrs (base time= $3/8 t_p$); and (t_L) is lag time from centroid of rainfall to peak discharge (q_p) in hours. The value for t_L can be estimated from watershed characteristics using curve number (CN), length of the watershed, and the slope. The curve number is an empirical parameter that ranges from 30 to 100 used to describe the runoff potential. A smaller curve number means less runoff potential and more permeable soil. With known q_p , t_p , and the specified dimensionless UH, an SUH can be derived for any ungauged basin (Bedient 2013; Singh 2014). Candela *et al.* (2014) use a bivariate representation of rainfall forcing (rainfall duration and intensity) and a rainfall runoff model based on the SCS method to estimate synthetic flood design hydrographs (SFDH).

The Nash model is a common and accepted method to approximate runoff response. Nash (1957) used a cascade of n equal linear reservoirs with equal storage coefficients (K) to derive an instantaneous unit hydrograph (IUH). In the model a uniform unit depth of rainfall is applied to only the n th reservoir and is routed through the other reservoirs. The outflow from one reservoir is the inflow to the next and the outflow from the first reservoir, nearest to outlet, is considered to be the IUH. Nash's model can be expressed numerically as:

$$\text{Eq. (12)} \quad q(t) = 1/KT(n)(t/K)^{n-1}e^{-(t/K)}$$

where K has units of time, n is dimensionless, and $q(t)$ is depth of runoff per unit time per effective rainfall at time t . Nash's model has been used to determine the direct runoff hydrograph and used in sediment modeling. While it is widely used, the Nash model has a few discrepancies such as the model ignores translation, rain falling only on the n th reservoir, and the number of

reservoirs (n) generally does not come out as a whole number (Singh 2014). Bhunya *et al.* (2005) created a more specific form of the Nash model where they use two serially connected reservoirs of unequal storage.

Another method used is the Geomorphic Instantaneous Unit Hydrograph (GIUH). The GIUH is developed by relating IUH peak and time to peak to geographic parameters of the catchment. Because geographic parameters are generally time-invariant in nature, the GIUH approach would utilize these parameters and would be one of the more suitable techniques for modeling the runoff response for ungauged basins (Swain *et al.* 2015). Rodríguez-Iturbe and Valdés (1979) developed a fully analytical and complicated expression for calculating the GIUH based on the final probability density function. They also assumed a linear reservoir to express an exponential holding time. Rodríguez-Iturbe and Valdés (1979) suggested that it is adequate to assume a triangular IUH and only need to express time to peak (t_p), time to base (t_B), and the peak value (q_p) of the IUH. These are expressed as:

$$\text{Eq. (13)} \quad q_p = \left(\frac{1.31}{L}\right) R_L^{0.43} v$$

$$\text{Eq. (14)} \quad t_p = 0.44 \left(\frac{L}{v}\right) R_B^{0.55} R_A^{-0.55} R_L^{-0.38}$$

$$\text{Eq. (15)} \quad t_B = 2/q_p$$

Where L is the length of main channel in km, v is average peak flow velocity in m/s. Rodríguez-Iturbe and Valdés (1979) also used a shaping factor β which is a function of only basin

characteristics whose values in nature are normally between 3 and 5 for R_B , between 1.5 and 3.5 for R_L and between 3 and 6 for R_A :

Eq. (16)
$$\beta = 0.584 \left(\frac{R_B}{R_A} \right)^{0.55} R_L^{0.05}$$

The GIUH yields a smooth and single valued shape representing a unit volume of runoff and provides benefits for application in ungauged basins because it avoids the requirement of streamflow data (Singh et al. 1985; Singh 2007; Swain *et al.* 2015).

Geographic Information Systems used in Unit Hydrograph Development

In more recent years, hydrological and geomorphological parameters have been derived with the use of digital elevation models (DEM) and geographic information systems (GIS) (Olivera *et al.* 1999; Maidment 2002; Maidment *et al.* 1996). Because hydrology is closely connected to geography, GIS methods were the natural next step in this age of computers and modeling. With GIS technologies more widely used, much work has been done associating GIS methods to hydrology. Maidment *et al.* (1996) uses a DEM to create flow paths and velocities at the grid cell level and then sums the sub area hydrographs to compute the watershed runoff response. Cleveland *et al.* (2008) presents a reasonable approach to estimate UH parameters using DEM and a classification of developed or undeveloped for areas within the watershed. By tracking a particle's direction and velocity at the cell level, a time-area curve at the outlet can be determined. Follum (2015) uses a DEM and a land cover raster to estimate a rainfall runoff response based on Clark's UH method. Grimaldi *et al.* (2012) incorporates the GIUH concept to calculate the travel time distribution using river network flow velocity and hill slope velocity derived from DEM and soil-use information.

Objective

This work proposes a tropical Geographic Unit Hydrograph (tGUH) derived from remotely sensed data in eastern Puerto Rico to accurately predict the time-area curve for basins draining the Luquillo Mountains. Historically, there has been little consideration given to the validity of the classically developed SUH and GUH methods in tropical island basins. This proposed method of GUH derivation uses GIS layers to represent geographic properties of the ungauged watershed to produce scaling parameters for the time-area diagram. Geographic properties such as slope, basin area, land use, channel length, surface soil type, and annual precipitation are unique to each watershed, so that each watershed has a unique time-area curve. High resolution geographic data describing spatial distribution of elevation, land use, and precipitation data are publicly available for any location in Puerto Rico as well as the continental United States. This allows a user to produce the rainfall runoff response with minimal prior knowledge required of the ungauged basin. This method also allows different users to produce similar hydrographs because the model inputs are consistent and do not require as much professional judgement to determine appropriate model parameter values.

CHAPTER 2

STUDY AREA

This study focuses on six watersheds that drain from the Luquillo Mountains in eastern Puerto Rico: Gurabo, Espiritu Santo, Mameyes, Sabana, Grande, and Canovanas (Figure 2.1). The Luquillo Mountains are located in eastern Puerto Rico and their peak, El Toro, has an elevation of 1,074 meters which receives around 4500 mm of precipitation each year. Puerto Rico's climate is heavily influenced by the ocean and is classified as tropical maritime climate (Weaver 2012). With steep topography and small water storage capacity, Puerto Rico is vulnerable to extreme floods and droughts (Murphy 2012). There has been a shift from agricultural to a more industrial economy which has led to a rise in urban population and a decline in rural population allowing for reforestation. Nonforested landscapes tend to have lower rates of evapotranspiration as product of canopy interception and transpiration compared to forested areas which can increase the runoff in these areas by as much as 500 mm a year (Murphy 2012).

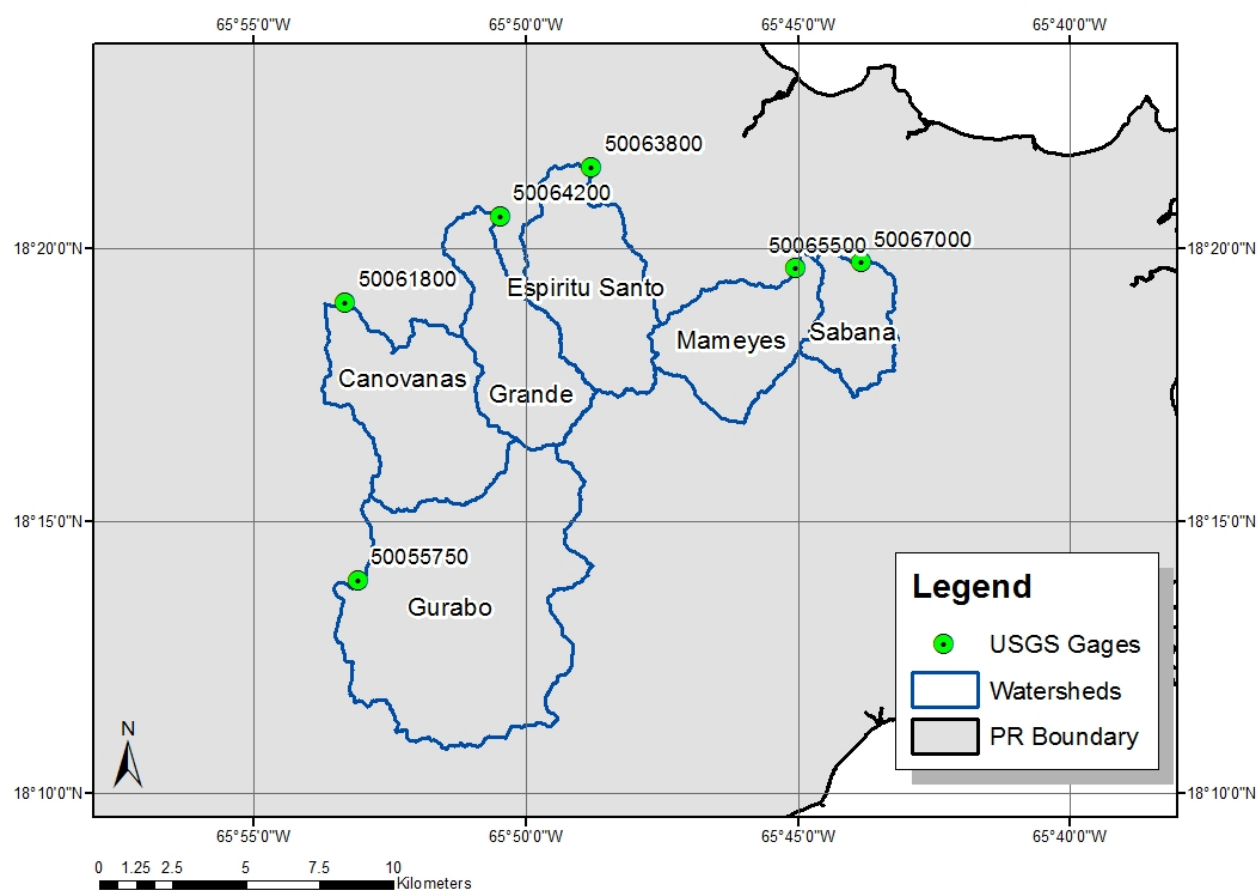


Figure 1: Six of the watersheds in the Luquillo Mountains in Puerto Rico

CHAPTER 3

MODEL INPUTS

All spatial data sets utilized in this work are available online from different government agencies. The National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS) produce one hour perception estimates and programs to manipulate the data. The United States Department of Agriculture (USDA) produce detailed soil data and is available through the Geospatial Data Gateway. Multi-Resolution Land Characteristics Consortium (MRLC) produces land use data sets and the United States Geological Survey (USGS) produces stream flow data and maintains stream flow gauges.

SSURGO (Soil Survey Geographic database) soil data was downloaded from the USDA Geospatial Data Gateway (Figure 2). Soils are classified into four types: A, B, C and D based on their hydrologic group (Hadadin 2012). Each hydrologic group is assigned a classification by an integer 1, 2, 3, or 4 that corresponds to the runoff potential with 1 being the least and 4 the most (Table 1). This allows for a numeric representation of soil type so that quantitative statistics can be calculated.

A digital elevation model (DEM) with 10 meter resolution was downloaded from USDA Geospatial Data Gateway. The DEM is used in ArcGIS to create features such as watershed boundaries, flow paths, stream networks, and slope (Figure 3). All the data layers were resampled to have consistent cell resolution and origin as the DEM. NLCD 2001 land use data are downloaded from the Multi-Resolution Land Characteristics Consortium (MRLC). Land use data are reclassified into four classifications: forest/woodland, grassland/shrubland,

developed/urban, and water (Figure 4). Using consecutive integers for land use types helps the statistical analysis of the watershed (Table 2). Annual precipitation layer (mm) is downloaded from water.weather.gov and is a National Weather Service Product (Figure 5). Stream flow data was collected from USGS gauges for the study basins (Table 3). One hour perception data is downloaded from NOAA. The one hour precipitation data set is a NEXRAD level 3 product that gives hourly precipitation estimates using a spatially distributed grid and is easily imported into ArcMap once processed using the Weather and Climate Toolkit available from NOAA.

Table 1: Soil type reclassified based on hydrologic group.

Soil Hydrologic Group	Runoff Potential	Infiltration Potential	Reclassified Value
A	Low	High	1
B	Moderate	Moderate	2
C	Moderate	Low	3
D	High	Low	4

Table 2: Land use type reclassified based on runoff potential.

Land Use Type	Runoff Potential	Reclassified Value
Forest/Woodland	Low	1
Grassland/Shrubland	Moderate	2
Developed/Urban	Moderate-High	3
Water	High	4

Table 3: USGS gauges with basin names and years of stream flow data used.

USGS Gauge Number	Basin Name	Year of Data Collected
50055750	Gurabo	2007-2015
50061800	Canovanas	2007-2015
50064200	Grande	2007-2015
50063800	Espiritu Santo	2007-2015
50065500	Mameyes	2007-2015
5006700	Sabana	2007-2015

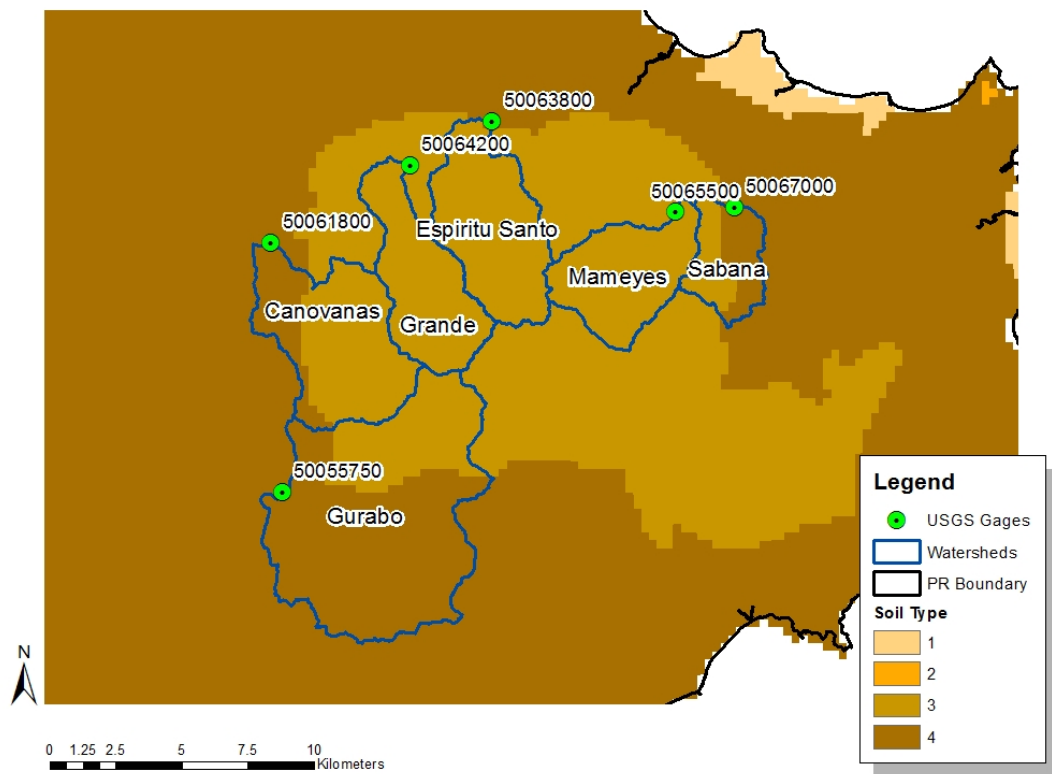


Figure 2: The six watersheds draining the Luquillo Mountains with reclassified soil data.

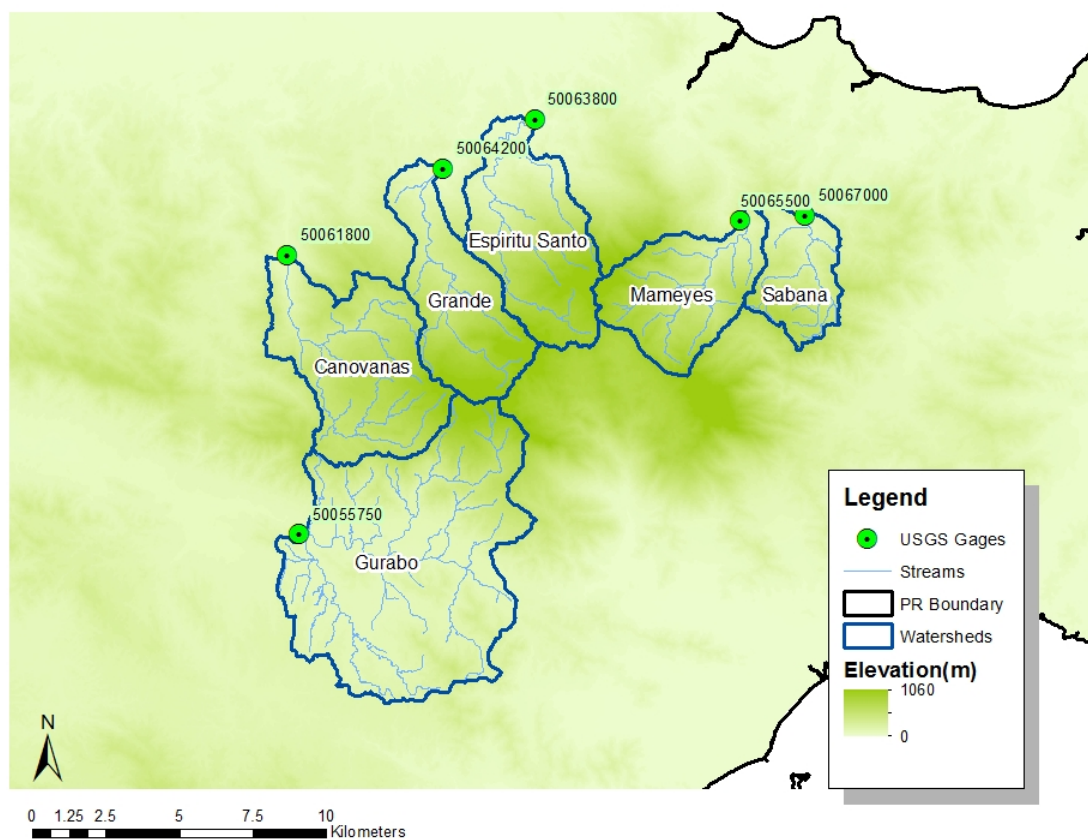


Figure 3: The six watersheds draining the Luquillo Mountains with stream networks and elevations.

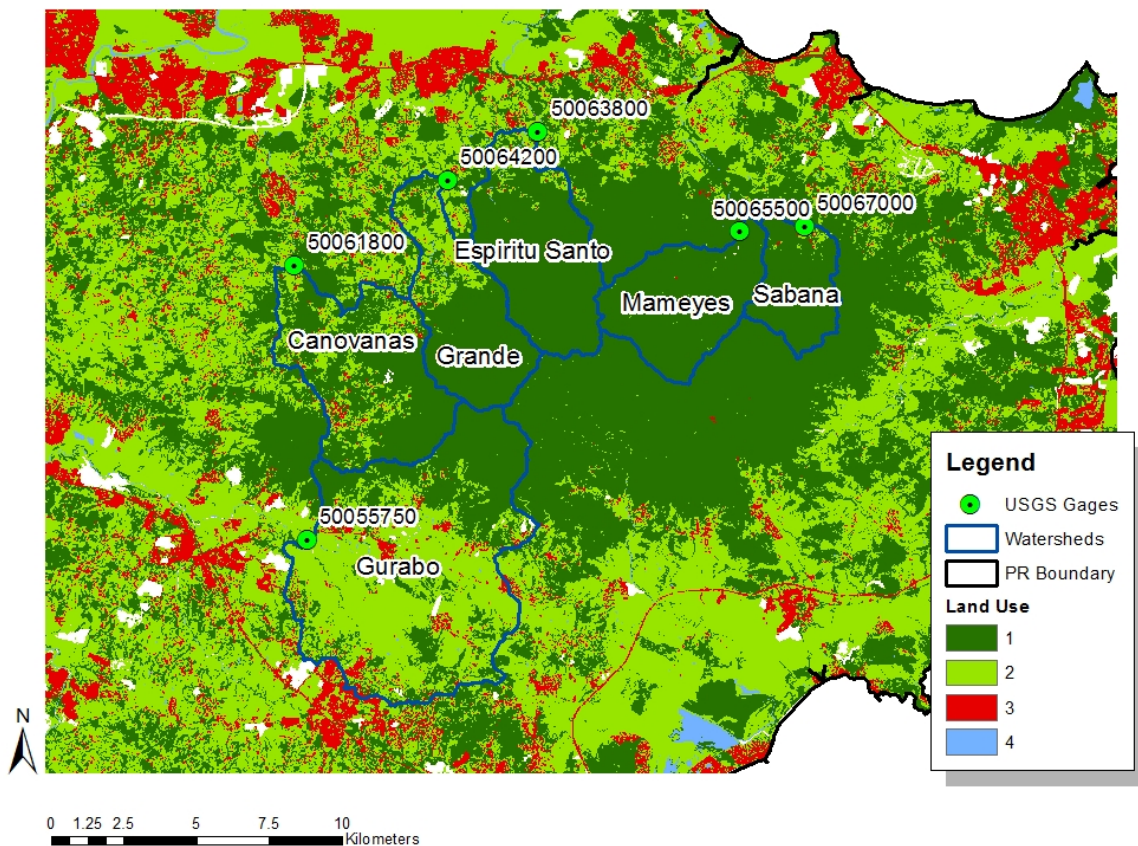


Figure 4: The six watersheds draining the Luquillo Mountains with reclassified land use data.

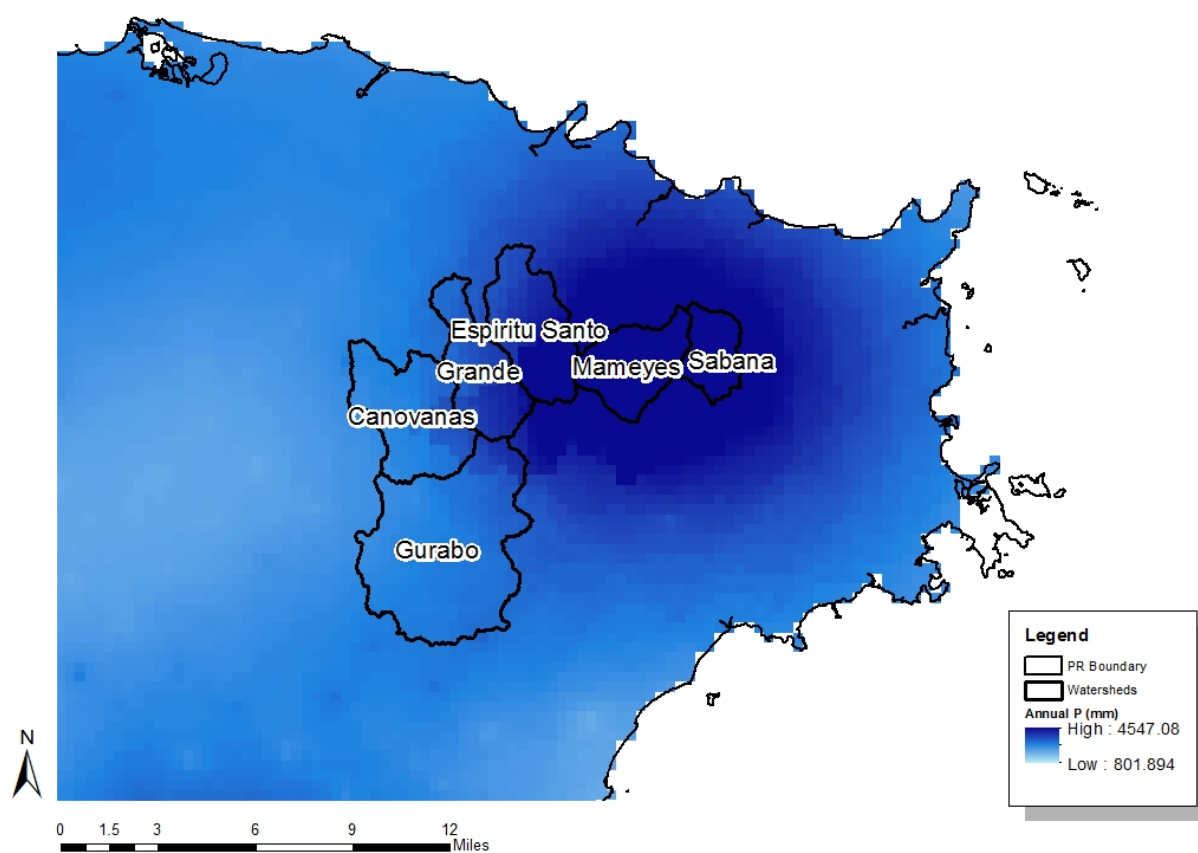


Figure 5: The six watersheds draining the Luquillo Mountains with annual precipitation data.

CHAPTER 4

METHODOLOGY

Unit Hydrograph Development

Tropical geographic unit hydrographs (tGUH) are produced from unit hydrographs for six gauged watersheds of gauged basins. Streamflow gauge data downloaded from the USGS for each of the six gages from 2007-2015. After locating runoff events from the gauge data, the corresponding one hour perception data is downloaded from NOAA. Using the Extract By Points tool in ArcMap a map is created showing hourly precipitation that fell on a watershed and its spatial distribution (Figure 6). This is a key step in advancing unit hydrograph development because the spatial distribution of rainfall can greatly affect the magnitude and timing of the runoff response. When developing unit hydrographs there is an assumption of uniform rain fall but some of the storms had an average rain fall that met the criteria but were not distributed evenly throughout the watershed. This was causing a quick response if the rainfall was located more towards the outlet and a delayed response if focused more towards the upper end of the watershed.

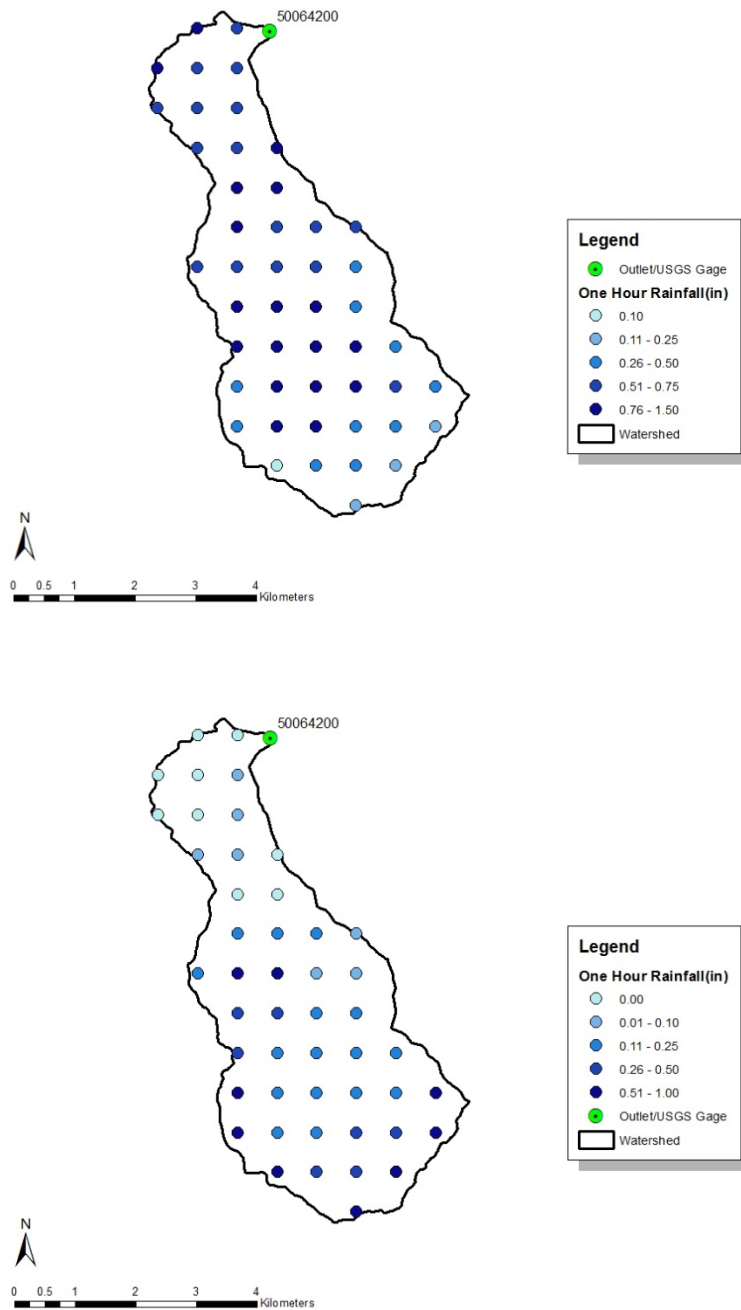


Figure 6: (Top) The Grande watershed with well distributed one hour rainfall. (Bottom) The Grande watershed with a poorly distributed one hour rainfall because there is no precipitation falling near the outlet and the more intense rainfall is at the top of the watershed.

Bedient (2013) describes the general rules to unit hydrograph development that need to be observed, including:

1. Storms need to have relatively uniform spatial and temporal distributions.
2. Watersheds should be between 1.0 and 100 mi².
3. Direct runoff should range from 0.5 to 2.0 inches.
4. Duration of rainfall excess should be approximately 25% to 30% of lag time.
5. A number of storms of similar duration should be analyzed to obtain an average unit hydrograph.

Observed candidate storms were screened to select events that were temporally isolated from other events to remove possible effects of antecedent rainfall. Once the storms were chosen, the one hour precipitation layers are exported to Excel to begin unit hydrograph derivation.

Following the steps of unit hydrograph derivation described by Bedient (2013), the process started by analyzing the hydrograph and separating base flow. In Excel the natural log of each of the hourly instantaneous stream flows are plotted to find the inflection point on the tailing end of the hydrograph. This is where the stream has returned to base flow. The base flow prior to rainfall is linearly connected to the inflection point streamflow (Figure 7). This is the base flow for the storm event and it is subtracted from the direct runoff hydrograph to produce the excess runoff hydrograph. Then by summing the total streamflow volume (ft³) of the excess runoff hydrograph and dividing by the basin area (ft²) we are left with feet of excess runoff which is then converted to inches.

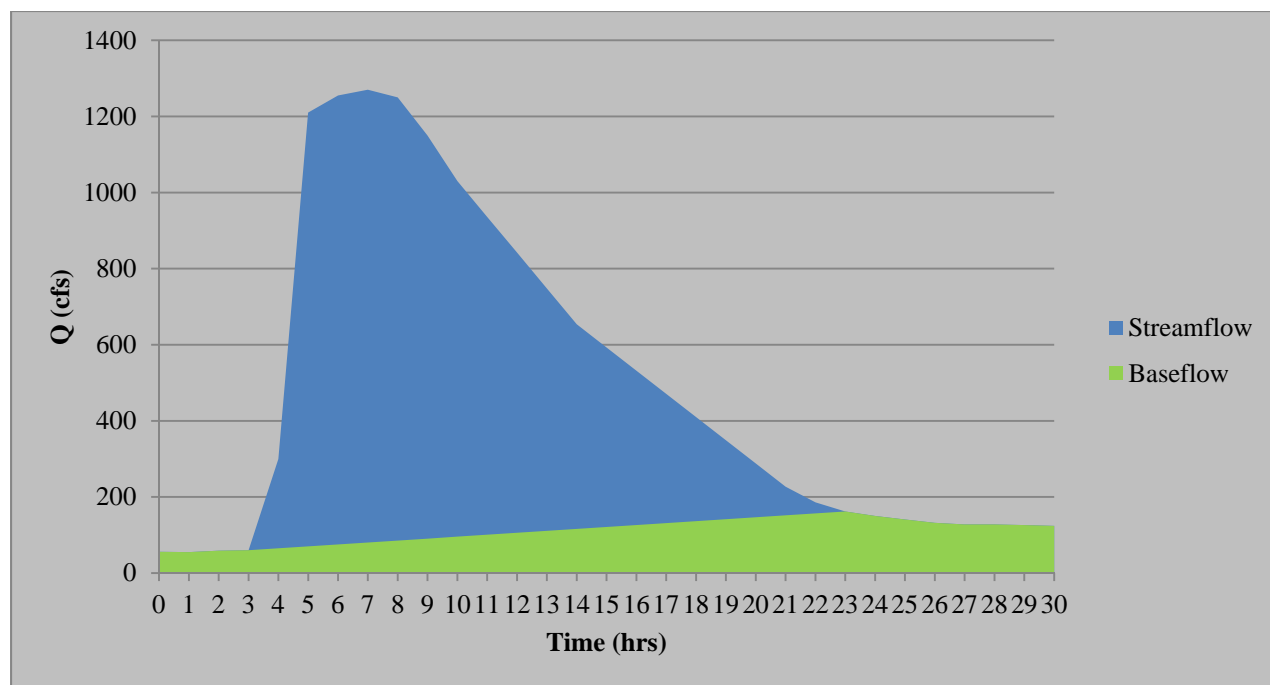


Figure 7: A plot showing streamflow and storm base flow.

The total rainfall to excess rainfall was converted by subtracting losses (i.e. infiltration, interception, evapotranspiration) so that excess rainfall (in) is equal to excess runoff (in). The UH ordinances are calculated using a simple script in MATLAB. The script runs based on the following equation:

$$\text{Eq. (17)} \quad [Q] = [P] [U],$$

where $[P]$ is precipitation, $[Q]$ is the storm hydrograph ordinates, and $[U]$ is the unit hydrograph ordinates. Given $[P]$ as a square precipitation matrix, equation 17 can be solved for $[U]$. Because the solution requires a square matrix with a nonzero determinant, the transpose matrix $[P^T]$ is used to generate and square symmetrical matrix $[P^T P]$ which is used to calculate the unit hydrograph ordinates $[U]$ as

$$\text{Eq. (18)} \quad [U] = [P^T P]^{-1} [P^T] [Q]$$

These steps are repeated for several storms for each of the basins and an average is taken to produce the basin's one hour unit hydrograph (Bedient 2013).

Time-Area Curves

Once the UH's were developed, time-area curves were created for these basins (Figure 8). By taking the UH ordinances (cfs/in) and converting the units to area per hour and summing each hour, to derive plot the area (mi^2) contributing to the outlet at an hourly time step. The time-area plots were used to develop an equation to describe the shape of the of the time-area curve (equation 19). From this equation the unique a , b and T_c values are calculated for each watershed based on the time-area curve.

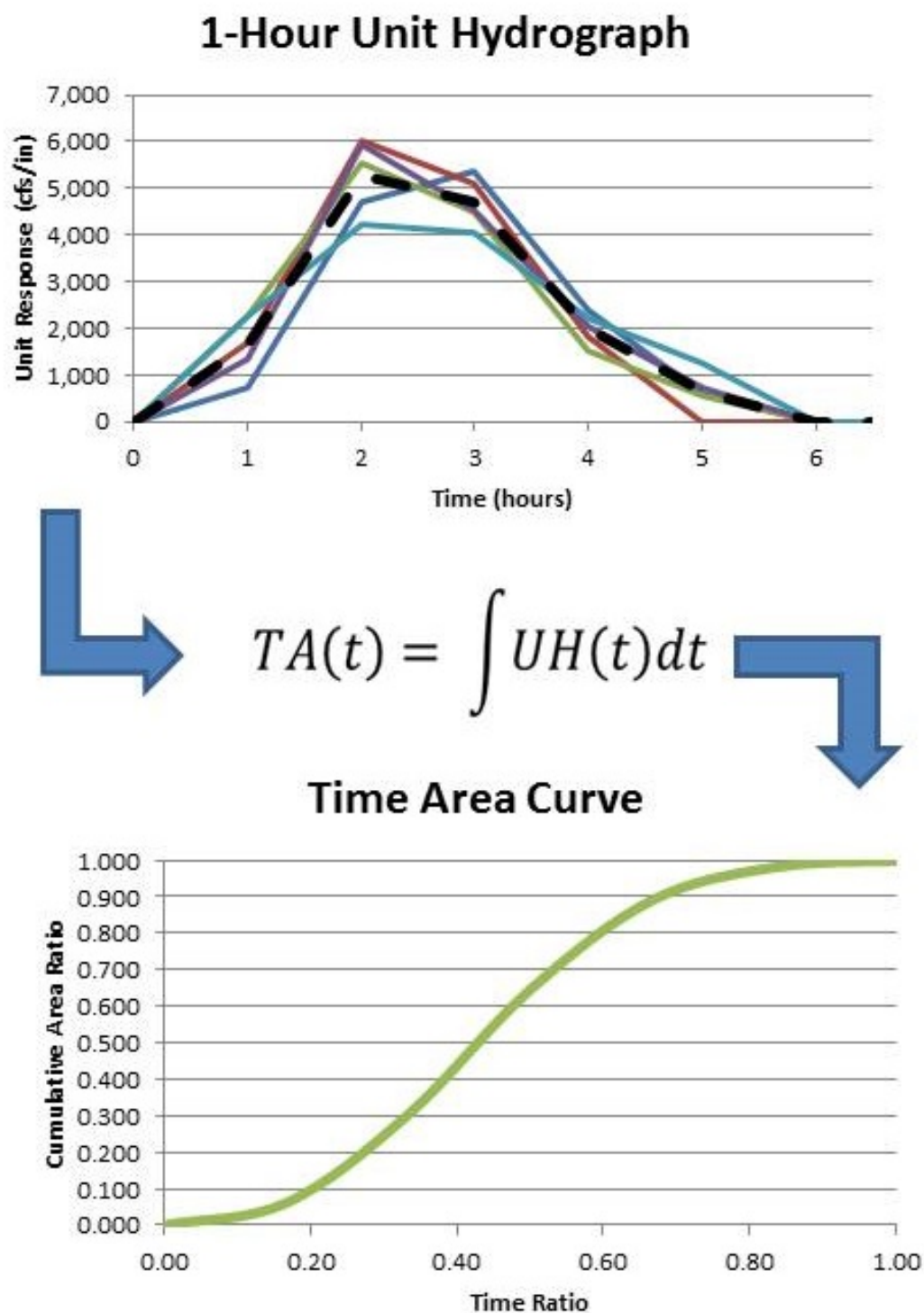


Figure 8: The time area curve (bottom) is the integration of the unit hydrograph (top).

Eq. (19)
$$TA(t) = \cos \left[\frac{\pi}{2} \left(e^{-at^b} \right) \right]$$

Where t is the time ratio (i.e., $\text{time}/(T_c+1)$), a and b are scaling parameters unique to each basin. The (T_c+1) used in the denominator of the time ratio is to account for the entirety of the storm flow called time to base (T_B). Time of concentration (T_c) is the time from the end of the rain fall until the return to base flow. Because one hour UH's were developed, the time to base would be T_c plus one hour (Figure 9). The cosine function was chosen because of its s-curve shape that resembles the time-area curve. The b parameter is used to explain the shape of the initial end of the cosine curve which is indicative of the area nearest to the outlet. The a parameter is used to show the shape of the tailing end of the cosine curve which is indicative of the area farthest from the outlet. By changing the a , b , and T_c parameters, the equation can fit observed time-area curves for a variety of basins.

Figure (10) shows the unique time-area curves for each of the study basins. The Gurabo basin and the Espiritu Santo basin have the most similar curves. The Mameyes basin and the Sabana basin have similar time-area responses but are much steeper initially and level off quicker than the Gurabo and the Espiritu Santo basins. The Grande basin is the quickest to respond with 90 percent of the basin contributing at only half of the time ratio. The Canovanas basin's time-area curve is the most unique of the study basins with a shallow initial slope leading to a much steeper slope. This shows that Canovanas initially responds slow and contributes at a higher rate during the course of the storm.

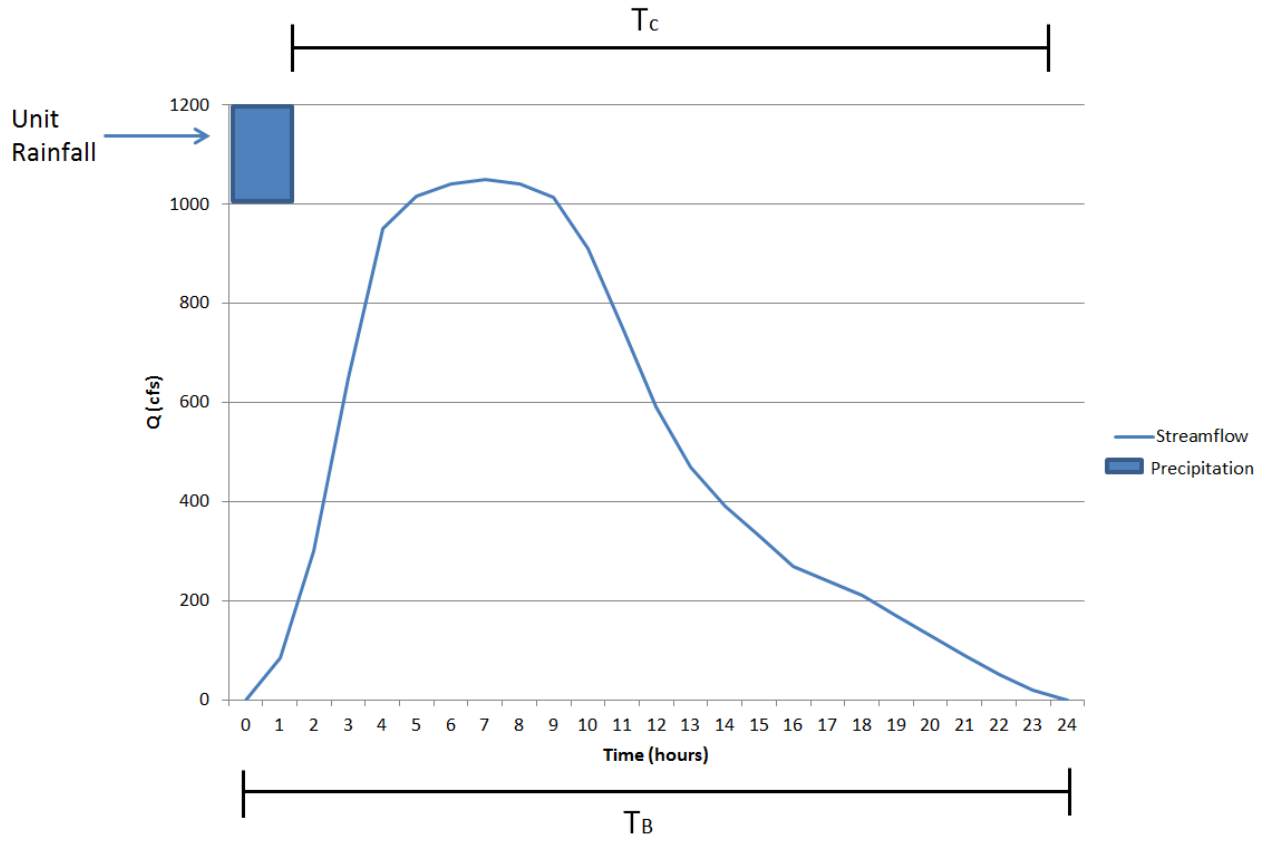


Figure 9: Hydrograph and hyetograph showing the time to base (T_B) and the time of concentration (T_c). For the T_c to account for the entire duration of excess runoff it must have the form of (T_c+1) for a one hour unit hydrograph.

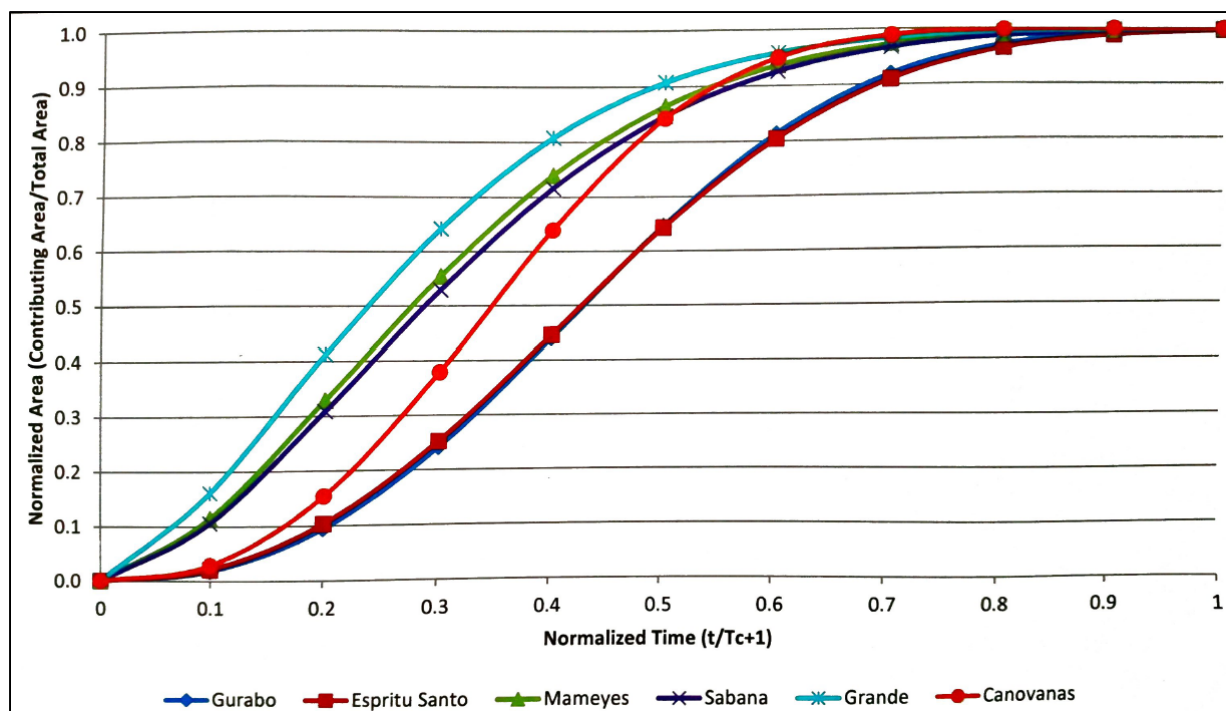


Figure 10: The unique time-area curves for each study basin.

Model Development

With developed time-area curves, a model is created using model builder within ArcGIS. The model calculates the unique T_c , a and b for any specified basin given DEM, soil layer, land use layer, annual precipitation layer and an outlet. The model starts by delineating the watershed that contributes to the outlet. In this process the DEM has the sinks filled so that there are no false outlets that the water would flow to instead of the specified outlet. The filled DEM is then used to create a flow direction raster (FDIR). The FDIR is then used to create the flow accumulation raster (FAC) which calculates how many cells would be contributing runoff to that cell. The outlet point is specified and the watershed is delineated by showing all the cells that that would contribute runoff to that outlet. The watershed is then converted to a shapefile (.shp) that will be used as a mask for extracting the rest of the data (Figure 11). The FDIR is then used to create a flow length raster (FLEN) that shows the flow path distance water on each cell would have to travel to reach the outlet. The FLEN is extracted to the watershed and the maximum value is stored (Figure 12). The slope is also calculated from the filled sinks DEM and is extracted using the mask. The soil, land use and annual precipitation layers are also extracted using the watershed mask. At this point in the model each of the layers needed for the analysis are clipped to just the basin area.

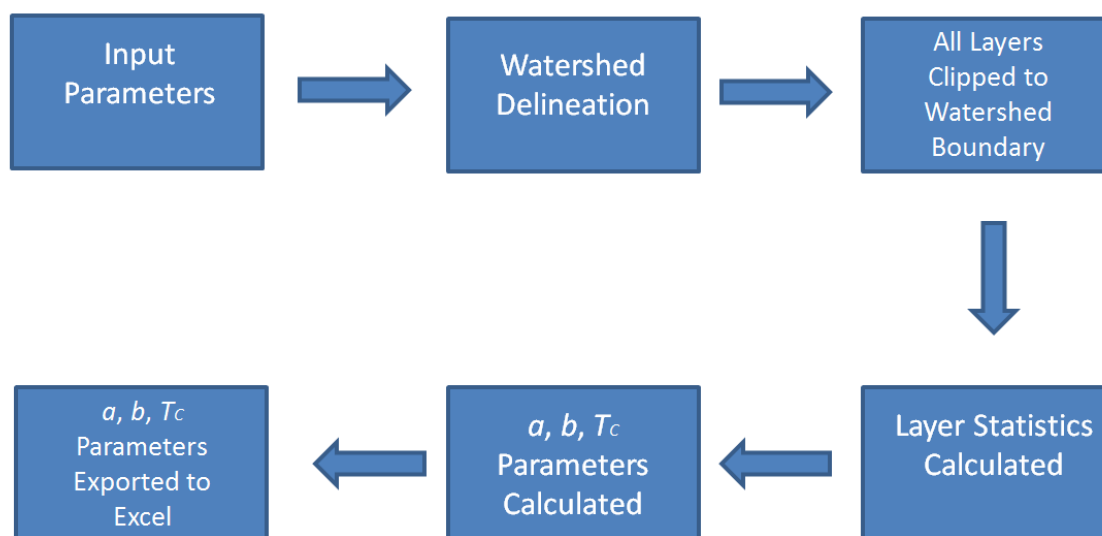


Figure 11: A flow diagram showing the general function of the model to calculate a , b and T_c values.

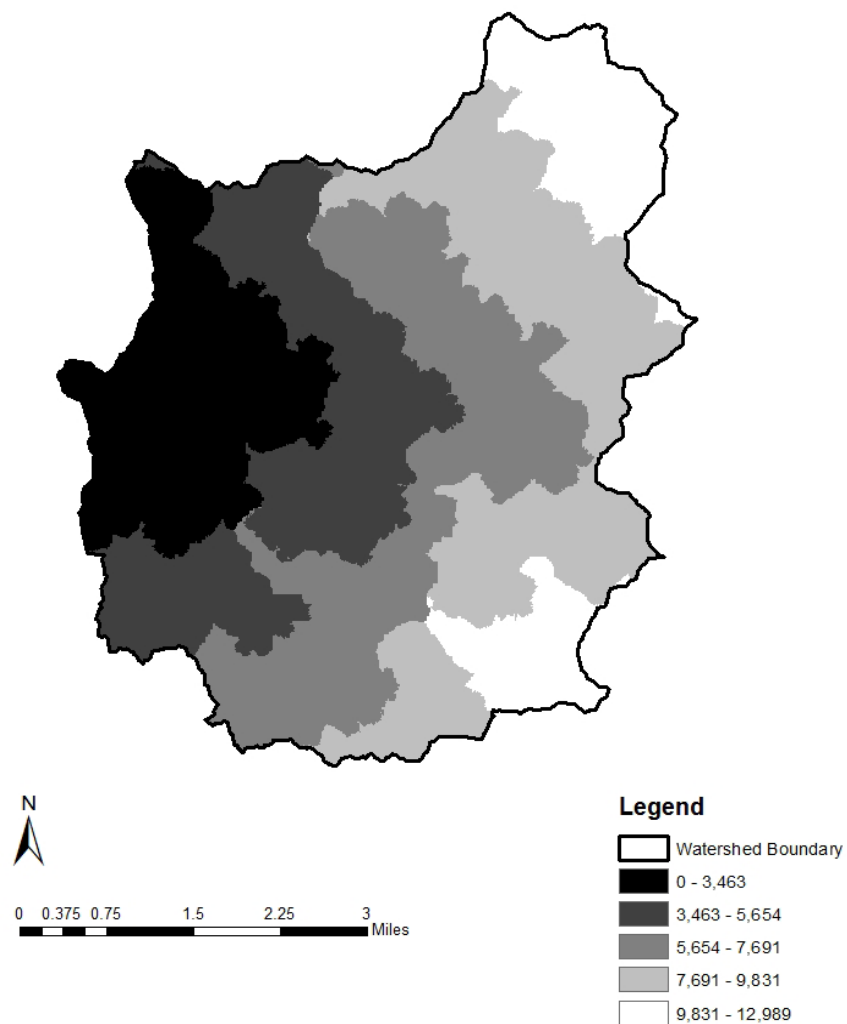


Figure 12: The Gurabo watershed showing the calculated flow lengths.

Now the model has an average layer for slope, land use, annual precipitation, elevation and soil. The average annual precipitation, average elevation, and maximum flow length are also calculated. The model also calculates a shape factor from the area divided by the length of the watershed to help describe the shape. A larger shape factor would mean a shorter and wider watershed while a smaller shape factor would mean the watershed is longer and thinner. Using the values for each of the geographic layers produced, the correlation function in Excel was used to find which layers best describe the a , b and T_c parameters (Table 4).

Table 4: The correlation values for a , b , and T_c for each of the geographic properties of the study basins.

	a	b	T_c
Average Elevation	0.310	-0.362	-0.125
Annual Precip.	-0.533	-0.652	-0.920
Shape Factor	-0.053	0.678	0.487
Area	-0.021	0.668	0.579
Slope Average	-0.056	-0.679	-0.658
Land Use Average	0.157	0.573	0.804
Soil Type Average	-0.046	0.342	0.252
Max Flow Length	0.274	0.783	0.626
(AvgElv*AvgLU)/Annual P	0.797	0.273	0.714

The geographic descriptor $(AvgElv * AvgLU) / Annual P$ was chosen to find a higher correlating value for the a parameter. The a parameter positively correlated with the *Average Elevation* and the *Land Use Average* while having a negative correlation with *Annual Precipitation*. The geographic properties that had positive correlation values were placed in the numerator and properties that had negative correlation values were placed in the denominator to develop $(AvgElv * AvgLU) / Annual P$. The b parameter positively correlated well with *Land Use Average*, *Max Flow Length*, and the *Shape Factor*. The b parameter negatively correlated with *Annual Precipitation* and *Slope Average*. The properties that had negative correlation values were placed in the denominator to describe the inverse relationship they share with the b parameter. The T_c parameter had a positive correlation with *Land Use Average*, $(AvgElv * AvgLU) / Annual P$, and negative correlation with *Annual Precipitation*. The Solver add-in for Excel was used to create equations to calculate the parameters using the correlating geographic layer values. Not all correlating geographic properties are used in the equations because they were reduced to zero in the Excel Solver analysis. Once these equations were developed, they were applied to the model in ArcMap to be able to calculate the a , b and T_c parameters to then be used in equation (19) to create a time-area curve for any watershed draining the Luquillo mountains in eastern Puerto Rico.

CHAPTER 5

RESULTS

The equations that were developed for calculating the a , b and T_c parameters are a product of statistical analysis and are empirical in nature. Table (2) shows the values for each geographic property. Table (3) shows the actual verses calculated values for each parameter and the corresponding R^2 values.

Eq. (20)

$$a = 3.24 + 329112 \left[\frac{(AvgElev * LUAvg)}{AnnualP} \right]^{9.97}$$

Eq. (21)

$$b = 1.61 - 0.642 \left[\frac{(ShapeFact * LUAvg)}{AnnualP} \right]^{15.57} + 6.59 \left[\frac{MaxFLN}{SlopeAvg} \right]^{8.38}$$

Eq. (22)

$$T_c = 3.77[LUAvg]^{0.456} + 3.31 \left[\frac{(AvgElev * LUAvg)}{AnnualP} \right]^{2.15}$$

$MaxFLN$ is the maximum cell flow distance (km) of the watershed. The maximum flow distance is important hydrologically because it describes the maximum distance water has to flow to reach the outlet. $AnnualP$ is average annual precipitation (mm) that falls on that basin. $AvgElev$ is the average surface elevation (m). $LUAvg$ is the average land use (1-4) of the basin. The land use is an important descriptor because different land use types have different runoff values such as a heavily vegetated area is going to have a slower response and an area that is

impervious is going to have a quicker response. *SlopeAvg* is the average slope (degrees) of the surface of the basin. The slope of the watershed describes the amount of elevation loss over the distance. This helps provide information on the timing of the runoff response. The steeper the slope, the quicker the runoff response of a basin of the same size and shape. *ShapeFact* is the shape factor (area/length) and is used as a descriptor of shape of the watershed. A larger shape factor would mean a shorter and wider watershed while a smaller shape factor would mean the watershed is longer and thinner.

Table 2: Study basins and the values for each geographic property used in the developed equations.

	Basin	LuAvg	SlopeAvg	MaxFln	Annual_P	Shapfact	AvgElev
1	Gurabo	1.689	13.20	12.98	2081.09	1403.63	218.65
2	Espiritu Santo	1.087	16.10	12.67	3096.62	916.16	459.43
3	Mameyes	1.003	22.58	7.746	3830.06	876.23	507.82
4	Sabana	1.046	19.59	6.429	3745.53	650.71	323.12
5	Grande	1.246	16.74	10.98	2556.10	788.26	519.23
6	Canovanas	1.301	16.74	12.48	2044.03	931.56	470.72

Table 3: Showing the actual versus calculated parameter values and the R^2 values for each parameter.

Watershed	<i>a</i>	Calculated <i>a</i>	<i>b</i>	Calculated <i>b</i>	<i>Tc</i>	Calculated <i>Tc</i>
Gurabo	3.259	3.257	2.460	2.463	5.000	5.011
Espiritu Santo	3.006	3.248	2.353	2.496	4.000	4.190
Mameyes	3.440	3.243	1.655	1.614	4.000	3.973
Sabana	3.279	3.243	1.672	1.614	4.000	3.935
Grande	3.726	3.718	1.535	1.806	5.000	4.788
Canovanas	5.713	5.713	2.493	2.177	5.000	5.103
R^2		0.980		0.805		0.935

CHAPTER 6

DISCUSSION

This model was favorable in calculating the parameters for basins in the Luquillo Mountains in Puerto Rico as describe by the high R^2 values. A small sample size of basins was used in this study but this methodology is transferrable to other tropical islands and continental sub-tropical locations. The tGUH parameters are found to be sensitive to non-stationary parameters including land use (attributable to anthropogenic change) and annual precipitation change (attributable to climate change). This allows the tGUH to be used in past, current, and future scenarios given these changes. The tGUH method of development does not require empirical coefficients or large scale modeling for the user, which in turn can provide a more consistent runoff estimate between users. This study also takes into consideration rainfall intensity and distribution in the unit hydrograph development. By using spatially and temporally uniform rainfall to develop unit hydrographs the tGUH is advancing the UH method to better represent the true storm hydrograph.

Another major takeaway from this study is the high negative correlation of annual precipitation to these basin parameters. This shows that the amount of annual precipitation a basin has affects the runoff response. Other geography based hydrologic models do not account for annual precipitation. This is important because the changing climate is going to have effect on weather and precipitation patterns which in turn will affect how basins respond to the rainfall. McDonnell and Beven (2014) studied hydrologic process using tracer test and found that during a rain even the water in the streams was from earlier events and not the current rainfall. This is

explained by the water being stored in the soil and slowly working to the streams and not a large overland flow associated with the event as believed. The wetter a basin is the quicker the response because the hydraulic connectivity is higher. This is why we see a negative correlation with precipitation and time to concentration.

CHAPTER 7

CONCLUSION

This work presented a model for calculating unit hydrographs (tGUH) for basins draining the Luquillo Mountains in eastern Puerto Rico using ArcGIS. The model is automated and requires only a few inputs related to precipitation and geographic features. This is a novel approach to unit hydrograph development based on statistical representation of basin's geographic properties. Many types of SUHs and GUHs exist but were not developed or tested for tropical basins. The tGUH has a low computational cost and does not require much expertise to use. This tool will help forest managers, ecologist, and hydrologist predict stream flows in ungauged basins for research and management decisions.

CHAPTER 8

FUTURE WORK

This work can be expanded by increasing the sample size of the number watershed and testing the model in different regions of Puerto Rico, the Tropics, and sub-tropical continental climates. There are plans to test the tGUH in Uganda and other areas in Puerto Rico. The output parameters from this model will also be used in a physics based soil compartment model prepared for the US Forest Service for El Yunque National Forest in Puerto Rico. This model will represent the physical processes before, during, and after a rainfall event. The tGUH parameters (a , b and T_c) are inputs in the model that control the runoff response of the model. The tGUH is also related to another project for El Yunque National Forest where ecologists are working on riverine connectivity and fish passage. The model will allow for them to delineate a watershed from any defined point and develop a unit hydrograph for that basin. The a , b and T_c parameters will be used in the compartment model to calculate stream flows. This allows ecologists to not be limited to gauged basins and to model the past streamflow scenarios.

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APPENDIX A

```

# tGUH.py

# Import arcpy module

import arcpy

# Script arguments

Land_Cover = arcpy.GetParameterAsText(0)

if Land_Cover == '#' or not Land_Cover:

    Land_Cover = "F:\\PR_SUH\\Data\\Model_Output\\Current_files\\landcoverrs" # provide a
default value if unspecified

DEM = arcpy.GetParameterAsText(1)

if DEM == '#' or not DEM:

    DEM = "F:\\PR_SUH\\Data\\Model_Output\\Current_files\\demrs" # provide a default value if
unspecified

Outlet = arcpy.GetParameterAsText(2)

if Outlet == '#' or not Outlet:

    Outlet = "F:\\PR_SUH\\Data\\Grande\\Outlet.shp" # provide a default value if unspecified

Annual_P = arcpy.GetParameterAsText(3)

if Annual_P == '#' or not Annual_P:

    Annual_P = "F:\\PR_SUH\\Data\\Model_Output\\Current_files\\yrmm1rprs" # provide a
default value if unspecified

soil = arcpy.GetParameterAsText(4)

if soil == '#' or not soil:

```

```

soil = "F:\\PR_SUH\\Data\\Model_Output\\Current_files\\soil" # provide a default value if
unspecified

Parameters_xls = arcpy.GetParameterAsText(5)

if Parameters_xls == '#' or not Parameters_xls:

    Parameters_xls = "F:\\PR_SUH\\Data\\Model_Output\\Current_files\\Parameters.xls" #
provide a default value if unspecified

# Local variables:

dempro = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\dempro"

FillDEM = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\FillDEM"

DropRAS = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\DropRAS"

FDIR = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\FDIR"

OutletPro = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\OutletPro"

FACC = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\FACC"

SPP = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\SPP"

Watershed__3_ = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\Watershed"

WS_Boundary_shp = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\WS_Boundary"

Modified_Input_Features = WS_Boundary_shp

centroid = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\centroid"

centroid__2_ = centroid

AvgElev = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\AvgElev"

Landcover_Pro = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\LULCPRO"

Extract2 = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\extract2"

LUAvg = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\LUAvg"

```

```

Annual_Pre = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\ANP"
AnnualP = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\AnnualP"
AvgAnnP = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\AvgAnnP"
a = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\a"
Area = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\Area"
Len = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\Len"
shpfact = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\shpfact"
FDIR_clip = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\FDIR_clip"
FlowLen = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\FLEN"
MaxFln = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\MaxFln"
MaxFlnKM = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\MaxFlnKM"
Slopewhole = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\Slopewhole"
Extract3 = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\extract3"
SlopeAvg = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\SlopeAvg"
b = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\b"
tc = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\tc"
Areasqm = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\Areasqm"
Extract1 = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\extract1"
SoilAvg = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\SoilAvg"
SoilAvg__2_ = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\SoilAvg"

# Set Geoprocessing environments
arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

```

```

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

# Process: Project Raster

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.ProjectRaster_management(DEM, dempro,

"PROJCS['NAD_1983_StatePlane_Puerto_Rico_Virgin_Islands_FIPS_5200',GEOGCS['GCS_N
orth_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,
298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTI
ON['Lambert_Conformal_Conic'],PARAMETER['False_Easting',200000.0],PARAMETER['Fal
se_Northing',200000.0],PARAMETER['Central_Meridian',-
66.43333333333334],PARAMETER['Standard_Parallel_1',18.03333333333333],PARAMETER
['Standard_Parallel_2',18.43333333333333],PARAMETER['Latitude_Of_Origin',17.833333333
33333],UNIT['Meter',1.0]]", "NEAREST", "10.0539979266283", "", "",
"PROJCS['NAD_1983_UTM_Zone_20N',GEOGCS['GCS_North_American_1983',DATUM['D
_North_American_1983',SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Gree
nwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PAR
AMETER['false_easting',500000.0],PARAMETER['false_northing',0.0],PARAMETER['central
_meridian',-
63.0],PARAMETER['scale_factor',0.9996],PARAMETER['latitude_of_origin',0.0],UNIT['Meter
',1.0]]")

arcpy.env.scratchWorkspace = tempEnvironment0

```

```

arcpy.env.workspace = tempEnvironment1

# Process: Fill

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.Fill_sa(dempro, FillDEM, "")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Flow Direction

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.FlowDirection_sa(FillDEM, FDIR, "NORMAL", DropRAS)

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Project

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

```

```

arcpy.Project_management(Outlet, OutletPro,
"PROJCS['NAD_1983_StatePlane_Puerto_Rico_Virgin_Islands_FIPS_5200',GEOGCS['GCS_N
orth_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,
298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTI
ON['Lambert_Conformal_Conic'],PARAMETER['False_Easting',200000.0],PARAMETER['Fal
se_Northing',200000.0],PARAMETER['Central_Meridian',-
66.43333333333334],PARAMETER['Standard_Parallel_1',18.03333333333333],PARAMETER
['Standard_Parallel_2',18.43333333333333],PARAMETER['Latitude_Of_Origin',17.833333333
33333],UNIT['Meter',1.0]]", "",
"GEOGCS['GCS_North_American_1983',DATUM['D_North_American_1983',SPHEROID['GR
S_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.01745329251
99433]]", "NO_PRESERVE_SHAPE", "")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Flow Accumulation

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.FlowAccumulation_sa(FDIR, FACC, "", "FLOAT")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Snap Pour Point

```

```

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.cellSize

arcpy.env.cellSize = "MAXOF"

tempEnvironment2 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.SnapPourPoint_sa(OutletPro, FACC, SPP, "0.001", "OBJECTID")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.cellSize = tempEnvironment1

arcpy.env.workspace = tempEnvironment2

# Process: Watershed

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.Watershed_sa(FDIR, SPP, Watershed__3_, "VALUE")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Raster to Polygon

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

```

```

arcpy.RasterToPolygon_conversion(Watershed__3_, WS_Boundary_shp, "SIMPLIFY",
"VALUE")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Feature To Point

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.FeatureToPoint_management(WS_Boundary_shp, centroid, "CENTROID")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Zonal Statistics (2)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ZonalStatistics_sa(WS_Boundary_shp, "GRIDCODE", FillDEM, AvgElev, "MEAN",
"DATA")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Project Raster (3)

```

```

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.ProjectRaster_management(Land_Cover, Landcover_Pro,
"PROJCS['NAD_1983_StatePlane_Puerto_Rico_Virgin_Islands_FIPS_5200',GEOGCS['GCS_N
orth_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,
298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTI
ON['Lambert_Conformal_Conic'],PARAMETER['False_Easting',200000.0],PARAMETER['Fal
se_Northing',200000.0],PARAMETER['Central_Meridian',-
66.43333333333334],PARAMETER['Standard_Parallel_1',18.03333333333333],PARAMETER
['Standard_Parallel_2',18.43333333333333],PARAMETER['Latitude_Of_Origin',17.833333333
33333],UNIT['Meter',1.0]]", "NEAREST", "10.0539979266283", "", "",
"PROJCS['NAD_1983_StatePlane_Puerto_Rico_Virgin_Islands_FIPS_5200',GEOGCS['GCS_N
orth_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,
298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTI
ON['Lambert_Conformal_Conic'],PARAMETER['False_Easting',200000.0],PARAMETER['Fal
se_Northing',200000.0],PARAMETER['Central_Meridian',-
66.43333333333334],PARAMETER['Standard_Parallel_1',18.03333333333334],PARAMETER
['Standard_Parallel_2',18.43333333333333],PARAMETER['Latitude_Of_Origin',17.833333333
33333],UNIT['Meter',1.0]]")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

```

Process: Extract by Mask (2)

```
tempEnvironment0 = arcpy.env.scratchWorkspace
```

```
arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"
```

```
tempEnvironment1 = arcpy.env.workspace
```

```
arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"
```

```
arcpy.gp.ExtractByMask_sa(Landcover_Pro, WS_Boundary_shp, Extract2)
```

```
arcpy.env.scratchWorkspace = tempEnvironment0
```

```
arcpy.env.workspace = tempEnvironment1
```

Process: Zonal Statistics (11)

```
tempEnvironment0 = arcpy.env.scratchWorkspace
```

```
arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"
```

```
tempEnvironment1 = arcpy.env.workspace
```

```
arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"
```

```
arcpy.gp.ZonalStatistics_sa(WS_Boundary_shp, "GRIDCODE", Extract2, LUGAv, "MEAN",  
"DATA")
```

```
arcpy.env.scratchWorkspace = tempEnvironment0
```

```
arcpy.env.workspace = tempEnvironment1
```

Process: Project Raster (2)

```
tempEnvironment0 = arcpy.env.scratchWorkspace
```

```
arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"
```

```
tempEnvironment1 = arcpy.env.workspace
```

```
arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"
```

```

arcpy.ProjectRaster_management(Annual_P, Annual_Pre,
"PROJCS['NAD_1983_StatePlane_Puerto_Rico_Virgin_Islands_FIPS_5200',GEOGCS['GCS_N
orth_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,
298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTI
ON['Lambert_Conformal_Conic'],PARAMETER['False_Easting',200000.0],PARAMETER['Fal
se_Northing',200000.0],PARAMETER['Central_Meridian',-
66.43333333333334],PARAMETER['Standard_Parallel_1',18.03333333333333],PARAMETER
['Standard_Parallel_2',18.43333333333333],PARAMETER['Latitude_Of_Origin',17.833333333
33333],UNIT['Meter',1.0]]", "NEAREST", "10.0539979266283", "", "",
"PROJCS['NAD_1983_StatePlane_Puerto_Rico_Virgin_Islands_FIPS_5200',GEOGCS['GCS_N
orth_American_1983',DATUM['D_North_American_1983',SPHEROID['GRS_1980',6378137.0,
298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]],PROJECTI
ON['Lambert_Conformal_Conic'],PARAMETER['False_Easting',200000.0],PARAMETER['Fal
se_Northing',200000.0],PARAMETER['Central_Meridian',-
66.43333333333334],PARAMETER['Standard_Parallel_1',18.03333333333334],PARAMETER
['Standard_Parallel_2',18.43333333333333],PARAMETER['Latitude_Of_Origin',17.833333333
33333],UNIT['Meter',1.0]]")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Extract by Mask (5)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

```

```

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ExtractByMask_sa(Annual_Pre, WS_Boundary_shp, AnnualP)

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Zonal Statistics (4)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ZonalStatistics_sa(WS_Boundary_shp, "GRIDCODE", AnnualP, AvgAnnP, "MEAN",
"DATA")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Raster Calculator

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.RasterCalculator_sa("3.24 + (329112 * (((\\\"%AvgElev%\\\") * (\\\"%LUAvg%\\\")) /(
\\\"%AvgAnnP%\\\"))**9.97)", a)

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

```

Process: Polygon to Raster (3)

```
tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.PolygonToRaster_conversion(WS_Boundary_shp, "Shape_Area", Area,
"CELL_CENTER", "NONE", "190")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1
```

Process: Polygon to Raster (2)

```
tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.PolygonToRaster_conversion(WS_Boundary_shp, "Shape_Length", Len,
"CELL_CENTER", "NONE", "190")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1
```

Process: Raster Calculator (3)

```
tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"
```

```

arcpy.gp.RasterCalculator_sa('" "%Area%" / "%Len%"', shpfact)

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Extract by Mask (4)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ExtractByMask_sa(FDIR, WS_Boundary_shp, FDIR_clip)

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Flow Length

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.FlowLength_sa(FDIR_clip, FlowLen, "DOWNSTREAM", "")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Zonal Statistics (3)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

```

```

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ZonalStatistics_sa(WS_Boundary_shp, "ID", FlowLen, MaxFln, "MAXIMUM",
"DATA")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Raster Calculator (5)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.RasterCalculator_sa("\\%MaxFln%\\"/1000", MaxFlnKM)

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Slope (3)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.rasterStatistics

arcpy.env.rasterStatistics = "STATISTICS 1 1"

tempEnvironment2 = arcpy.env.resamplingMethod

arcpy.env.resamplingMethod = "NEAREST"

tempEnvironment3 = arcpy.env.tileSize

arcpy.env.tileSize = "128 128"

tempEnvironment4 = arcpy.env.pyramid

```

```

arcpy.env.pyramid = "PYRAMIDS -1 NEAREST DEFAULT 75 NO_SKIP"

tempEnvironment5 = arcpy.env.nodata

arcpy.env.nodata = "NONE"

tempEnvironment6 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.Slope_sa(dempro, Slopewhole, "DEGREE", "1")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.rasterStatistics = tempEnvironment1

arcpy.env.resamplingMethod = tempEnvironment2

arcpy.env.tileSize = tempEnvironment3

arcpy.env.pyramid = tempEnvironment4

arcpy.env.nodata = tempEnvironment5

arcpy.env.workspace = tempEnvironment6

# Process: Extract by Mask (3)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.terrainMemoryUsage

arcpy.env.terrainMemoryUsage = "false"

tempEnvironment2 = arcpy.env.parallelProcessingFactor

arcpy.env.parallelProcessingFactor = ""

tempEnvironment3 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ExtractByMask_sa(Slopewhole, WS_Boundary_shp, Extract3)

```

```

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.terrainMemoryUsage = tempEnvironment1

arcpy.env.parallelProcessingFactor = tempEnvironment2

arcpy.env.workspace = tempEnvironment3

# Process: Zonal Statistics (13)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ZonalStatistics_sa(WS_Boundary_shp, "GRIDCODE", Extract3, SlopeAvg, "MEAN",
"DATA")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Raster Calculator (2)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.RasterCalculator_sa("1.61-(.0642
*(((("%LUAvg%"*("%shpfact%")/(("%AvgAnnP%"))**15.57)))+(6.59*((("%MaxFlnKM%"\\
"%SlopeAvg%")**8.38))), b)

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

```

Process: Raster Calculator (4)

```
tempEnvironment0 = arcpy.env.scratchWorkspace
```

```
arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"
```

```
tempEnvironment1 = arcpy.env.workspace
```

```
arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"
```

```
arcpy.gp.RasterCalculator_sa("(3.77*(\\\"%LUAvg%\\\") ** 0.456)+(3.31*(\\\"%AvgElev%\\\" * \\\"%LUAvg%\\\")/\\\"%AvgAnnP%\\\")**2.15)", tc)
```

```
arcpy.env.scratchWorkspace = tempEnvironment0
```

```
arcpy.env.workspace = tempEnvironment1
```

Process: Add Geometry Attributes

```
arcpy.AddGeometryAttributes_management(WS_Boundary_shp, "AREA", "",
```

```
"SQUARE_MILES_US", "")
```

Process: Polygon to Raster (4)

```
tempEnvironment0 = arcpy.env.scratchWorkspace
```

```
arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"
```

```
tempEnvironment1 = arcpy.env.workspace
```

```
arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"
```

```
arcpy.PolygonToRaster_conversion(Modified_Input_Features, "POLY_AREA", Areasqm,
```

```
"CELL_CENTER", "NONE", "190")
```

```
arcpy.env.scratchWorkspace = tempEnvironment0
```

```
arcpy.env.workspace = tempEnvironment1
```

Process: Extract Multi Values to Points

```

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ExtractMultiValuesToPoints_sa(centroid,
"F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\a
a;F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\b
b;F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\tc
tc;F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb\\Areasqm Area__sq_mi", "BILINEAR")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Table To Excel

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.TableToExcel_conversion(centroid__2_, Parameters_xls, "ALIAS", "CODE")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Extract by Mask

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

```

```

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ExtractByMask_sa(soil, WS_Boundary_shp, Extract1)

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Zonal Statistics (12)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ZonalStatistics_sa(WS_Boundary_shp, "GRIDCODE", Extract1, SoilAvg, "MEAN",
"DATA")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

# Process: Zonal Statistics (16)

tempEnvironment0 = arcpy.env.scratchWorkspace

arcpy.env.scratchWorkspace = "F:\\PR_SUH\\Data\\Model_Output\\Scratch.gdb"

tempEnvironment1 = arcpy.env.workspace

arcpy.env.workspace = "F:\\PR_SUH\\Data\\Model_Output\\Current.gdb"

arcpy.gp.ZonalStatistics_sa(WS_Boundary_shp, "GRIDCODE", Extract1, SoilAvg__2_,
"MEAN", "DATA")

arcpy.env.scratchWorkspace = tempEnvironment0

arcpy.env.workspace = tempEnvironment1

```