

A Methodology for Prediction of Geomorphological
Changes of Alluvial Valleys in Sites with Limited Historical Data

By

Victor M. Vargas Lugo

A proposal submitted in partial fulfillment of the requirements for the degree of

DOCTOR of PHILOSOPHY
in CIVIL ENGINEERING

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
AUGUST 2016

Approved by:

_____ Walter F. Silva Araya, Ph.D. President, Graduate Committee	_____ Date
_____ Raúl E. Zapata López, Ph. D. Member, Graduate Committee	_____ Date
_____ Jorge Rivera Santos, Ph. D. Member, Graduate Committee	_____ Date
_____ Luis Pérez Alegría, Ph. D. Member, Graduate Committee	_____ Date
_____ Ismael Pagán Trinidad, M.S.C.E. Chairperson of the Department	_____ Date

Table of Contents

Introduction and Justification	3
Proposed Work.....	5
Geologic and Climatic Conditions of the Rivers included in this proposal	8
Fluvial geomorphology.....	12
Channel evolution theory.....	14
Evolution of drainage net	16
Sediment transport and geomorphological modeling software	19
Objective.....	24
Methodology.....	24
Bibliography.....	29

List of Figures

Figure 1. AOI Watersheds. A: Number of years with flow discharge at USGS stations. B: Number of years with suspended sediment data at USGS station. 7

Figure 2. AOI alluvial valleys. North to South: Río Culebrinas Valley, Río Añasco Valley and Río Guanajibo Valley [44]. 7

Figure 3. Geologic maps of the AOI. A) Culebrinas Valley and Río Culebrinas Watershed; B) Añasco Valley and Río Grande de Añasco Watershed; and C) Guanajibo Valley and Río Guanajibo Watershed. 9

Figure 4. Stages of the channel evolution. h_c = critical bank height (maximum height in which the banks will keep its stability). Arrows are the direction of banks movement [21]. 15

Figure 5. Different Channel drainage movement by migration [43]. 16

Figure 6. Flowchart of the available data processing options before it enters to the model. 26

List of Tables

Table 1. Coefficients for Anthony et al. equations. 18

Table 2. Summary of capabilities of the proposed 1-D movable boundary models. 22

Table 3. Summary of capabilities of the proposed 2-D movable boundary models. 23

Introduction and Justification

The geomorphological characteristics of the rivers are in constant evolution due to sediment transport phenomena which predominate along the alluvial valleys. Sediment transport depends on the geologic composition of the area, river hydraulic characteristics; as well as, the influence of the climatologic and hydrologic conditions. The interaction of those factors produces a continuous process of changes in the geomorphological characteristics which are visible during long periods of time. This process is the objective of the current study about fluvial geomorphology (FG).

The fluvial systems have major impacts in the economic development. Large agricultural areas, mining, fishing, urban water supply sources, urban and industrial developments and, other economic activities related to natural resources, occurs within alluvial valleys and are important components of the river management [1]. Also, the fluvial system is the scenario of natural disasters such as floods and other processes such as channel migration, bank erosion and river aggradation or degradation.

The geologic formations of the area determine the composition of the soil. The sedimentary and others heavily weathered rock formations are more vulnerable to break into loose soil in a short period and contribute to the sediment transport process. This depends on layer compactation, grain size, the angle of repose and the layer's inclination angle of the formation. Along the river stream, these layers are naturally exposed by the process of constant erosion. Water erosion is the action of a surface flow or raindrops impacts which separates the soil particle. The particle may be moved from the point of origin into a stream and transported downstream of the river or land surface [2]. The erosion process depends on the conditions of the soil surface which include:

geometry, slope, surface roughness, water depth, shear stress exerted by the water on the surface and the maximum shear stress that the layer formation is able to resist.

The capacity to transport sediments as bed material load or washload increases when flow discharge increases. The increase of the sediment transport depends on the hydrological characteristics and the existing geologic formation. Rain causes surface runoff which goes into channel, increasing the water velocity and depth. This action increases erosion of the exposed surface and sediment transport toward the downstream river reaches. Under normal conditions, this process slowly changes channel alignment and shape; as well as, the floodplain landscape. The same changes could occur at a faster rate, in a short time period, with low-frequency events such as hurricanes or tropical storms. Either way, the evolution of the geomorphology is more evident in alluvial valleys with non cohesive soils. The alluvial material is a stratified deposit of gravel, sand, silt, clay and other debris carried by the streamflow from a high altitude to a lower ground elevations of the valley [3]. The climate conditions in the tropical regions impact the rate at which geomorphological changes occur, accelerating the evolution of the river processes [4]. This is more important nowadays because climate change in the tropics is expected to increase runoff, floods frequency and intensities [5].

Erosion can be accelerated or decelerated by human impacts, which may affect the equilibrium established by nature. Some of these human impacts are river material extractions, construction of bridges, dams, and weirs. Previous research has focused on protecting structures such as bridges and culverts from local scour; and regulations are available to control their impact on the river; however; much has to be done in understanding channel and floodplain evolution on a larger scale both, in time and space.

The alluvial valleys in Puerto Rico are located near coastal areas and normally show a meandering pattern. The meanders are part of the constant evolution of the geomorphology of these zones. Oxbow lakes and dry channels are visible by examination of aerial photos. These natural changes are produced by the process which involves the FG. Quantitative research on prediction of geomorphological changes of floodplain in rivers in tropical islands is scarce and, in Puerto Rico, it is almost non-existent.

The lack of historical data and field measurements limits the estimation of changes in river morphology during the useful life of major hydraulic structures or planning land development covering the range between 50 and 100 years. The use of state-of-the-art movable boundary hydraulic models combined with radar data and geographic information systems supplemented with limited field information presents an alternative for development of possible scenarios on the future behaviour of streams in floodplains. This work proposes to develop a methodology to obtain simple geomorphological relations that provide non-experts with basic channels characteristics in alluvial valleys within the useful life of such long-term projects. The methodology will be developed using data from three rivers in Puerto Rico with different geologic features.

Proposed Work

This research will develop a methodology aiming to provide relations for estimation of geomorphological evolution of the river and floodplain characteristics. A field reconnaissance and data collection effort will be pursued in the alluvial valleys of three rivers of Puerto Rico in order to gather information from natural and anthropogenic impacts on the geomorphological changes in river reaches. This information will be supplemented with historical geometric, flow and sediment

data; as well as, LIDAR radar data to cover the alluvial zone. The database will be incorporated into Geographic Information Systems (GIS).

Data collected from different sources will serve as input for computer simulations using state-of-the-art 1D and 2D movable boundary models. Multiple scenarios covering a period of approximately 100 years will be tested. Historical data will be used to calibrate the computer models. A sensitivity analysis will help to determine those parameters that have more influence in the prediction process. Computer outputs will be used to obtain geomorphic relations for rivers covering time periods of 25, 50, 75 and 100 years. The new relations for geomorphological parameters will be compared with generally accepted relations developed for rivers in other geographical latitudes.

The rivers included in this study to test the new findings are: Río Culebrinas, Río Grande de Añasco and Río Guanajibo (Figure 1). Río Yagüez, which is located between Río Grande de Añasco and Río Guanajibo, will not be included because it has suffered intensive urban development and channelization. The area of study covers the alluvial valleys of each watershed (Figure 2). Each valley has at least one United States Geological Survey (USGS) gaging station with more than 40 years of discharge data (Figure 1-A). Some of these stations are located outside of the valley area; however, this information could be useful in estimating downstream discharges using hydrologic methods. Also, in some USGS Stations data of suspended solids material has been collected (Figure 1-B). A more detailed description of the geology and climatology of the region selected for this study will help to highlight other benefits expected from the findings of this research.

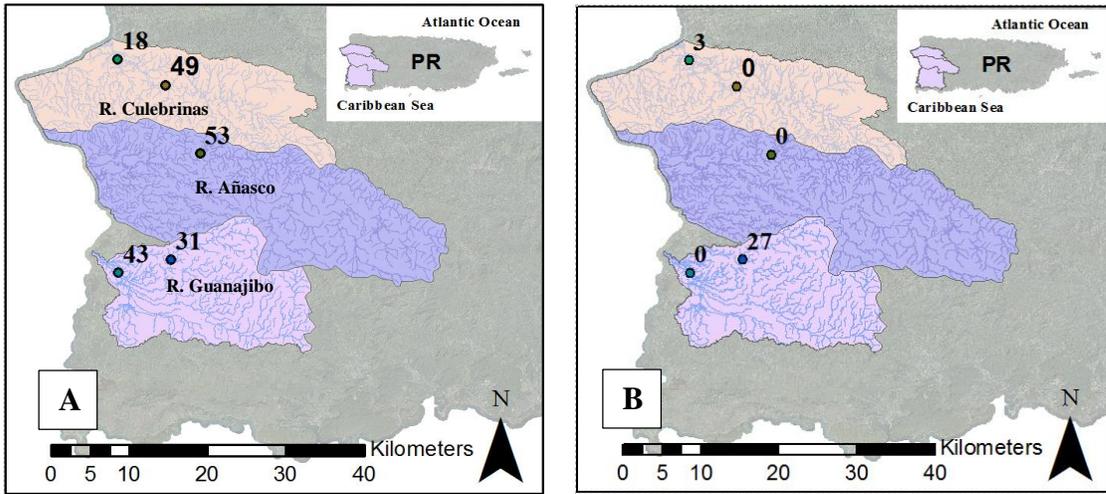


Figure 1. AOI Watersheds. A: Number of years with flow discharge at USGS stations. B: Number of years with suspended sediment data at USGS station.

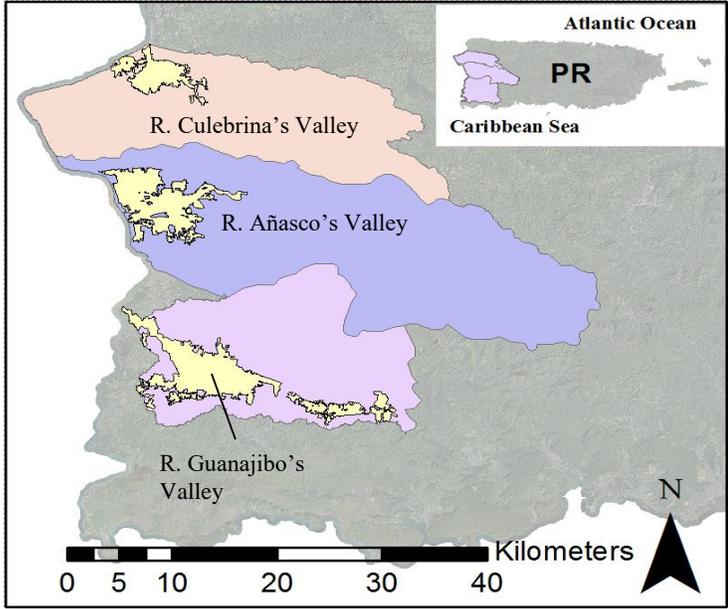


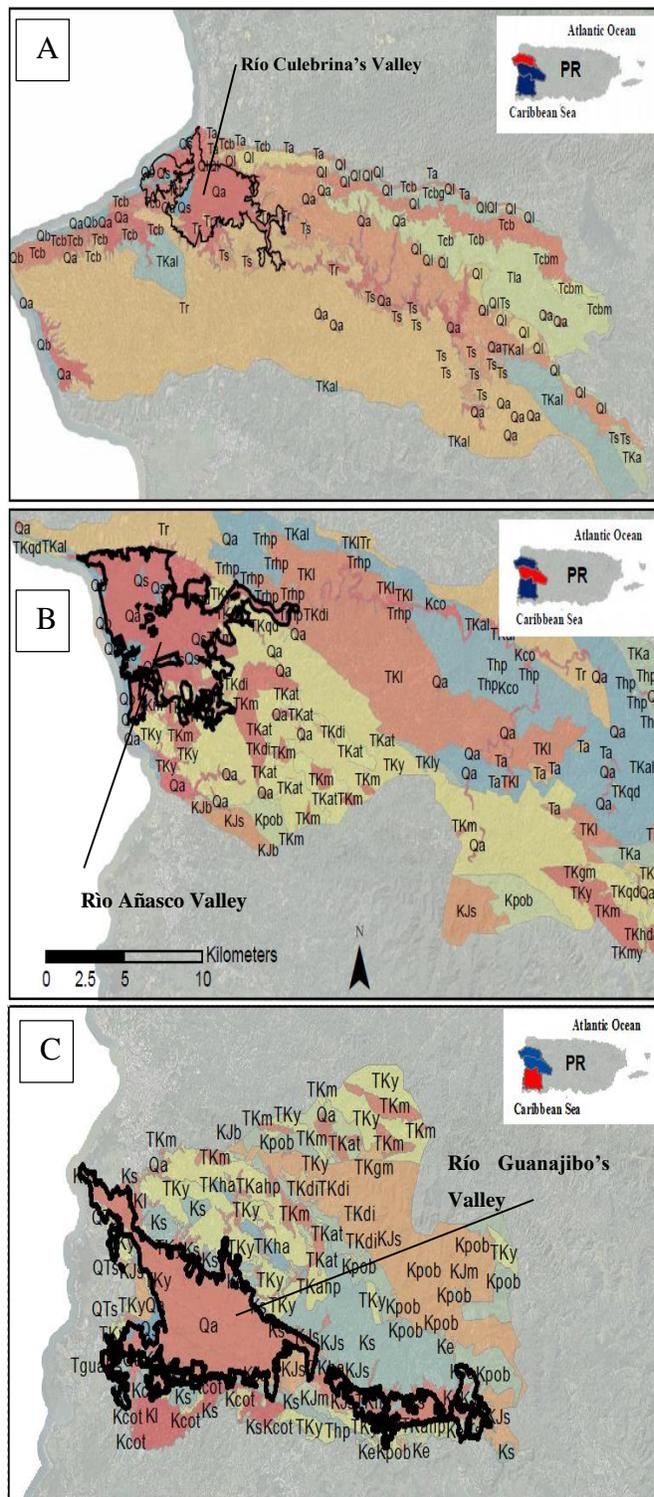
Figure 2. AOI alluvial valleys. North to South: Río Culebrinas Valley, Río Añasco Valley and Río Guanajibo Valley [44].

Geologic and Climatic Conditions of the Rivers included in this proposal

Puerto Rico and its outlying islands are part of an island arc, in which the geology consists in volcanoclastic and sedimentary rocks, which have been locally intruded by igneous rocks [6]. The center of Puerto Rico is dominated by mountains (Cordillera Central), in which the volcanic and sedimentary rock predominate. The coastal area are mostly dominated by alluvial valleys. This project will be focus on the west coast of the island which includes the valleys of Río Culebrina, Río Grande de Añasco and Río Guanajibo. Figure 3 shows a map with the geologic formations available in this region.

Culebrina's Valley

Culebrina's Valley (Figure 3-A) includes the areas at the southern part of Aguadilla municipality, northern part of Aguada municipality and the western part of Moca municipality. The valley has Quaternary alluvial deposits in which volcanic rocks fragments and quartz are the dominant material. The predominant material in the alluvium is been supplied from areas composed of limestone, volcanic rocks, sandstones and shales, and a plutonic body of granodiorite, quartz diorite and gabbro [7]. The average annual precipitation for the watershed is about 88 inches and about 72 inches in the alluvial valley, near Central Coloso in Aguada [8]. The rainy seasons are between May to June and September to December. The dry season starts in July thru August. The evapotranspiration in the watershed is between 49 and 45 inches yearly depending on the dry season. The net annual watershed runoff has been estimated in about 291,000 acre-ft and the sediment transport discharge in the area measured by the USGS have been estimated in about of 369,000 tons by year measured at USGS 50148890 Rio Culebrinas At Margarita Damsite NR Aguada [8].



Legend

Kbo	Boquerón Basalt
Kco	Concepción Formation
Kcoa	Coamo Formation
Kcot	Cotuí Limestone
Ke	El Rayo Formation
KJa	Amphibolite
KJas	Amphibolite-Serpentine
KJb	Spilitized Basalt
KJc	Cajul Basalt
KJm	Mariquita Chert
KJs	Serpentine
Kl	Lajas Formation
Km	Melones Limestone
Kp	Parguera Limestone
Kpe	Peñones Limestone
Kpob	Two pyroxene olivine basalt
Ks	Sabana Grande Formation
Kta	Tabonuco Formation
Qa	Alluvium
Qb	Beach Deposits
Ql	Landslide Deposits
Qs	Swamp Deposits
Qts	Blanket Sand Deposits
Ta	Aguada Limestone
Tcb	Cibao Formation
Tcbg	Cibao Formation; Guajataca Member
Tcbm	Cibao Formation; Montebello Limestone Member
Tgua	Guanajibo Formation
Thp	Hornblende quartz-diorite
Tj	Jicara Formation
Tjd	Juana Díaz Formation
Tka	Anón Formation
TKahp	Augite-hornblende porphyry
TKal	Lago Garzas-Anón Formations Interbedded
TKat	Augite trachybasalt
TKay	Anón and Yauco Formations Interbedded
TKaym	Anón, Yauco, and Maricao Formations Interbedded
TKdi	Diorite
TKgm	Granodiorite quartz monzonite
TKgu	Guaracanal Formation
TKh	Hornblende quartz-diorite porphyry
TKha	Hydrothermally altered rock
TKhda	Hydrothermally altered rock
TKl	Lago Garzas Formation
TKly	Lago Garzas and Yauco Formations Interbedded
TKm	Maricao Formation
TKmly	Maricao, Lago Garzas, and Yauco Formations Interbedded
TKmy	Maricao and Yauco Formations Interbedded
TKqd	Quartz diorite-granodiorite
TKy	Yauco Formation
Tla	Lares Limestone
Tpo	Ponce Limestone
Tr	Río Culebrinas Formation
Trhp	Rhyodacite porphyry
Ts	San Sebastián Formation
W	Surficial water bodies

Figure 3. Geologic maps of the AOI. A) Culebrinas Valley and Río Culebrinas Watershed; B) Añasco Valley and Río Grande de Añasco Watershed; and C) Guanajibo Valley and Río Guanajibo Watershed.

Añasco's Valley

The Añasco's Valley (Figure 3-B) is located between the Mayagüez and Añasco municipalities; with the Río Grande de Añasco as the principal stream. The climate in the valley is mostly wet during summer and dry periods occurs between January to April. The annual average rainfall of the Río Grande de Añasco watershed is about 93 inches at Lares municipality, about 68 inches in Mayagüez area, but exceeds 100 inches at upstream boundary near of the Cordillera Central (USGS 50141500 Lago Guayo at Damsite NR Castañer) [9]. The evapotranspiration of the watershed is an annual average of 48 inches. The annual runoff of the watershed is about 331,290 acres-ft and the sediment transport discharge is high with about 2,331 tons per square mile per year [10]. The valley is composed of alluvial material, base in silt, clay or sand material [11]. This material come from weathered and break down of igneous rocks from the early tertiary and cretaceous. Also, the valley has sand deposits of beach and dune in the coast, sand and gravel of alluvial deposits and disturbed material from urban development [9].

Guanajibo's Valley

The Guanajibo's valley (Figure 3-C) extends from San Germán to Mayagüez and contains the principal stream of the area, Río Guanajibo. Its principal tributaries are Río Rosario, Río Caín, Río Viejo, Río Duey, and Río Hoconuco. The average annual precipitation of the valley is about 56 inches with the rainy season from early August through November and the driest period occurs from December through March [12]. The average evapotranspiration for the watershed is about 46 inches by year. The average runoff is about 142,888 acres-ft in a year and there is no information available about its sediment transport discharge [13].

The soil of the valley is mainly composed of alluvial material which includes clay material near the surface, sand, sand and clay or sand and gravel. The northeast part of the valley has no presence of limestone in the subsurface. Sandy and gravelly clay is directly overlaid by part of the valley, probably a dark basaltic andesite. The limestone formation is limited to the southwestern between Cabo Rojo and Lajas [12].

In the United States and other continents the geologic formations spread for long distances. In Puerto Rico, the geologic formations change significantly in short distances. The difference between geologic formations produces a variation in the composition of the alluvial material. These changes in composition reflect in changes of erodibility and stability of the river banks.

The Culebrinas river is surrounded by limestone formations which suffer two consequences, the rock chemical composition reacts with water and dissolves and easily erode due to weak bonding between particles. On the other hand, the Guanajibo river is surrounded by volcanic rocks which produce heavy materials particles, hard to erode. Because these rivers have two types of geology formations, a hypothesis is proposed that a different response on the geomorphological behaviour is expected. Moreover Culebrinas river is expected to have a higher evolution rate than Guanajibo river. Certainly, the applicability of the results will be enhanced by selecting different geologic formations in this study.

Literature Review

This section expand in literature review on geomorphology topics related to the present research.

Fluvial geomorphology

The changes in channel geomorphology occurs constantly with time. This evolution is determined by the geologic composition of the banks. Banks in which the geologic composition are mostly sand and coarser particles are more susceptible to erosion than those dominated by cohesive material or rock outcrops. When water begins to erode the channel banks, the non-cohesive material becomes unstable until the bank failure occurs. Failure also can occur in cohesive material because the erosion process will depend on the shear stress forces exerted by the water into the bank and the resisting force of the bank material. In banks composed with cohesive material failures occurs in the “*failure plane*” where the shear stress of water exceeds the shear strength resisted by the bank [2, 14]. Other type of failures that contribute to the bank erosion are the cantilever, soil fall, rotational slip and slab failures [15].

In the long term, the river changes the platform along the valley. Several processes occur simultaneously which, acting together, leads to the evolution of landscape at a macro scale and are the focus of fluvial geomorphology. Erosion and sediment transport are two mechanisms responsible for changes in the geomorphology of the channel. The concentration of sediment transport depends directly on the amount of flow, velocity, its angle of attack and depth of the channel. Other factors that govern bank erosion are the antecedent condition, vegetation growth, rainfall intensity and man-made impacts. The sediments load, specially the suspended load, increases when the flow increases due to the improvement of its soil detachment capability [16] [17]. If the channel section has presence of vegetation in the bank and in the channel bottom, the

resulting velocity of water and shear stress will decrease. Vegetation effects depend on roots, which help as a streambank stabilization device [18]. This type of stabilization can reduce the water velocity in the river banks which will reduce the impact of erosion. Erosion could be also produced by man-made impacts on the channel. Bridges, pipes, weirs, dams are structures capable to expand or reduce the flow area in the channel in a form to provide an increase or decrease the erosion, but it can also generate deposition of sediments in the surroundings zones of the structure.

The time scale is an important factor to consider in the channel's geomorphological evolution. Some geologic compositions are more susceptible to erosion than others. The evolution in channel geomorphology will take month, years or centuries depending on the flow and geology, but significant changes in the longitudinal profile of the channels can take over ten years. Due to the lag of time between high flow events and geomorphic changes, it is difficult to link the amount of flow and sediment transport with the geomorphological changes of the channel [2].

To determine the historic geomorphic evolution is necessary to collect data of sediment movement, stream flow, climate, frequency and magnitude of events such as floods and, human activities [19]. These data will help to understand the geochronology of the channel system and establish a precedent of what happened in the channel and what could occur in the future. There are analyses; such as, dendrochronology (study of the tree rings to determine the time intervals), archeological methods, varves (lamination of lacustrine deposits) and others methods which helps to identify historical events and geomorphic processes [19, 20].

Channel evolution theory

According to the natural behavior of the river channel and the human interaction, the river suffers a serie of stages (Figure 4) in order to restablish its dynamic equilibrium [21, 22, 23]:

- Stage I: Stable system – The channel system is at equilibrium condition. The sediment transport is based in suspended load with only a low percentage of bedload sediments. The stability of the bank is provided by vegetation and the cohesive material. The river channel geometry is normally straight or meandering and supports the energy dissipation by the presence of bed features such as pools, steps, riffles, and rapids, which are important for the channel's stability.
- Stage II: Disturbance – The channel system is not in equilibrium and the bottom is deeply incised, promoting the increasing of the channel height. A typical cause of this disturbance is any human activity or structure which causes river alteration including channelization and hydrologic modifications such as urban development and changes in the drainage pattern. In this stage the bank heigh (h) do not exceed the critical bank height (h_c), in other words the banks is geotechnically stable. The channel gradient and stream power increases.
- Stage III: Degradation – An increase of the stream power occurs, the system begins to incise the base of the channel, increasing the banks height (h) over h_c . The increase of the bank height increases the mass failures as they exceeds a stable height, with the consequence of future channel widening [24].
- Stage IV: Degradation and Widening – Since stage III, decreases the banks stability, the channel height and the gradient, increases. The channel starts to loose power and

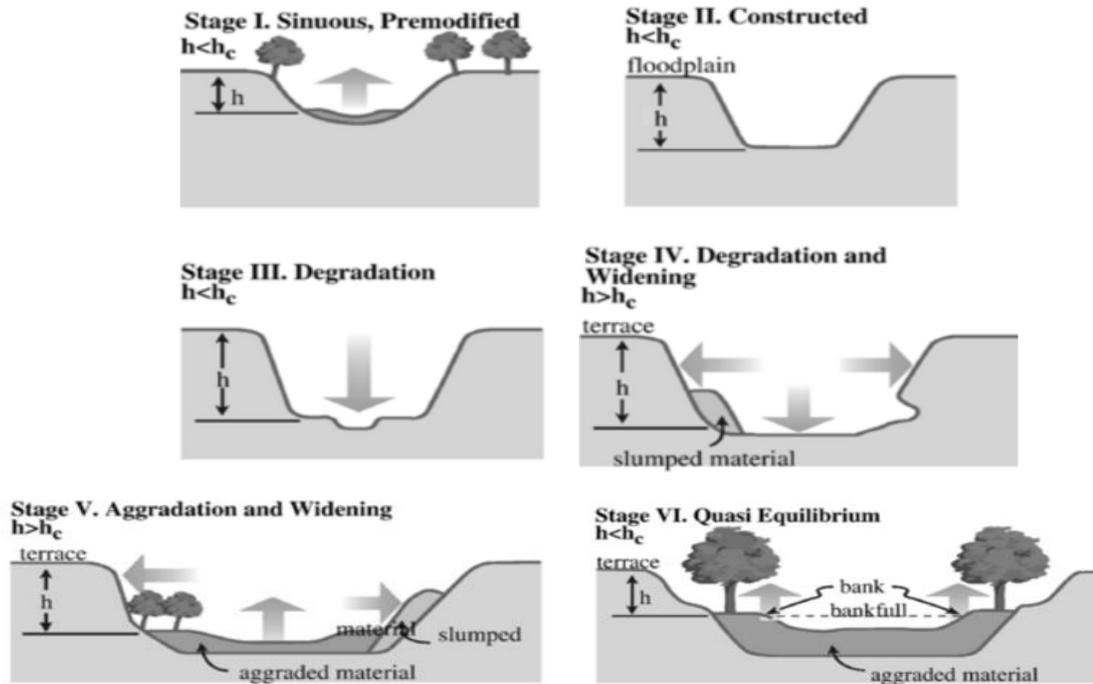


Figure 4. Stages of the channel evolution. h_c = critical bank height (maximum height in which the banks will keep its stability). Arrows are the direction of banks movement [21].

decreases the gradient; as consequence, degradation starts upstream and aggradation downstream. This action promotes the channel to start a widening process.

- Stage V: Aggradation and Widening – In this stage, the aggradation and the channel widening continues with severe erosion. The degradation starts occurring upstream and, as consequence, increases the downstream sediment load. Due to channel widening, the gradient becomes more flat and the stream power decreases considerably, which increases the sediment deposition. The channel bank becomes more unstable and the channel continues in a cycle of aggradation and degradation until it reaches the next stage.
- Stage VI: Quasi Equilibrium – The aggradation and degradation cycle ends and the channel adjustment process is almost completed. At this point, the channel obtains the dynamic equilibrium and occurs a natural balance, the water flows and sediment

transport decreases, as the bed scour and bank erosion decreases. The bank surrounding areas start to develop vegetation and the flow begins the meandering formation as the equilibrium originally observed in Stage 1.

The channel evolution theory helps to determine in which stage of evolution is the river reach at present and establish a hypothesis on its future changes.

Evolution of drainage net

Part of the channel evolution includes channel migration [20] which encompasses many types of movement; such as, translation, extension, expansion, rotation and possible combinations of these movements (Figure 5). Translation movement occurs when the channel moves downstream without altering its shape. The extension movement occurs when the channel moves in lateral direction increasing its amplitude and length. The channel expansion increases the amplitude and the length of the entire shape. Rotation occurs when the channel bend is rotated to a different orientation. Normally the rivers can change in a combination of these patterns and will depends on the geometry of the channel and the geologic stratas that conforms the banks [20].

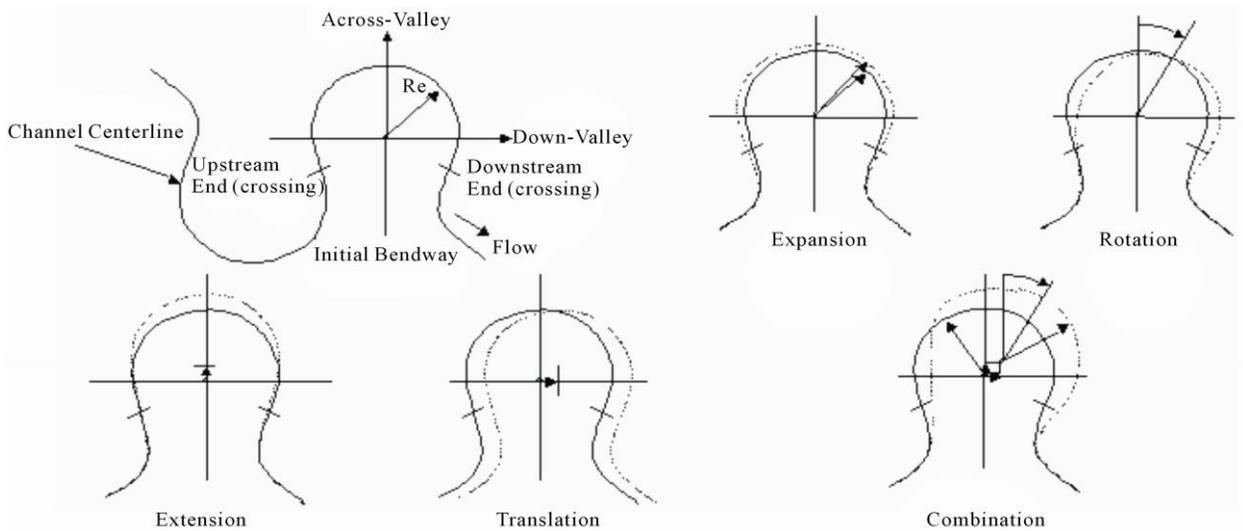


Figure 5. Different Channel drainage movement by migration [43].

According to Anthony, et al. and Booth and Fischenich [14, 25], the evolution of the channel does not have a good correlation between channel morphology and sediment size but, a good correlation can be obtained from the channel width and water depth using an index of silt and clay. Using the mean annual flow and the percentage of silt and clay, Schumm developed the following empirical equations [14]:

$$W = 2.3 \frac{Q^{0.38}}{M^{0.39}} \quad (1)$$

$$H = 0.6Q^{0.29}M^{0.34} \quad (2)$$

$$\lambda = 1890 \frac{Q^{0.34}}{M^{0.74}} \quad (3)$$

$$S = \frac{60}{M^{0.38}Q^{0.32}} \quad (4)$$

$$Q = \frac{WH\lambda}{S} \quad (5)$$

$$Q_s = \frac{WS\lambda}{H} \quad (6)$$

where:

- W = channel width (ft³/s),
- H = water depth (ft),
- λ = meander wave length (ft),
- S = channel slope,
- Q = channel flow (ft³/s),
- M = percentage of silt and clay, (fractional) and
- Q_s = sediment discharge (ft³/s).

These equations provide an idea of the river evolution in a section depending on the channel discharge and sediment load. According to Equation (6) the sediment discharge (Q_s) is proportional

to the channel width, meander wave length and slope; but, it is inversely proportional to water depth [20, 14]. From a geomorphological point of view, these equations provide characteristics of the river geometry, discharge and sediment using simple wave-like meandar patterns.

Anthony et al. [14] proposed another set of equations for non cohesive alluvial channel which requires the initial values of average flow (Q , m^3/s), particle size mean diameter (d_{50} , m), and dimensionless Shield number (τ_θ). These equations involve a predetermined coefficient and exponents of discharge, grain size and slope:

$$W = aQ^b d_s^c \tau_\theta^d \quad (7)$$

$$H = aQ^b d_s^c \tau_\theta^d \quad (8)$$

$$S = aQ^b d_s^c \tau_\theta^d \quad (9)$$

$$U = aQ^b d_s^c \tau_\theta^d \quad (10)$$

Where the exponents and coefficients are obtained from Table 1.

Table 1. Coefficients for Anthony et al. equations.

$m = 1/\ln(12.2 H/d_{50})$	Coefficient a	Discharge, b	Grain Size, c	Shields Num., d
Flow depth, H (m)	0.133	$\frac{1}{2 + 3m}$ $0.28 < b < 0.5$	$\frac{-1 + 6m}{4 + 6m}$ $-0.25 < c < 0.28$	$\frac{-1}{4 + 6m}$ $-0.25 < c < 0.14$
Top Width, W (m)	0.512	$\frac{1 + 2m}{2 + 3m}$ $0.5 < b < 0.57$	$\frac{-1 - 4m}{4 + 6m}$ $-0.42 < c < -0.25$	$\frac{-1 - 2m}{4 + 6m}$ $-0.28 < c < -0.25$
Mean Flow Velocity U (m/s)	14.7	$\frac{1}{2 + 3m}$ $0 < b < 0.14$	$\frac{2 - 2m}{4 + 6m}$ $0.14 < c < 0.5$	$\frac{2 - 2m}{4 + 6m}$ $0.43 < c < 0.5$
Slope, S	12.4	$\frac{-1}{2 + 3m}$ $-0.5 < b < -0.28$	$\frac{5}{4 + 6m}$ $0.71 < c < 1.25$	$\frac{5 + 6m}{4 + 6m}$ $1.14 < c < 1.25$

The computation process start guessing H to obtain the number m from the m -equation. The second step is to solve Equation 8 for H using coefficients from Table 1. Repeat the process until the value of H guessed is equal to the value obtained with Equation 8. W, S and U are computed with the m value obtained after convergence.

The evolution of the channel in terms of bend wavelenght and radius of curvature can also be computed using the water discharge, and the channel width [26]. Also there is a close relation between channel width and meander length and, between the radius of curvature and the channel width [19]. One example of this equation is the one developed by [19]:

$$L_c = 11.03W^{1.01} \quad (11)$$

where:

L_c = meander length by center line and,,

W = channel width along the meander.

These formulations were derived from limited field and laboratory data [14]. However, none has been tested for rivers in Puerto Rico or any tropical island.

One product of this research will be the development of similar relations applicable to a range of several years into the future. Computer software for simulation of movable boundary hydraulics and sediment transport will be used to estimate the channel evolution.

Sediment transport and geomorphological modeling software

The sediment transport in a natural channel is very complex and, if human interaction is present in the channel, the complexity increases. The proposed research will develop empirical equations to estimate the sediment eroded and its association with the evolution of the channel

planform geometry. Due to lack of complete field data sets the proposed relations will be developed in combination with computer simulations. Movable boundary computer models will be used to simulate changes in the cross sectional geometry due to sediment transport over a long period of time. The most appropriate sediment transport functions will be selected by using criteria associated with flow and sediment conditions that most resemble those used for derivation of the empirical function. One-dimensional (*1-D*) and two-dimensional (*2-D*) models will be used. Some advantages of using these models are [27]:

1-D Modeling

- Allows efficient assessment of hydraulic condition and sediment transport balance in a established reach.
- Uses a database which includes cross sectional data and provides boundary conditions that can be used with the *2-D* models. The cross-sectional data are obtained from field work as part of the instream flow studies or high-precision radar data

2-D modeling

- *2-D* modeling can provide a better understanding of the hydraulic conditions and sediment transport processes contributing to future evolution of the channel.
- Provide an accurate representation of the complex hydraulic conditions of the channel and more detailed results than the *1-D* models.
- Provides estimates of the possible meander displacement along the floodplain with time.

There are computer algorithms available to model the channel evolution, as well as, the channel hydraulic conditions and sediment transport. In order to choose which model to use, the user has to consider the level of detail needed for research, type of hydrologic conditions wanted to be modeled, geological characteristics of the area of interest (AOI) and the necessary data to solve the model equations.

1-D sediment transport and channel evolution will be evaluated using two proposed algorithms. 1) Hydrologic Engineering Center – River Analysis System (**HEC-RAS** [28]); 2) Sedimentation and River Hydraulics –One Dimension (**SRH-1D** [29]). These *1-D* models have limitations including: neglecting secondary currents, transverse sediment movement, lateral variations in transport rate and others. Also these models cannot simulate point bar formation, pool-riffle formation, and other channel changes as meandering geometry and local bank erosion [27]. The capabilities of these 1D models are summarized in Table 2.

2-D models to be considered are: 1) **SRH - 2D** [30], 2) Coastal and Hydraulics Laboratory the Adaptive Hydraulics Modeling **CHL-ADH** [31] 3) Multidimensional Surface-Water Modeling System or **MDSWMS-Storm** [32]. These models are capable to simulate lateral channel evolutions. Some of the capabilities of these 2D models are summarized in Table 3.

A new type of models based on cellular theory provide an alternative in which there is no need to solve complex differential equations. In geomorphology, this approach assumes that landforms are represented by a group of cells interacting through the routing of water and sediment, using simple rules to incorporate the physics of the evolution [33]. Consideration of this type of models could be given once their advantages and disadvantages are evaluated based on the data available for Puerto Rico.

Table 2. Summary of capabilities of the proposed 1-D movable boundary models.

	HEC-RAS [34]	SRH-1D [35]
Cross Section (XS)	Maximum 25000 XS allowed	Maximum XS apart L/30
Ineffective areas (IA)	Allowed IA until the water raise over the IA.	Allowed as HEC-RAS
Manning Roughness (n)	Up to one n value between each station in a cross section.	1 to 10 n values in the XS
Contraction and Expansion Coefficient	Option to input the contraction or expansion coefficients	N/A
Flow and velocity	Field Work or gauge	Time vs Stage, Time vs flow rate.
Lateral inflow	Included as Upstream boundary condition. Also is computed for ungagged lateral inflow	Included as Upstream boundary condition
In-stream structure	Bridges, dams, weirs and lateral structures	Inline weir, lateral weir
River bed Layers (RBL)	Only has 1 river bed layer	The default number of RBL are 3. Each layer has its own thickness.
Particle Size Distribution	Grain size distribution curve data of the bed layer.	Grain size distribution curve data for each layer.
Sediment Boundary Conditions	6 sediment transport functions available, Rating curve, Sediment load series, Flow weighted sediment split, threshold weighted sediment split and Sediment split by grain class	Sediment input at junctions, sediment transport formula plus 16 sediment transport functions, rating curve, Flow vs sediment discharge, time vs sediment discharge, time vs sediment discharge by size of fraction
Sediment Transport Computation Model	Quasi-Unsteady Flow and Unsteady flow	Quasi-Unsteady Flow and Unsteady flow

Y = Depth, S_0 = Bed slope, L= length of the physically important flood wave

Table 3. Summary of capabilities of the proposed 2-D movable boundary models.

	SRH-2D [36]	MDSWMS-Storm (IRIC) [37, 38, 39]	CHL-ADH [40]
Mesh or Grid	Mesh should be prepared on third-party mesh generation program	Mesh should have a pair of coordinates (X and Y) and elevation (Z) for each pair of coordinate. Also Grid can be imported or exported (Extension .csv).	Mesh should have a pair of coordinates (X and Y) and elevation (Z) for each pair of coordinate. Also Grid can be imported or exported from GIS.
Manning Roughness (n)	Roughness value can be assigned to the general project or may be assigned to the different material types created during mesh generation	Roughness data must be included as part of the grid information.	Roughness data must be included as part of the mesh material properties.
Particle size distribution	Two Options: Volume fraction of each size or bed gradation using cumulative distribution.	No grain distribution is required. Only the diameter of uniform bed material	Sediment transport is no currently supported in the SMS interface

Objective

The underlying hypothesis of the proposed work is:

The rate of geomorphological changes of the alluvial channel in Culebrinas river is faster than that of the Guanajibo river as the result of different geological conditions found in both river systems.

The objective of the current project is:

To develop a methodology to create an empirical model capable of producing estimates of the geomorphological changes of alluvial channels projected into the future.

The new model will be derived by using limited field data supplemented with numerical simulations. Existing relations, such as those presented in equations 7 to 11, will be used as a basis for developing the new model. A series of scenarios, including possible climate change effects, will be used to determine possible geomorphological changes expected during approximately the next 100 years. Results at 25, 50, 75 and 100 years are expected results.

Methodology

There is a series of issues to be addressed in order to develop the research. This methodology will combine watershed level issues and local scale issues with the modeling approach. The proposed methodology can be summarized as follows:

1. Identify the geologic characteristics of the channel zone using geological maps and verifying the geological conditions on the field.

2. Establish geomorphologic differences in the chosen AOIs. These include channel width, bank height, meander wavelength, river flow and velocity.
3. Determine the state of dynamic equilibrium of the AOIs and establish the historical changes with respect to the dynamic equilibrium. Channel evolution theory and a stream classification such as Rosgen [41] , will be used for this task.
4. The project will be concentrated on the valley of each selected river. The boundaries of the stream reach will be determined such as to avoid downstream tidal effects in the channel and non-alluvial zones or zones with limited sediment transport activity in the upland region.
5. Identify sources of hydrological and hydraulics data (Figure 6). The use of data for calibration and model input depend on the findings during the process of gathering information. Two possible scenarios are presented:
 - a. Sufficient flow data from USGS stations gauges and other possible sources:
 - i. Sufficient flow data can be used for model calibration and/or using similar series for predicting future conditions. The weather in Puerto Rico, follows a pattern where the dry season and rainy season are remarkable during the year, this provide a possibility to consider repetition of historical events in the future.
 - ii. Use stochastic simulation to extend discharge records
 - b. Discharge data is not enough or quality is unacceptable; but sufficient rainfall data is available:
 - i. Rain data from National Oceanic and Atmosphere Administration (NOAA) gauge stations and NexRad radar will be collected.

- ii. Use stochastic simulation to extend rainfall records
 - iii. Rainfall-runoff models, such as GEISHA and HEC-HMS, will be used to produce flow data from historical rains
- c. Major changes in the river geomorphology occur during extreme weather conditions such as tropical storms and hurricanes. The frequency of hurricanes is expected to increase due to climate change. Therefore, some scenarios with higher frequency of extreme weather events will be tested.

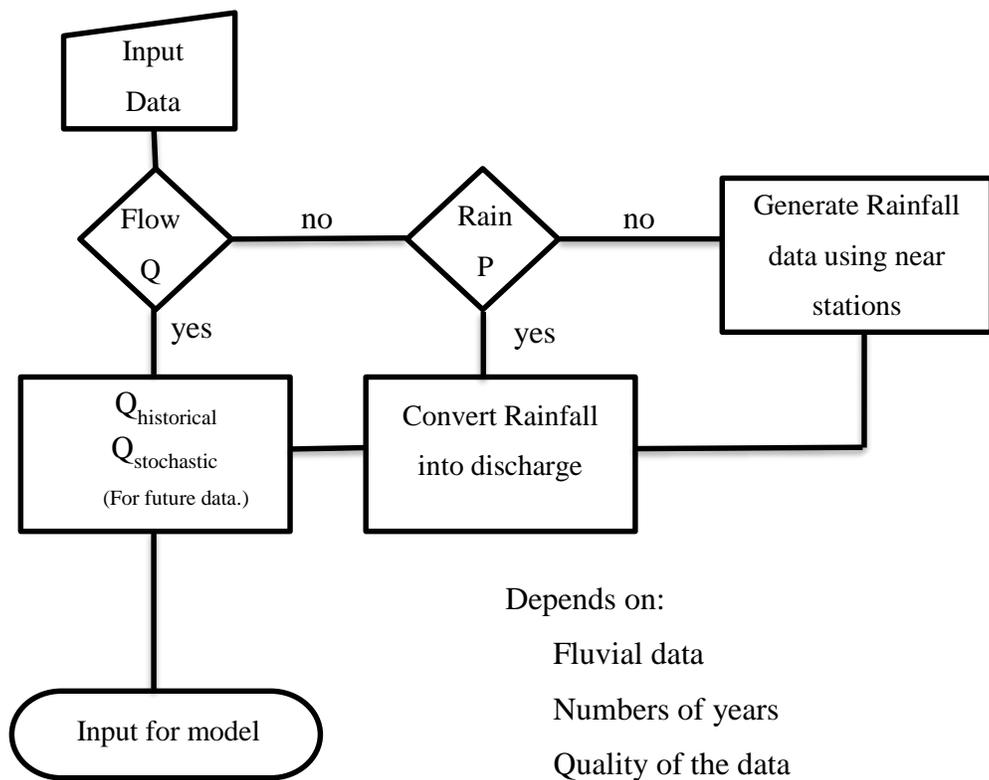


Figure 6. Flowchart of the available data processing options before it enters to the model.

6. Conduct field investigation combined with Lidar elevation data to characterize existing conditions of the chosen rivers. This will include:

- a. Surveying of the channel to determine the actual geometry of the channel in different areas, hydraulic characteristics as channel width and slope conditions.
- b. Identify geomorphological features which are present in the channel.
- c. Characterize the floods history in the zone.
- d. Identify changes caused by human activities (urban development, land use changes, deforestation, agricultural practices), existing structures, land use records and natural events,
- e. Take samples of soils along the channel to obtain the representative particles grain size distribution and soil characterization.
- f. Vegetation interaction with the hydraulic conditions of the channel.

7. Use Lidar information to determine the ground and river topography to generate spacial information using GIS. This technique has improved during the last few years and is capable of providing accurate topographic data [42], however, it has not been tested in Puerto Rico.

8. Use computer simulations to run several scenarios and determine the posible morphologic evolution of the river channels:

- a. Determine changes in bed material mobility in terms of particle size for different flow frecuencies and simulation times.
- b. Establish potential changes in channel dimensions and meandering due to changes in flow conditions.
 - i. Equations similar to the presented in the Sediment Transport section will be adapted or modify to determine changes in the hydraulic characteristics of the river.

- c. Use selected model to predict river stage due to changes of the channel geometry, bed profile, and channel hydraulic roughness.
 - d. The models mentioned in the Sediment Transport section will be calibrated using historical data in order to select the most appropriate for this analysis.
9. Historical data will be used to calibrate the computer models. Also with the calibration process, a sensitivity analysis will determine those relevant parameters which can have a major influence in the prediction process.
10. Possible scenarios of hydrologic and hydraulic conditions will be studied with the computer model to examine the geomorphological response and test the proposed hypothesis.

Bibliography

- [1] C. Thorne, R. Hey and M. Newson, *Applied Fluvial Geomorphology for River Engineering and Management*, Chichester, England: John Wiley & Sons, 1997.
- [2] R. Charlton, *Fundamentals of fluvial Geomorphology*, NY: Routledge, 2008.
- [3] US Department of Interior (USGS), "Alluvial deposits," 3 Sep. 2004. [Online]. Available: http://geomaps.wr.usgs.gov/archive/scamp/html/scg_surf_alluv.html. [Accessed 4 April 2016].
- [4] M. Garcin and B. a. P. R. Poisson, "High Velocity Geomorphological Processes in a Tropical Area: the Remparts River case study," *Geomorphology*, pp. 335-350, 2004.
- [5] P. H. Gleik, *The World's Water*, Washington: Island Press, 2009.
- [6] P. G. Olcott, "Ground Water Atlas of the United States Alaska, Hawaii, Puerto Rico and U.S. Virging Islands," USGS, 1999.
- [7] J. Morelock, "Beach Sand Budget For Western Puerto Rico," [Online]. Available: http://geology.uprm.edu/Morelock/GEOLOCN_/coast/westprsandbdg.htm. [Accessed 8 May 2016].
- [8] Departamento de Recursos Naturales y Ambientales, "Cuenca del Río Culebrinas," [Online]. Available: <http://drna.pr.gov/historico/oficinas/saux/secretaria-auxiliar-de-planificacion-integral/planagua/inventario-recursos-de-agua/cuencas-hidrograficas/Cuenca%20del%20Rio%20Culebrinas.pdf>. [Accessed 11 June 2016].
- [9] J. R. Díaz and D. G. Jordan, "Water Resources of the Río Grande de Añasco-Lower Valley, Puerto Rico," Department of the Interior - U.S. Geological Survey, San Juan, 1987.
- [10] Departamento de Recursos Naturales y Ambientales, "Cuenca del Rio Grande de Añasco," [Online]. Available: <http://drna.pr.gov/historico/oficinas/saux/secretaria-auxiliar-de-planificacion-integral/planagua/inventario-recursos-de-agua/cuencas-hidrograficas/Cuenca%20del%20Rio%20Grande%20Anasco.pdf>. [Accessed 11 June 2015].
- [11] F. Gómez-Gómez, J. Rodríguez-Martínez and M. Santiago, "Hydrogeology of Puerto Rico and the outlying Islands of Vieques, Culebra, and Mona," US. Department of the Interior, U. S. Geological Survey, 2014.
- [12] E. Colón-Dieppa and F. Quiñones-Márquez, "A Reconnaissance of the Water Resources of the Centra Guanajibo Valley, Puerto Rico," US Department of the Interior, U.S. Geological Survey, San Juan, 1985.

- [13] Departamento de Recursos Naturales, "Cuenca del Rio Guanajibo," [Online]. Available: [http://drna.pr.gov/historico/oficinas/saux/secretaria-auxiliar-de-planificacion-integral/planagua/inventario-recursos-de-agua/cuencas-hidrograficas/Cuenca% 20del% 20Rio% 20Guanajibo.pdf](http://drna.pr.gov/historico/oficinas/saux/secretaria-auxiliar-de-planificacion-integral/planagua/inventario-recursos-de-agua/cuencas-hidrograficas/Cuenca%20del%20Rio%20Guanajibo.pdf). [Accessed 11 June 2016].
- [14] D. J. Anthony, M. D. Harvey, J. B. Laronne and M. P. Mosley, *Applying Geomorphology to Environmental Management*, Denver, CO: Water Resources Publications, LLC, 2001.
- [15] D. S. Biedenharn, C. M. Elliot and C. C. Watson, *The Wes Stream Investigation and Stream Bank Stabilization Handbook*, Vicksburg, MS: U.S. Army Engineer, 1997.
- [16] D. a. S. F. Simon, *Sediment Transport Technology*, Colorado: Water Resources Publications, 1992.
- [17] P. Julien, *Erosion and Sedimentation*, Cambridge, UK: Cambridge University Pres, 2010.
- [18] Georgia Environmental Protection Division, "Stream Bank and Shoreline Stabilization, Techniques to Control Erosion and Protect Property," Department of Natural Resources, Environmental Protection Division, Georgia, 2011.
- [19] L. B. Leopold, M. G. Wolman and J. P. Miller, *Fluvial Processes in Geomorpholgy*, San Francisco: W. H. Freeman and Company, 1992.
- [20] D. Knighton, *Fluvial Forms and Processes, A New Perspective*, Great Britain: Oxford University Press inc., 1998.
- [21] J. Collison, "Channel Evolution Model," *Stream and Watershed Restoration*, [Online]. Available: <http://riverrestoration.wikispaces.com/Channel+evolution+model>. [Accessed 12 June 2016].
- [22] Vermont Department of Environmental Conservation, "An Introduction to River Channel Evolution," *Vermont River Channel Evolution Models*, 12 Apr. 2011. [Online]. Available: http://dec.vermont.gov/sites/dec/files/wsm/rivers/docs/rv_introduction_to_channel_evolution.pdf. [Accessed 12 June 2016].
- [23] A. Simon and M. Rinaldi, "Disturbance, Stream Incision, and Channel Evolution: The Roles of Excess Transport Capacity and Boundary Materials in Controlling Channel Response," *Geomorphology*, vol. 79, no. 3-4, pp. 361-383, 2006.
- [24] D. B. Booth and C. J. Fischenich, "A Channel Evolution Model to Guide Sustainable Urban Stream Restoration," 2015.

- [25] K. Van Wilson, Jr. and D. P. Turnipseed, "Geomorphic Response to Channel Modifications of Skuna River at the State Highway 9 Crossing at Bruce, Calhoun County Mississippi," U.S. Geological Survey, Jackson, Mississippi, 1994.
- [26] J. S. Bridge, *Rivers and Floodplains Forms, Processes and Sedimentary records*, Binghamton, NY: Blackwell Science Ltd, 2003.
- [27] Alaska Energy Authority, "Fluvial Geomorphology Modeling for Sustina-Watana Hydroelectric Project," Alaska Energy Authority, Anchorage, Alaska, 2012.
- [28] U.S. Army Corps of Engineers, "Hydrologic Engineering Center," 16 March 2016. [Online]. Available: <http://www.hec.usace.army.mil/software/hec-ras/downloads.aspx>. [Accessed 22 May 2016].
- [29] Bureau of Reclamation, "Technical Service Center," 03 march 2016. [Online]. Available: <http://www.usbr.gov/tsc/techreferences/computer%20software/models/srh1d/index.html>. [Accessed 22 may 2016].
- [30] AQUAVEO, "Surface Water Modeling System SRH-Model," 2016. [Online]. Available: <http://www.aquaveo.com/software/sms-srh>. [Accessed 22 May 2016].
- [31] US Army Corps of Engineers, "Costal and Hydraulics Laboratory," 12 January 2015. [Online]. Available: http://adh.usace.army.mil/new_webpage/main/main_page.htm. [Accessed 22 May 2016].
- [32] U.S. Geological Survey, "Multidimensional Surface-Water Modeling System," 2005. [Online]. Available: <http://wwwbrr.cr.usgs.gov/gstl/project-MDSWMS.html>. [Accessed 22 May 2016].
- [33] A. P. Nicholas, "Cellular modelling in fluvial geomorphology," *Earth Surface Processes and Landforms*, vol. 30, pp. 645-649, 2005.
- [34] G. W. Brunner and C.-H. , *HEC-RAS User Manual*, 5 ed., Davis, CA: US Army Corps of Engineers, 2016.
- [35] J. V. Huang and B. Greimann, *SRH-1D 3.0 User`s Manual*, Denver, CO: Bureau of Reclamation, 2012.
- [36] Y. G. Lai, *SRH-2D Version 2: Theory and User`s Manual*, Denver, CO: Bureau of Reclamation, 2008.
- [37] F. J. Simões, *Using Storm - A Short Primer*, Golden, CO: USGS Geomorphology and Sediment Transport Laboratory, 2013.

- [38] iRIC - Project, "iRIC Software, Users Manual," 30 January 2015. [Online]. Available: <http://i-ric.org/en/download/get/CKyk8w>. [Accessed 26 July 2016].
- [39] iRIC - Project, "iRIC Software Developers Manual," 13 March 2015. [Online]. Available: <http://i-ric.org/en/download/get/WppUvd>. [Accessed 26 July 2016].
- [40] AQUAVEO, SMS 12.1 Tutorial ADH Hydrodynamics, Provo, UT: AQUAVEO, 2015.
- [41] D. Rosgen and L. Silvey, Field Guide for Stream Classification, Pagosa Springs, CO: Wildland Hydrology books, 1998.
- [42] National Oceanic and Atmospheric Administration, "2004 USACE Lidar: Puerto Rico Point Cloud files with Orthometric Vertical Datum NAVD88 Using GEOID12A," NOAA Office for Coastal Management, 29 July 2011. [Online]. Available: https://coast.noaa.gov/htdata/lidar1_z/geoid12a/data/560/. [Accessed 29 June 2016].
- [43] D. Mithun, D. Dabojani and U. Misbah, "Evaluation of Meandering Characteristics Using RS and GIS of Manu River," *Journal of Water Resources and Protection*, vol. 4 No. 3(2012), no. 17950, p. 9, 2012.
- [44] Gobierno de Puerto Rico, "Portal Datos Geográficos Gubernamentales," [Online]. Available: <http://www2.pr.gov/agencias/gis/Pages/default.aspx>. [Accessed 20 February 2016].