Restoration of Río Humacao Fluvial System

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Abstract — *Río Humacao is located in the southeast coast of Puerto Rico and generally flows eastward into the Vieques Passage along a trapezoidal earth channel that runs approximately 7 kilometers upstream from the river mouth. For many years, the traditional way of canalizing rivers for flood control has been using prismatic, straight, single-section trapezoidal channel geometries. This single-section channel design approach, which uses the same cross section to convey low flows, bankfull discharges and flood events, has its roots in the design of irrigation channels with uniform flow, and lack the ability to transport sediment in a natural streamflow environment. As a consequence, these types of channels suffer sedimentation, lose hydraulic capacity, and require frequent maintenance. The main objective of this project is to replace the existing trapezoidal channel with a naturalized channel designed to meander, be self maintaining, and that can withstand 100-year floods.*

Key Terms — *fluvial geomorphology, natural channel design, Río Humacao, river restoration.*

BACKGROUND

Río Humacao has a length of 26 kilometers, drains an area of approximately 77 km^2 (30 mi^2), and enters a wide alluvial floodplain below the town of Humacao, located 6 kilometers from its mouth.

The largest storm of record occurred on September 6, 1960. The United States Geological Survey (USGS) station 50082000, located at state road PR-3, recorded a peak discharge of 1,134 m^3/s (40,000 ft^3/s). According to hydrology performed by the Federal Emergency Management Agency (FEMA), the return interval for this event is close to 100 years. In response, in 1975 the Puerto Rico Department of Transportation designed a trapezoidal earth channel with a length of 6.7 kilometers. The existing channel does not have capacity for the 100-year event.

A river may be classified as stable when it has the capacity to transport its flow and sediment load over time without degrading or aggrading, while maintaining its dimensions, profile and pattern. The objective of this project is to design a natural and stable reach of river to replace 3.5 kilometers of existing trapezoidal channel that runs from the river mouth to the PR-53 highway bridge. Benefits include:

- reduce flood risk,
- enhance wildlife habitat,
- increase aesthetic value of the river corridor,
- increase recreational use of river and surrounding areas,
- produce a river geometry, profile and planform that will minimize long term deposition or erosion, and thus minimize channel maintenance, and
- create awareness about natural channel design.

In recent years the idea of natural stream design has gained increasing acceptance in the engineering community in the United States and Europe. The concept of natural channel design incorporates a meandering multi-stage channel that can convey bankfull discharges and flood events, and are stable, self maintaining, and aesthetically pleasing.

This project would bring attention and awareness to Puerto Rico about the positive impact natural stream design can have on the ecosystem, and the social and economic benefits the restored area will bring to the town of Humacao in the form of tourism and recreation.

PREVIOUS HYDROLOGIC-HYDRAULIC STUDIES

No hydrologic-hydraulic study exists for Río Humacao prior to canalization, and there is no record of detailed study for the canalization project. In 1967 the USGS published the Hydrologic Investigations Atlas HA-265, "*Floods at Humacao, Puerto Rico*" to document the flood events that occurred in the watershed on September 6, 1960 and August 27, 1961. River topography was not included in that study.

FEMA has performed two detailed studies of Río Humacao in the last 25 years. The first Flood Insurance Study (FIS) was published in 1984. The study provided peak discharge and flood elevations along 10.6 kilometers of river extending upstream from the river mouth. It used topographic data taken in 1978; just a few years after the channelization project ended. This FIS states that by the time of the study the channel had already suffered silting that had reduced its flood capacity, and that between one and two meters of sedimentation has occurred on the lower reaches. Furthermore, the study indicates that the levees on the sides of the channel lack "adequate" freeboard and could be overtopped by the 100-year event [1].

The most recent FIS was published by FEMA on 2009, and it covers a distance of approximately 10.8 kilometers, it revises peak discharge data and uses topographic data taken in 2004. The study increases both peak discharges and base flood elevations when compared to the previous FIS. Hydrology was performed with approximate methods based on USGS regional regression equations.

The PR Highway and Transportation Authority (PRHTA) also performed a study of the river for construction of the PR-53 highway bridge in 1989. Channel cross sections were field surveyed along a distance 270 meters downstream and 630 meters upstream of the highway bridge.

USGS Gage Stations

USGS station 50082000 at PR-3 has a drainage area of 44.8 km^2 (17.3 mi^2) and a period of record from 1960-1985. USGS station 5008100, located in the municipality of Las Piedras, is currently the only operational gage station inside the watershed. It has a drainage area of 17.2 km^2 (6.7 mi^2), and daily periods of record from 1974-1977 and from 1987- to the present. The mean daily stream flow at that station is 0.66 m^3/s (23.3 ft^3/s). The largest event in record, which also occurred on September 6, 1960, is 589 m^3/s (20,800 ft^3/s).

GEOMORPHIC ANALYSIS

Alluvial rivers are active and dynamic by nature. They respond to changes in its fluvial system; constantly adjusting their morphology according to channel and watershed conditions until it reaches a balance between flow regime and sediment transport. A river's geomorphology is directly influenced by factors such channel width, depth, velocity, discharge, channel slope, roughness of channel materials, sediment load, and sediment size. A change in one of those factors initiates a natural series of channel adjustments that leads to changes in other channel variables.

The purpose of the analysis is to assess and classify past and present geomorphic conditions along the river based on field reconnaissance, review of historical and current aerial photography, and collection of data from previous studies. The analysis will help understand the physical changes observed in the river, and will provide insight into the direction of future geomorphic changes and possible design alternatives.

Watershed Characteristics

Río Humacao's headwaters begin between Sierra de Luquillo and the Cayey Mountains, at an elevation of 350 meters above sea level. Major tributaries include Quebrada Mariana, Quebrada Mabú, and Quebrada Cataño. Quebrada Mariana and Mabú discharge into the river at the town of Humacao, while Quebrada Cataño discharges into the channel downstream of highway PR-53. The annual rainfall in the watershed ranges from 80 to 90 inches. The vegetative cover in the upper watershed is dense, and land use consists of forested areas and rural housing. Land use changes dramatically as the river travels downstream.

Land use up to the 1970's had been mainly sugarcane with pasture along hillsides. Since then, land use in the municipality of Humacao has changed from agricultural to industrial and urban development, and the population has grown from 36,000 to 59,000.

The major concentration of development has occurred around the town of Humacao, upstream of the coastal floodplain. Vegetative cover in the floodplain is mainly pasture used for cattle grazing. There is also a history of instream sand extraction activities within the past decades at different location along the river.

Description of Fluvial System

The river begins in the mountains where slopes are steep (15%) and the river channel has low sinuosity. The current river canalization covers a total length of 6.7 kilometers, which extend from the river mouth to 1 kilometer upstream of state road PR-3. As a comparison, pre-canalization river length along that same reach was 9.2 kilometers. Figure 1 shows pre-canalization and existing stream alignments on the USGS topographic quadrangle.

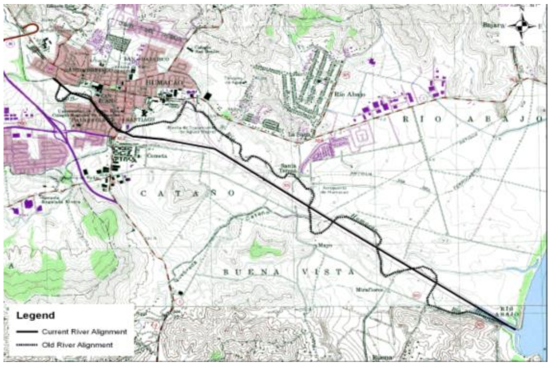

Figure 1
Pre-canalization and Current Stream Alignment

Bed material range from boulders along the upper reaches, to gravel and sand along the lower reaches. A sieve analysis was performed to determine the bed material's grain size distribution at two locations upstream and downstream of the Quebrada Cataño confluence (Figure 2). D_{50} corresponds to coarse sand.

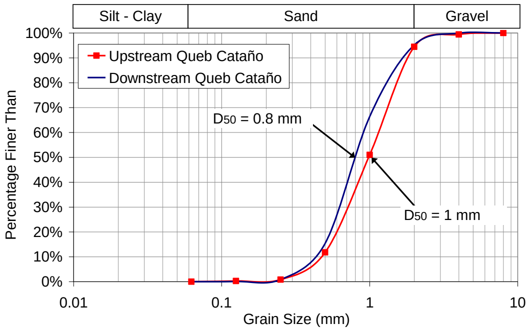

Figure 2
Grain Size Distribution

Field Observations

At USGS gage station 5008100, road PR-921 (5.5 kilometers upstream of Humacao), the river is moderately entrenched, and even though sand bars are present, channel morphology is dominated by bedrock and boulders.

Two major bridge structures are located upstream of the town of Humacao, the PR-30 and PR-30 exit ramp bridges. One of the exit ramp bridge piers is located inside the active channel and the pier pilings have been exposed by river incision and degradation. The PR-30 piers, however, are located outside of the river channel. Immediately upstream of the river canalization project, the river is entrenched and slightly meandering, and begins to form a defined floodplain. Bed material is predominately sand with some gravel.

At the state road PR-3 bridge, grade control has been provided in the form of sheet piles. Gabions used to stabilize the banks downstream of the bridge have failed by corrosion and abrasion. Downstream of PR-3, channel morphology is dominated by depositional features such as central and point bars. The active channel meanders within the original trapezoidal channel, and floodplain deposits are present along either side of the active channel. At the highway PR-53 bridge, 3.5 kilometers from the river mouth, the pier's foundations have been exposed by river incision.

Sand extraction activities have been observed at several locations downstream of highway PR-53.

Historical Change in Bed Elevations

Past and present stream bed elevations were obtained from several sources for comparison: 1) the 1975 PR Department of Transportation canalization project drawings, 2) the 1984 FIS, 3) the HH study performed by PRHTA in 1989, and 4) the 2009 FIS. Figure 3 presents the variation in stream bed elevations over the past 30 years, showing that bed elevations have decreased as much as 4 meters at some locations, and that bed elevations at the highway bridges, for example, have decreased 2 meters since construction.

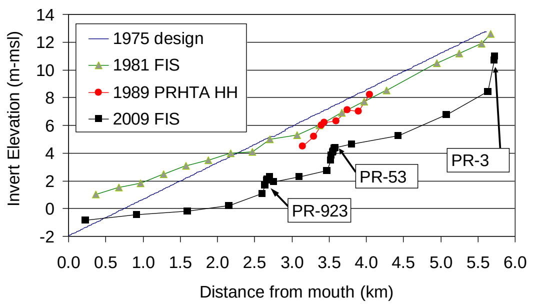

Figure 3
Historical Comparison of Stream Bed Elevations

The channel cross section obtained from the 1975 canalization project was compared to the cross section obtained from the FIS published in 2009. Figure 4 compares FEMA cross "C", located 2,157 meters upstream from the mouth. The figure shows how an active channel approximately 3 meters deep has formed inside the original trapezoidal section.

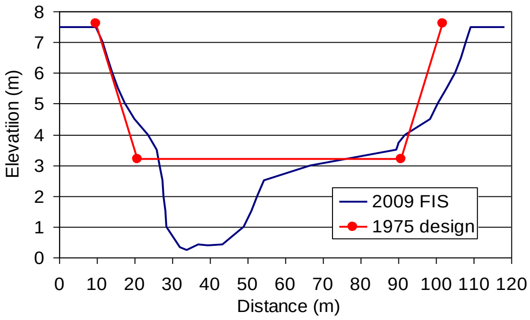

Figure 4
Comparison of FEMA Channel Cross Section "C"

Conclusions of Geomorphic Analysis

The geomorphic changes that have occurred in Río Humacao can be best explained by Lane's Balance, which provides a qualitative geomorphic relationship among the major variables affecting river form in the form of an equilibrium equation:

$$Q_sD \,\alpha\, QS \qquad (1)$$

Where Q_s and Q refer to sediment and water discharge respectively, D to grain diameter, and S to bed slope.

According to this relationship, activities that reduce sediment supply, or reduce sediment size, such as dam construction or instream mining activities for example, affects a river reach by producing downstream degradation since all of these actions tend to reduce the slope required to maintain equilibrium. Similarly, increased discharge as a product of increased development also affects a river reach by producing downstream degradation since it tends to reduce the slope required to maintain equilibrium.

The interplay among these and other factors (armoring, tributary inflows, encroachment by vegetation) will determine the extent and speed of channel adjustment below an area of intervention. Nearly all human influences on rivers in Puerto Rico, instream mining, urbanization, channeling, and dam construction, tend to create changes which work in the same direction in Lane's Balance by promoting channel incision.

In the last 30 years the Rio Humacao fluvial system has undergone a series of major changes that have altered river morphology. The canalization project which increased channel slope significantly, land use change from agricultural to pasture for grazing and residential development, and both permitted and non-permitted sand extraction activities are all factors contributing to the pattern of channel incision and bed degradation that we see today.

The river has responded by forming a meandering channel inside the trapezoidal canal in an attempt to decrease and naturally stabilize its slope and sediment transport. This lateral migration is retarded by the levees, impeding any further increase in meander width.

Pre-canalization channel slope was 0.11%, while the original channel design slope was more than double, 0.26%. As seen in Figure 3, over the last 30 years the river has naturally decreased its channel slope, looking to reach a gentler gradient. Below kilometer 5.5, current channel slope is now 0.15% (Figure 3).

RIVER CLASSIFICATION

River classification was based on the Rosgen Classification System, summarized in Figure 5, which defines seven major classifications of relatively homogeneous stream types based on valley type, channel entrenchment, gradient, width/depth ratio and sinuosity [2].

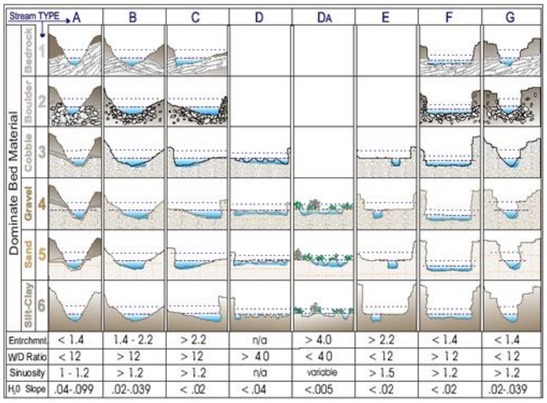

Figure 5
Rosgen River Classification System

The active channel that has formed inside the earthen trapezoidal canal shows the geomorphic characteristics of a Stream Type F5 by the Rosgen Classification System. This type of stream is sand dominated, and has an entrenched and meandering channel incised in gentle terrain. The visible top-of-bank for this type of river is much greater than the bankfull stage, indicative of deep entrenchment. Depositional features are common, and they tend to promote the long term development of a floodplain inside the bankfull channel. Central and transverse bars may be present, related to the high sediment supply.

Historical aerial photographs and topographic mapping show that the river's pre-canalization characteristics such as slope and sinuosity are compatible with a C5 stream type channel with geomorphology dominated by point bars and high sediment loads.

A stream of this type has a high to very high sediment supply, is slightly entrenched and meandering, and bed material is predominantly sand. The channel's morphology is characterized by point bars and other depositional features, a riffle/pool system and a well defined floodplain. The stream type has broad valleys and can be found in low relief basins typical of coastal floodplains. The alluvial floodplain can be classified as a Valley Type VIII, also by the Rosgen Classification System. This valley type is identified by multiple river terraces and a gentle down-valley slope. The presence of depositional landforms such as alluvial terraces and floodplains produce a high sediment supply.

As seen in Figure 5, a C5 Stream Type has a bankfull width/depth ratio greater than 12, Entrenchment ratio greater than 2.2, sinuosity greater than 1.2, and a slope less than 0.02. Table 1 compares pre-canalization and current river characteristics.

Table 1
Channel Characteristics

Parameter	Pre-canalization	Current
Length	4.5 km	3.2 km
Chanel slope	0.0011	0.0015
Sinuosity	1.44	1.10
Valley slope	0.002	0.002
Maximum belt width	493 m	80 m

RESTORATION COMPONENTS

The restoration project consists of various design components which include levee removal and relocation, bridge improvements, and channel stability structures. Channel and valley slope, as well as alignment and meander lengths, were designed to simulate pre-canalization characteristics compatible with a C5 stream type.

Levee Replacement

The existing levees run along both sides of the canalization. The restoration project requires the elimination of the existing levees from the river mouth to the PR-53 highway bridge, a total levee distance of 6.4 kilometers, and the construction of a new levee system consisting of a total distance of 1.6 kilometers, and a minimum 1-meter freeboard for the 100-year event. The location of the proposed levees is shown in Figure 6.

The northern levee was set to begin at the Wastewater Treatment Plant, which is located above the proposed 100-year flood elevation (floor elevation of 7.5 m). It runs 1,040 meters northeast until it intersects with PR-923, which is also above the proposed 100-year flood level. The southern levee runs for 1,615 meters from a point 1 kilometer upstream from the river mouth to PR-923. The proposed levee system will contain the 100-year flood within the restored river corridor.

Bankfull Channel

The bankfull discharge, area and elevation are arguably the most important parameters for river restoration, design of bank stabilization structures, and river classification. The bankfull discharge is directly related to channel width, meander length, radius of curvature and meander belt width, among other channel characteristics. This discharge represents the channel-forming flow that transports the bulk of available sediment. The bankfull discharge provides the channel with natural sediment transport maintenance, forming bars and other depositional features, forming or changing bends, and controls the major geomorphic characteristics of the channel [3].

The bankfull channel was designed for an event having a return interval of 1.5-years, which has commonly been linked to the bankfull discharge. Figure 6 shows the alignment of the bankfull channel. Figure 7 shows a typical cross section of the bankfull channel, which has been conceptualized with mild, 3:1 (H:V), side slopes. Table 2 presents the proposed channel parameters.

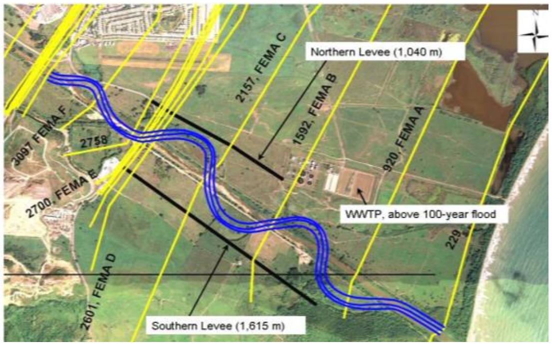

Figure 6

Proposed Channel Alignment and Levee System

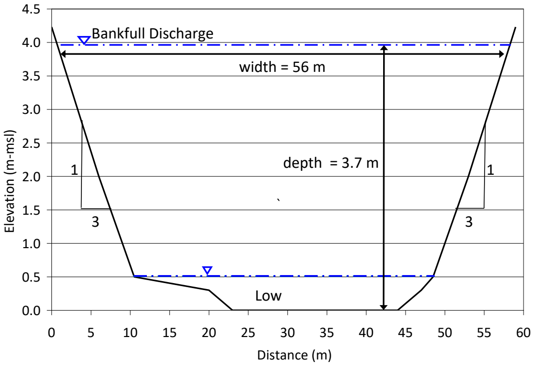

Figure 7

Proposed Bankfull Channel Cross Section

Table 2

Proposed Bankfull Channel Design Parameters

Parameter	Value
Length	3.8 km
Average top width	56 m
Average flow depth	3.7
Channel slope	0.0011
Width/depth ratio	15
Entrenchment ratio	9.6
Average channel area	166 m^2
Sinuosity	1.25
Valley Slope	0.002

Improvements to Road PR-923

The proposed project requires that the PR-923 bridge, which consists of an opening of 110 meters, be widened to 235 meters to allow for increased floodplain flow under the bridge.

Even though the proposed channel restoration does not require changes to the existing PR-53 bridge, grade control measures are recommended for both PR-923 and PR-53 bridges as part of the restoration effort.

Instream Rock Structures

The project features bank stabilization and grade control measures built from rock of stable size that not only provide channel stability, but also serve as habitat enhancement, and provide the aesthetic component of a natural river environment.

Meanders will be stabilized with the use of rock vanes, as illustrated schematically in Figure 8. These structures redirect flow velocity and near-bank shear stress away from the bank, and towards the center of the channel, to maintain lateral stability. The structure creates a zone of quiescent flow adjacent to the bank, encouraging sediment deposition. The vanes are designed to function under submerged conditions, and they begin at the bankfull elevation and slope downwards towards the channel, a distance 1/3 the bankful width. The scour hole created on the downstream side of the rock weir provides adequate fish habitat.

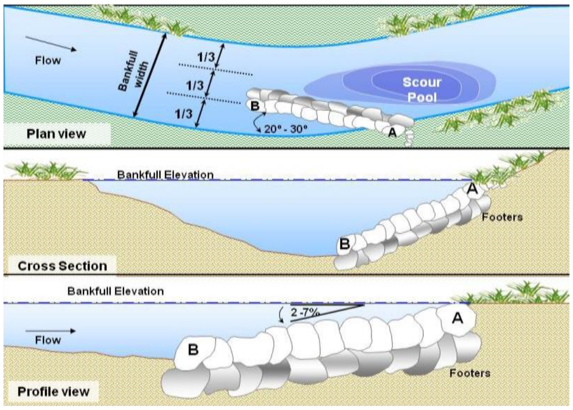

Figure 8
Schematic Design of Rock Vanes for Bank Stabilization

Grade control measures will consist of cross vanes built from rock and boulder, as seen schematically in Figure 9. These measures are particularly important at the downstream side of the highway PR-53 and road PR-923 bridges, where river incision has exposed pier foundations. These structures, besides having a more “natural” appearance, allow fish migration, unlike other structures used for grade control such as sheet piles or check dams.

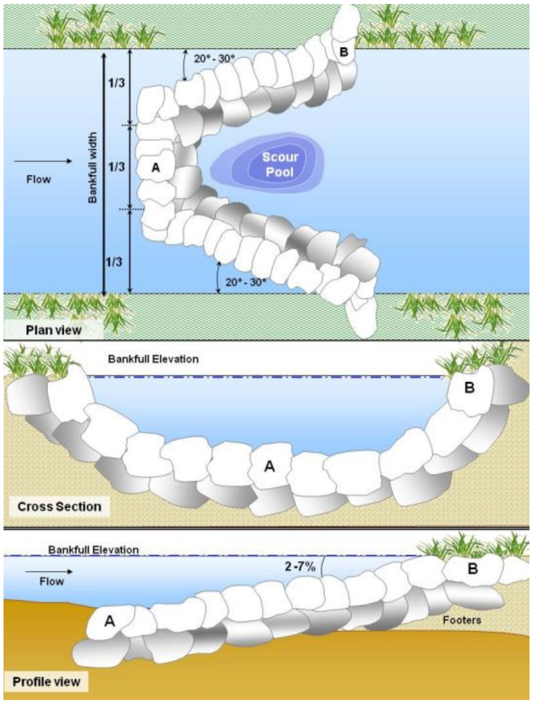

Figure 9
Schematic Design of Grade Control Structures

HYDROLOGIC ANALYSIS

Peak discharge was calculated with a rainfall-runoff model based on the National Resource Conservation Service (NRCS) Unit Hydrograph methodology. Rainfall data was obtained from the National Oceanic and Atmospheric Administration Atlas 14. Time of Concentration was calculated based on the NRCS TR-55 methodology, and soil types within the watershed were obtained from Soil Survey Geographic. An Antecedent Moisture Condition-II was used for the analysis. Peak discharge was calculated for the 1.5-, 10-, 50-, and 100-, and 500-year return interval events. The watershed was divided into 8 sub-basins, as seen in Figure 10.

Calculated 100-year discharges have been verified against FEMA 2010 FIS values, as seen in Table 3. Table 4 presents 1.5-, 10-, 50-, and 500-year calculated peak discharges.

FEMA hydrology has been determined with approximate methods, mainly USGS regional regression equations, which do not take into consideration the effects of hydrograph routing from the lower floodplain watersheds that drain into the river before the rest of the watershed reaches the floodplain. This methodology overestimates peak discharge at the lower Humacao reach. The discharge hydrograph obtained through modeling produces values that are close to FEMA at every location, except the river mouth.

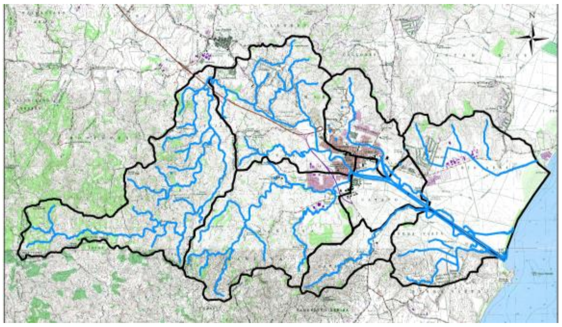

Figure 10
Río Humacao Watershed

Table 3
FEMA FIS 100-year Discharge Comparison

Location	Drainage Area (km^2)		Peak Discharge (m^3/s)	
	FEMA	modeling	FEMA	modeling
DS Queb Mariana	45.22	44.64	1,329	1,417
DS Queb Mabu	51.84	50.03	1,544	1,570
DS Queb Catano	58.79	58.22	1,692	1,604
Mouth	77.00	76.29	2,171	1,890

Table 4
Calculated 1.5-, 10-, 50-, and 500-year Discharge

Location	Peak Discharge (m^3/s)			
	1.5-yr	10-yr	50-yr	500-yr
DS Queb Mariana	257	615	1,183	2,001
DS Queb Mabu	295	682	1,245	2,067
DS Queb Catano	328	761	1,376	2,231
Mouth	399	939	1,585	2,660

HYDRAULIC ANALYSIS

Flood levels were determined with the Army Corps of Engineers HEC-RAS program, based on FEMA's most recent Effective Model which uses current topographic data and river cross sections. Existing and Proposed Condition Models were prepared to compare flood levels. The models were also used to obtain other design data such as velocity and flow depths.

Figure 11 shows model cross section locations. The model prepared for this study extends from FEMA model cross section 229 to 3799 (FEMA cross section "I"). The proposed restoration begins at cross section 229 and ends at cross section 3475 (FEMA cross section "G").

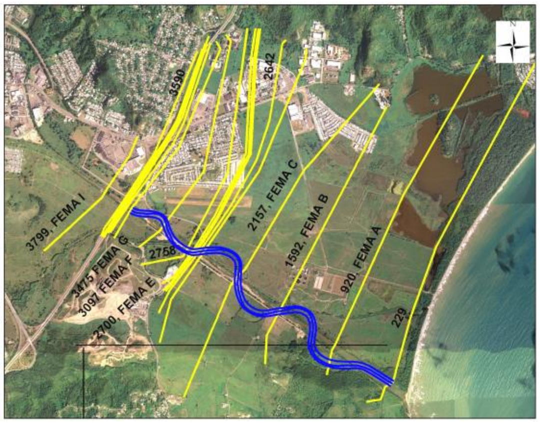

Figure 11
Model Cross Section Location

Results of Hydraulic Modeling

Table 5 compares proposed condition 100-year levels with FEMA flood levels. The proposed project raises food levels a maximum of 0.9 meters, 1.6 kilometers upstream of the mouth (cross section B). Existing ground elevations at the Wastewater Treatment Plant are 7.5 m-msl, which is above the proposed flood level. Flood waters will be contained inside the proposed levee system, reducing flood risk to the Humacao valley.

Table 5
Results of Hydraulic Modeling

FEMA Cross Section	Distance to ocean (m)	Water Surface Elevation (m-msl)		Difference
		Existing	Proposed	
A	920	4.4	3.7	-0.7
B	1,592	5.8	6.7	0.9
C	2,157	7.7	8.0	0.3
D*	2,601	8.3	8.7	0.4
E	2,700	8.9	9.5	0.6
F	3,097	9.0	9.7	0.7
G**	3,475	11.3	10.2	-1.1
H	3,590	12.0	11.9	-0.1
I	3,799	12.2	12.1	-0.1

*road PR-923, **highway PR-53

Figure 12 compares a typical proposed cross section to current conditions. Figure 13 compares existing and proposed channel profiles. River elevations are being raised up to 2 meters, 2.2 kilometers from the river mouth.

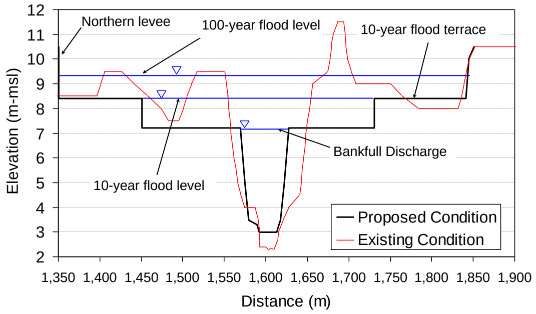

Figure 12
Typical Cross Section Comparison

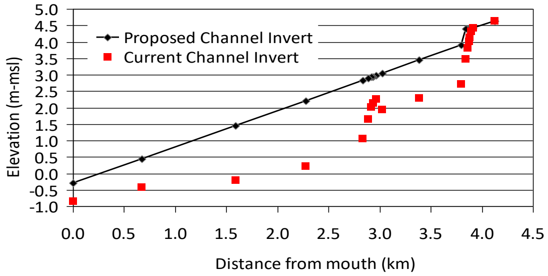

Figure 13
River Profile Comparison

Rock Sizing

This analysis was performed to determine the size of stable rock required for construction of the proposed structures for channel stability and habitat enhancement. The structures will be designed to withstand the shear stresses and velocities under a 100-year flood event. Methods recommended for stream restoration by the NRCS were used for rock sizing.

The Isbash Method was developed for construction of dams by depositing rocks into moving water. The method is appropriate for quick estimates or for comparison [4]. Critical velocity is calculated by (2):

$$V_c = C\left(2g\frac{\gamma_s-\gamma_w}{\gamma_w}\right)^{0.5}\left(D_{50}\right)^{0.5} \tag{2}$$

Where Vc = critical velocity (17.32 ft/s), C = 0.86 for high turbulence, g = 32.2 ft/s, γ_s = stone density (165 lb/ft^3), γ_w = water density (62.4 lb/ft^3), and D_{50} = median stone diameter (ft).

The US Bureau of Reclamation method was developed for sizing riprap below stilling basins [4]. D_{50} is determined by (3):

$$D_{50} = 0.0122V^{2.06} \tag{3}$$

Where D_{50} = median stone diameter (ft), and V = channel velocity (17.32 ft/s).

The USGS Blodgett method is based on field data from 39 large event sites in the western United States. Rip Rap failed in 14 of those 39 cases. D_{50} is determined by (4):

$$D_{50} = 0.01V^{2.44} \tag{4}$$

Where D_{50} = median stone diameter (ft), and V = channel velocity (ft/s). The USGS method typically yields overly conservative results [4]. Table 6 summarizes stone sizing results for the 100-year event.

Table 6
Stone Sizing Results

Method	D_{50} (m)
Isbash	1.2
Bureau of Reclamation	1.3
USGS (Blodgett 1981)	3.2

Incipient Motion

This analysis was performed to determine the critical velocity required to initiate the movement of particles in the river channel bed, based on the Shield's diagram method for incipient motion. The Shield's parameter reflects the ratio of the force producing sediment motion to the force resisting motion [5]. Shear stress was calculated with (5):

$$\tau = \gamma_w RS \tag{5}$$

Where τ = shear stress, γ_w = water unit weight (9,810 kg*m/s^2), R = hydraulic radius (3.7 m), and S = slope (0.0011). Hydraulic depth can be used instead of hydraulic radius in wide channels.

Incipient motion is defined by the Shield's relationship based on the critical value of the dimensionless Shield's parameter, F_{CR}. The Shield's relationship is given by (6):

$$F_{CR} = \frac{\tau}{[(\gamma_S - \gamma_W)D]} \tag{6}$$

Where F_{CR} =0.047 for turbulent flow, τ = shear stress from (5) (40 N/m^2 for bankfull event), γ_s = stone unit weight (26,000 $kg*m/s^2$), γ_w = water unit weight ($kg*m/s^2$), and D = sediment diameter (m). The size of stable particles was determined by solving (6) for sediment diameter.

For a bankfull event, the stable particle diameter is 52 mm. This means that the coarse sand particles found in the river bed (D_{50} = 1 mm) will effectively be transported under bankfull conditions.

Summary, Conclusions and Recommendations

- Data shows that Río Humacao was once a C5 stream type at the coastal floodplain, while the active channel that has formed inside the trapezoidal canalization shows characteristics of a F5 stream type.
- Changes in land use and practices within the watershed, combined with urbanization and an increased river slope, have caused up to 4 meters of river bed incision.
- FEMA hydrology was performed with approximate methods, and it overestimates peak discharge along the lower river reach.
- The proposed river corridor provides a total of 359 acres of land that can be used for recreational facilities, such as parks, trails, open-faced gazebos. This area must be kept clear of buildings or placement of fill, or any large structure that may become an obstruction to flow.
- Even though flood levels increase a maximum of 0.9 meters, the 100-year flood will be contained inside the proposed levee system, reducing flood risk throughout the Humacao valley.
- The proposed restoration project will not impact existing communities or major infrastructure, other than improvements to road PR-923 bridge.
- No grazing will be permitted along the proposed river corridor. Tree planting plans and other land use and watershed management practices that promote bank stability and erosion control should be implemented.
- It is recommended that instream mining practices stop immediately along the entire watershed. Current state and municipal permitting policies towards these practices should be revised.
- Rocks to be used for the channel stability structures shall be hard igneous in nature, flat faces, angular in shape, resistant to weathering and water erosion, and with a minimum specific gravity of 2.65. A minimum stone diameter of 1.3 m, and weight of 3,100 kg, is recommended.

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