Rio Humacao Channelization Viability Study

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Abstract *— Río Humacao is located in the southeast coast of Puerto Rico and it flows generally northeastward and then southeastward and enters the alluvial floodplain at the town of Humacao, 6 kilometers upstream from its mouth. Major tributaries are Quebrada Mabu, and Quebrada Mariana. Quebrada Mabu, flows southward and Quebrada Mariana flows eastward. Both tributaries cross through the town of Humacao. A great portion of the town lies on the Special Flood Hazard Areas as designated by the Federal Emergency Management Agency (FEMA) on its Flood Insurance Rate Map (FIRM). This happens because mostly of the town of Humacao was developed around the river in their floodplain before the FEMA FIRM's were adopted by the PR Planning Board on 1984. The main objective of this project is to determine the preliminary extent of the channelization of the Rio Humacao and its tributaries to remove out the portion of the town from the Special Flood Hazard Area, and if it is economically viable.*

Key Terms *— Quebrada Mabu, channelization, Special Flood Hazard Area, economical viability.*

BACKGROUND

The headwaters of Río Humacao lie between the Sierra de Luquillo and Cayey Mountains, approximately 450 meters above sea level. Río Humacao flows generally northeastward and then southeastward through the deeply weathered plutonic rock of the interior uplands and enters the alluvial floodplain at the town of Humacao, 6 kilometers upstream from its mouth. The river drains an area of approximately 62 km^2 (23.9 mi^2), and has a length of approximately 26 kilometers. In the mountain areas, the channel slopes of Río Humacao are very steep, and stream velocities are extremely high. The slopes become less steep from the foothills to its mouth. The coastal plain becomes progressively wider downstream from Humacao and is approximately 3.2 kilometers wide at the coast [1].

Major tributaries are Quebrada Mabu, and Quebrada Mariana. Quebrada Mabu, flows southward toward Rio Humacao passing through the town of Humacao. Quebrada Mariana flows eastward toward Río Humacao passing through the southwest portion of the town of Humacao.

Many of the areas where these streams pass get affected when flooding occurs. Approximately 50% of the town of Humacao is subject to inundation by the 1% annual chance flood, or the 100-year peak discharge, as it is portrayed on the FEMA FIRM's for this streams.

The last major flooding on this area was recorded on September 6, 1960 due to the passing of Hurricane Donna about 100 miles north of San Juan [2], according to the United States Department of the Interior Geological Survey. The largest rainfall total reported was 18.76 inches on the northeast slope of the Luquillo Mountains near Sabana, The estimated return period for this flood approximately 100 years [2].

There were 117 lives lost, 90 of them were drowned as flood waters of the Rio Humacao swept through low lying areas of the city, 30 persons missing, and 136 injured. Total damage was estimated in excess of $7,000.000.00 [2], $56,315,000.00 taking into account inflation. Several thousand persons were forced from their homes by the floods as 484 houses were destroyed and more than 3,600 others were damaged. All main highways and most secondary roads were impassable for a short period during the floods and damage to them was heavy [2].

That's why FEMA, as a federal government agency, which is mission is to prepare for, prevent, respond to and recover from disaster, administers the National Flood Insurance Program (NFIP) created by the United States Congress in 1968 through the National Flood Insurance Act of 1968.

Through that program, Flood Insurance Studies (FIS) were prepared. FIS are a compilation and presentation of flood risk data for specific watercourses, lakes, and coastal flood hazard areas within a community. When a flood study is completed for the NFIP, the information and maps are assembled into the FIS. The FIS report contains detailed flood elevation data in flood profiles and data tables. These maps are the FIRMs, which are used to determine if a property needs flood insurance or not.

FLOOD INSURANCE STUDIES

FEMA has performed two detailed studies of Río Humacao in the last 32 years. The first FIS for this basin was performed on April 16, 1984 by PBS&J and Lebrón, Sanfiorenzo & Fuentes. A revision was made on June 2007 by Medina Consultants and was published on November 18, 2009 [3].

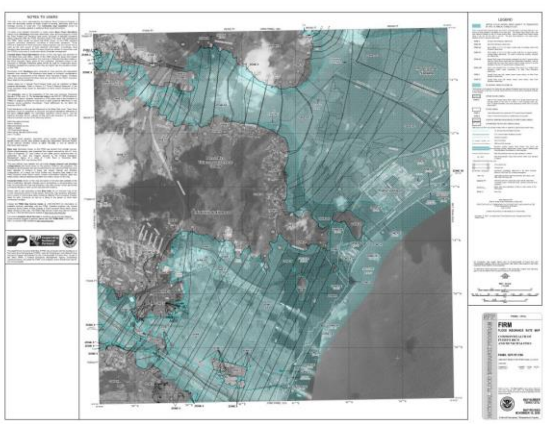

Figure 1
Flood Insurance Rate Map 72000C01270J Rio Humacao November 18, 2009

The data used for the FISs cross sections were obtained from aerial photographs flown in November 1978 enlarged to a scale of 1:5,000 by Continental Aerial Surveys, Inc. [4]. Also, for the FIS, all bridges, dams, and culverts were field surveyed to obtain elevation data and structural geometry. Figure 1 and Figure 2 are the most recent FIRMs for the study area.

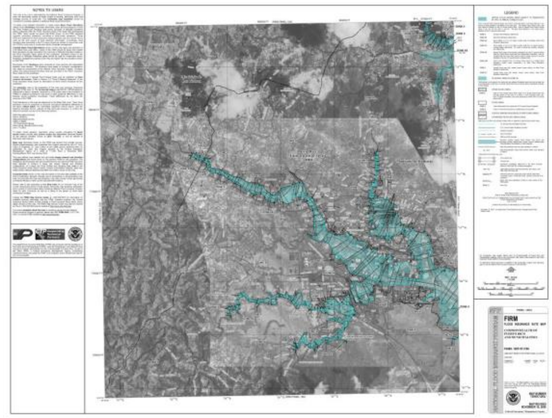

Figure 2
Flood Insurance Rate Map 72000C01265J Rio Humacao, November 18, 2009

SITE VISIT

A site visit to the three streams was done on August 20, 2015. The following information was obtained:

- The three streams are heavy vegetated and site is heavy vegetated with grass and brush.
- Rio Humacao downstream of crossing with bridge from State Road PR-53 is heavy vegetated on both sides and sediment deposits, mostly sand, on the bottom of the stream channel as seen on Figure 3.

Figure 3
Downstream view of Rio Humacao from State Road PR-923

- The levee along Rio Humacao channel is covered with brush and grass as observed in Figure 4. This levee extends from State Road PR-3 to the river mouth. This channelization also included the downstream reaches of Quebrada Catano and Quebrada Mabu from its mouth to downstream of PR Highway 3. According to the FIS, this channel was designed in 1975 by the Puerto Rico Department of Transportation and Public Works to provide protection against a flood with a recurrence interval of approximately 100 years. However, silting (as observed) has reduced the flood-carrying capacity of the channel. The levees on each side of the channel can be overtopped or are lacking adequate freeboard to protect against the 1-percent annual chance flood [5].

Figure 4
Downstream view of Right Side Levee of Rio Humacao from Bridge on State Road PR-53

HYDRAULIC ANALYSIS

The hydraulic analysis was performed using the US ARMY Corps of Engineers HEC-RAS River Analysis System (v4.1) software. The HEC-RAS program uses uniform, steady and unsteady and one-dimensional flow to estimate the effects produced by changes in geometry, roughness and flow. The program also considers hydraulic structures like culverts and bridges. The hydraulic analysis was performed for the 100-year event, and under a sub-critical flow regime, to match the elevations that appear on the FIRMs, which was the scope of this study.

There was no need to perform any hydrologic analysis because the FIS have the 100-year peak discharge necessary for this analysis.

Model Calibration

The existing condition model was necessary to calibrate to verify the data of the FIS with the water surface elevations that are portrayed in the FIRMs. Table 1, Table 2, and Table 3 presents the 100-year water surface elevations for the existing condition and channelization model for Rio Humacao, Quebrada Mabu and Quebrada Mariana.

Table 1
100-year Water Surface Elevations for Existing Condition and Channelization Model Rio Humacao

FEMA FIS Cross Section	Water Surface Elevation (m-msl)	FEMA FIRM Cross Section	Water Surface Elevation (m-msl)	Difference
10818	46.46	AC	47.2	0.74
10564	43.42	AB	43	-0.42
10087	35.52	AA	36.8	1.28
9690	32.83	Z	34.3	1.47
9303	31.59	Y	32.8	1.21
8998	29.95	X	30.7	0.75
8872	29.16	W	29.7	0.54
8738	28.56	V	29.1	0.54
8428	27.64	U	28.1	0.46
7956	26.2	T	26.6	0.4
7820	25.08	S	25.4	0.32
7692	24.42	R	24.3	-0.12
7481	23.54	Q	23.7	0.16
7025	21.39	P	22.4	1.01
6588	21.04	O	21.6	0.56
6297	20.79	N	21	0.21
6107	19.61	M	20	0.39
5717	18.44	L	18.1	-0.34
5082	16.66	K	15.3	-1.36
4436	13.82	J	13.7	-0.12
3799	12.45	I	12.2	-0.25
3590	12.31	H	12	-0.31
3475	11.74	G	11.3	-0.44
3097	9.96	F	9	-0.96

2700	8.66	E	8.9	0.24
2601	8.47	D	7.3	-1.17
2157	7.55	C	7.7	0.15
1592	5.82	B	5.8	-0.02
920	4.28	A	4.4	0.12
	Average difference (m)			0.173793

Table 2
100-year Water Surface Elevations for Existing Condition and Channelization Model Quebrada Mabu

FEMA FIS Cross Section	Water Surface Elevation (m-msl)	FEMA FIRM Cross Section	Water Surface Elevation (m-msl)	Difference
3652	43.3	W	43.3	0
3572	40.82	V	40.8	-0.02
3472	38.44	U	38.5	0.06
3306	36.68	T	36.7	0.02
3216	35.57	S	35.6	0.03
3190	34.49	R	34.5	0.01
3031	30.44	Q	30.4	-0.04
2868	28.61	P	28.6	-0.01
2701	26.59	O	26.6	0.01
2634	26.1	N	26.1	0
2567	24.57	M	24.6	0.03
2500	24	L	24	0
2368	22.6	K	22.6	0
2279	22.37	J	22.4	0.03
2196	22.03	I	22	-0.03
2066	21.38	H	21.4	0.02
1917	20.69	G	20.6	-0.09
1738	20.3	F	20.3	0
1436	18.5	E	18.5	0
1274	17.47	D	17.5	0.03
942	16.36	C	16.4	0.04
679	15.79	B	16.1	0.31
418	14.97	A	15.9	0.93
	Average difference (m)			0.057826

The average difference in elevation for Rio Humacao, Quebrada Mabu and Quebrada Mariana was 0.17, 0.06 and 0.01 meters respectively, which tells us that the data is trustworthy.

Table 3
100-year Water Surface Elevations for Existing Condition and Channelization Model Quebrada Mariana

FEMA FIS Cross Section	Water Surface Elevation (m-msl)	FEMA FIRM Cross Section	Water Surface Elevation (m-msl)	Difference
4102	75.2	N	75.23	0.03
3906	56.4	M	56.42	0.02
3721	51.8	L	51.83	0.03
3155	40.8	K	40.75	-0.05
2906	39.9	J	39.87	-0.03
2575	36.2	I	36.16	-0.04
2272	28.2	H	28.24	0.04
1775	24.6	G	24.61	0.01
1248	23.4	F	23.42	0.02
863	22.7	E	22.74	0.04
734	22.5	D	22.47	-0.03
669	21.3	C	21.32	0.02
590	20.4	B	20.42	0.02
154	19.1	A	19.1	0
	Average Difference (m)			0.005714

Proposed Model

The proposed model is used to determine channel cross section geometry to accommodate the 100-yr peak discharge and take all of the adjacent areas of the streams out of the Special Flood Hazard Areas Subject to inundation by the 1% annual chance flood.

Hydraulic Analysis Results

The Rio Humacao, Quebrada Mabu and Quebrada Mariana streams cross section geometry and slope were modified. The geometry of the channel used for this channelization was rectangular. The mean cross section area on the Rio Humacao was increased by 22%, by 46% on Quebrada Mabu and decreased by 25% on Quebrada Mariana. Table 4, Table 5, and Table 6 presents the flow area inside the channel for existing conditions and channelization of Rio Humacao, Quebrada Mabu and Quebrada Mariana.

Table 4
100-year Flow Area of the Channel for Existing Condition and Channelization Model Rio Humacao

Cross Section	100-year Flow Channel (m2)		Difference
	Existing Condition	Channelization	
10818	151.3	184.03	32.73
10564	181.61	146.13	-35.48
10087	122.37	177.87	55.5
9690	117.32	180.29	62.97
9303	149.65	153.02	3.37
8998	223.76	208.68	-15.08
8872	230.15	255.16	25.01
8738	225.46	249.09	23.63
8428	205.66	230.71	25.05
7956	252.53	368.78	116.25
7820	255.04	358.84	103.8
7692	258.98	368.62	109.64
7481	304.67	300.42	-4.25
7025	253.69	319.17	65.48
6588	215.66	355.54	139.88
6297	416.52	373.82	-42.7
6107	297.64	374.91	77.27
5717	488.91	263.4	-225.51
5082	446.95	511.6	64.65
4436	434.33	566.05	131.72
3799	418.01	502.91	84.9
3590	443.19	483.36	40.17
3475	449.98	591.21	141.23
3097	408.2	586.95	178.75
2700	429.4	502.65	73.25
2601	423.12	614.94	191.82
2157	410.38	626.35	215.97
1592	344.59	540.85	196.26
920	339.85	388.95	49.1
Average change in flow channel area (m2)			65.0131

Table 5
100-year Flow Area of the channel for Existing Condition and Channelization Model Quebrada Mabu

Cross Section	100-year Flow Channel Area (m2)		Difference
	Existing Condition	Channelization	
3652	22.68	17.26	-5.42
3572	20.5	17.78	-2.72
3472	11.69	17.57	5.88
3306	18.48	18.61	0.13
3216	15.68	25.68	10
3190	38.37	35.92	-2.45
3031	18.02	26.47	8.45
2868	40.33	52.36	12.03
2701	35.25	46.68	11.43
2634	17.77	58.74	40.97
2567	17.99	61.17	43.18
2500	5.19	40.45	35.26
2368	4.92	44.66	39.74
2279	15.41	49	33.59
2196	31.69	46	14.31
2066	31.24	62.93	31.69
1917	63.91	82.8	18.89
1738	73.99	82.82	8.83
1436	40.67	59.79	19.12
1274	36.09	86.68	50.59
942	63.69	106.14	42.45
679	95.6	110.58	14.98
418	130.01	87.41	-42.6
Average change in flow channel area (m2)			16.88391

Table 6
100-year Flow Area of the channel for Existing Condition and Channelization Model Quebrada Mariana

Cross Section	100-year Flow Channel Area (m2)		Difference
	Existing Condition	Channelization	
3652	22.68	17.26	-5.42
4102	35.17	52.54	17.37
3906	78.63	60.7	-17.93
3721	63.68	67.31	3.63
3155	87.29	136.67	49.38
2906	144.62	115.38	-29.24
2575	42.53	67.32	24.79
2272	92.91	77.62	-15.29
1775	123.51	161.4	37.89
1248	395.84	193.71	-202.13
863	341.41	181.44	-159.97
734	344.22	161.36	-182.86
669	170.33	177.13	6.8
590	136.22	172.74	36.52
154	313.02	159.11	-153.91
Average change in flow channel area (m2)			-41.7821

Table 7, Table 8, and Table 9 presents the water surface elevations for existing conditions and channelization of Rio Humacao, Quebrada Mabu and Quebrada Mariana.

Table 7
100-year Water Surface Elevations for Existing Condition and Channelization Model Rio Humacao

Cross Section	100-year Water Surface Elevations (m-msl)		Difference
	Existing Condition	Channelization	
10818	46.46	44.16	-2.3
10564	43.42	39.28	-4.14
10087	35.52	34.38	-1.14
9690	32.83	32.32	-0.51
9303	31.59	29.83	-1.76
8998	29.95	27.81	-2.14
8872	29.16	26	-3.16
8738	28.56	25.4	-3.16
8428	27.64	24.16	-3.48
7956	26.2	23.56	-2.64
7820	25.08	22.22	-2.86
7692	24.42	21.77	-2.65
7481	23.54	20.5	-3.04
7025	21.39	19.08	-2.31
6588	21.04	18.03	-3.01
6297	20.79	17.48	-3.31
6107	19.61	17.03	-2.58
5717	18.44	13.62	-4.82
5082	16.66	12.12	-4.54
4436	13.82	11.16	-2.66
3799	12.45	10	-2.45
3590	12.31	9.51	-2.8
3475	11.74	8.89	-2.85
3097	9.96	8.39	-1.57
2700	8.66	7.55	-1.11
2601	8.47	7.43	-1.04
2157	7.55	6.89	-0.66
1592	5.82	5.46	-0.36
920	4.28	3.75	-0.53
Average Change in Water Surface Elevation (m)			-2.39931

Table 8
100-year Water Surface Elevations for Existing Condition and Channelization Model Quebrada Mabu

Cross Section	100-year Water Surface Elevations (m-msl)		Difference
	Existing Condition	Channelization	
3652	43.3	41.92	-1.38
3572	40.82	39.86	-0.96
3472	38.44	37.68	-0.76
3306	36.68	34	-2.68
3216	35.57	32.27	-3.3
3190	34.49	31.99	-2.5
3031	30.44	28.2	-2.24
2868	28.61	26.31	-2.3
2701	26.59	25	-1.59
2634	26.1	24.68	-1.42
2567	24.57	24.04	-0.53
2500	24	22.91	-1.09
2368	22.6	21.95	-0.65
2279	22.37	21.51	-0.86
2196	22.03	20.82	-1.21
2066	21.38	20.04	-1.34
1917	20.69	19.56	-1.13
1738	20.3	18.97	-1.33
1436	18.5	16.99	-1.51
1274	17.47	16	-1.47
942	16.36	15.44	-0.92
679	15.79	14.02	-1.77
418	14.97	12.17	-2.8
Average Change in Water Surface Elevation (m)			-1.55391

Table 9
100-year Water Surface Elevations for Existing Condition and Channelization Model Quebrada Mariana

Cross Section	100-year Water Surface Elevations (m-msl)		Difference
	Existing Condition	Channelization	
4102	75.23	74.86	-0.37
3906	56.42	54.07	-2.35
3721	51.83	50.43	-1.4
3155	40.75	38.39	-2.36
2906	39.87	37.76	-2.11
2575	36.16	34.64	-1.52
2272	28.24	26.24	-2
1775	24.61	21.44	-3.17
1248	23.42	20.67	-2.75
863	22.74	19.44	-3.3
734	22.47	18.72	-3.75
669	21.32	18.37	-2.95
590	20.42	18.08	-2.34

154	19.1	13.84	-5.26
Average Change in Water Surface Elevation (m)			-2.545

Inline Structures

On the inline structures across the streams, on Rio Humacao, four (4) of the eight (8) bridges were replaced. The average span of the new bridges were no less than 100 meters.

On Quebrada Mabu, one (1) culvert was eliminated at cross section 1550, seven (7) of the eight (8) bridges were replaced, and four (4) of the five (5) culverts were replaced with bridges. Figure 5 shows one of the bridges that had to be replaced.

Figure 5
Bridge that has to be replaced on Quebrada Mabu

The culvert on Quebrada Mabu was eliminated because it had no infrastructural use as road or pedestrian sidewalk or anything else, Figure 6 and Figure 7 shows the box culvert that had to be eliminated.

Figure 6
Box Culvert at Quebrada Mabu that has to be eliminated

Figure 7
Box Culvert at Quebrada Mabu that has to be eliminated

The average span of the new bridges on Quebrada Mabu was no less than 26 meters.

On Quebrada Mariana, one (1) of the two (2) bridges on Quebrada Mariana was replaced. The span of the new bridge is no less longer than 50 meters. Table 10, Table 11, and Table 12 presents the existing condition and channelization spans for the bridges and culverts on Rio Humacao, Quebrada Mabu and Quebrada Mariana.

Table 10
Inline Structure Span for Existing Condition and Channelization Model Quebrada Mabu

Cross Section	Span of bridge or Culvert (m)		Difference
	Existing Condition	Channelization	
700 BR	16.75	27.75	9.00
805 BR	5.58	25.75	20.17
1425 BR	9.71	25.75	16.04
1550 CU	10.20	Deleted	15.55
1747 CU	5.66	25.75	20.09
1930 CU	7.80	25.75	17.95
2205 BR	4.50	25.75	21.25
2350 BR	9.80	25.75	15.95
2487 CU	7.90	25.75	17.85
2600 BR	261.71	261.71	0
3196 CU	6.20	22	15.80
3316 BR	5.00	18.00	13.00
3580 BR	4.95	15.00	10.05
Average Change in Bridge Span (m)			16.058

Table 11
Inline Structure Span for Existing Condition and Channelization Model Rio Humacao

Cross Section	Span of bridge or Culvert (m)		Difference
	Existing Condition	Channelization	
2670 BR	110.00	110.00	0.00
3540 BR	682.23	682.23	0.00
3560 BR	680.82	680.82	0.00
5740 BR	61.30	102.00	40.70
6215 BR	72.23	102.00	29.77
7830 BR	78.00	78.00	0.00
7855 BR	129.37	129.37	21.25
8895 BR	24.30	46.00	21.70
Average Change in Bridge Span (m)			28.355

Table 12
Inline Structure Span for Existing Condition and Channelization Model Quebrada Mariana

Cross Section	Span of bridge or Culvert (m)		Difference
	Existing Condition	Channelization	
132 BR	20.17	50.00	29.83
700 BR	46.55	46.55	0.00
Average Change in Bridge Span (m)			29.83

ECONOMICAL ANALYSIS

The economical analysis was based on the five main activities involved to perform this type of project: land, commercial and residential acquisition by expropriation, to accommodate the channelization; demolition of structures which include residential, commercial and industrial, and bridges and culverts; earth movement for the widening of the stream; building of new bridges; and construction of the side retention walls of the new channel, which for a rectangular geometry, are vertical and are required for slope stability on the banks. Quebrada Mabu is the most impacted in terms of residential expropriations with 54.57%. Rio Humacao is the most impacted in terms of land expropriations with 96.48%.

Table 13 presents land and residential/commercial acquisition costs. Approximately 100 residences and 70 acres have to be expropriated to carry out the project.

Table 13
Land and Residential/Commercial Expropriation Approximate Costs

Stream	Land Expropriation	Residential /Commercial Expropriation	% of Residential Expropriations	% of Land Expropriations
Rio Humacao	$2,855,952.00	$906,000.00	12.20%	96.48%
Quebrada Mabu	$87,780.00	$4,051,833.32	54.57%	2.97%
Quebrada Mariana	$16,500.00	$2,467,666.59	33.23%	0.56%
Total	$2,960,232.00	$7,425,499.91		

Table 14 presents the demolition and construction approximate costs for the rectangular geometry option.

Table 14
Demolition and Construction Approximate Costs

Stream	Demolition of Structures	Earth Movement	Bridge Replacement	Reinforced Concrete Walls
Rio Humacao	$125,000.00	$6,910,511.36	$13,750,000.00	$29,576,666.67
Quebrada Mabu	$460,000.00	$1,449,350.98	$14,465,000.00	$11,626,977.78
Quebrada Mariana	$190,000.00	$1,058,316.00	$2,750,000.00	$13,707,222.22
Total	$775,000.00	$9,418,178.34	$30,965,000.00	$54,910,866.67

Table 15 presents total channelization costs with and without reinforced concrete wall construction and the percentage of savings if the project goes with a natural channelization.

Table 15
Total Channelization Approximate Costs with and without Reinforced Concrete Wall Construction

Stream	Total Channelization Cost	Total channelization cost without Reinforced Concrete Walls	% of savings without Reinforced Concrete Wall Construction
Rio Humacao	$54,124,130.02	$33,554,415.36	38.00%
Quebrada Mabu	$32,140,942.08	$27,998,577.62	12.89%
Quebrada Mariana	$20,189,704.81	$10,236,649.18	49.30%
Total	$106,454,776.91	$71,789,642.16	32.56%

Table 16 presents the comparison between the total costs of the rectangular channel against the trapezoidal channel.

Table 16
Total Rectangular Geometry Channelization and Total Trapezoidal Geometry Channelization Approximate Costs

Total Cost	Rectangular Channel	Trapezoidal Channel	Increase or decrease in relation to rectangular channel
Land Expropriation	$2,960,232.00	$5,920,464.00	100.00%
Residential Expropriation	$7,425,499.91	$14,850,999.82	100.00%
Demolition of Structures	$775,000.00	$1,230,000.00	58.71%
Earth Movement	$9,418,178.34	$9,418,178.34	0.00%
Bridge Replacement	$30,965,000.00	$40,370,000.00	30.37%
Reinforced Concrete Walls	$54,910,866.67	$0.00	-100.00%
Total Project Cost	$106,454,776.91	$71,789,642.16	32.56%

HYDRAULIC DESIGN RECOMMENDATIONS

The hydraulic design recommendations are based on the results obtained from the analysis performed for this study and the different variables studied.

Channel Geometry and Material

The channel geometry on the stream used for this study was rectangular, with its bottom sloped to the center of it to minimize sediment deposition and promote its transport. The channel material consists of reinforced concrete retaining walls due to the vertical slopes on the banks of the stream. Those walls have to be protected on the toe against erosion by construction of a hydraulic structure to prevent it from tilting. The bottom of the stream should be the native material of it, which is mostly sand, as observed on the field visit.

Nonetheless, trapezoidal cross sections, should be the choice, because are more efficient than rectangular cross sections and the channelization wouldn’t need concrete at all, but would require more transversal space than rectangular ones. Circular cross sections is the most efficient cross sectional area, but not constructible for this application due to the size of the cross sections.

Bridge and Culvert Replacement

92% of all the inline structures, bridges and culverts, on Quebrada Mabu were replaced with new bridges with spans of no less than 26 meters to avoid the hydraulic control on the stream or in common terms, bottleneck effect. The culvert at cross section 1550 was eliminated because it lies between the back of two lines of residences and its ends up on bridges, one on each end. This culvert had no infrastructural use as road or pedestrian sidewalk or anything else, etc.

50% of all the inline structures on Rio Humacao were replaced with new bridges of no less than 100 meters. 50% of all the inline structures on Quebrada Mariana was replaced with a new bridge of no less than 30 meters.

SUMMARY AND CONCLUSIONS

On Rio Humacao:

- Water surface elevation was lowered an average of 2.40 meters.
- Average cross section increased 22%.
- Four (4) out of eight (8) bridges must be replaced, 50%.
- Average bridge spans increase of 28.36 meters.
- 259,632 square meters of land must be expropriated.
- 15 residences must be expropriated.
- 96.48% of the total land expropriation cost of the project, mostly governmental property.
- 12.20% of the total residential/commercial expropriation cost of the project.
- 16.13% of demolition of structures of the project.
- 73.37% of the earth movement cost of the project.
- 44.40% of the bridge replacement cost of the project.
- 53.86% of reinforced concrete construction cost of the project.

On Quebrada Mabu:

- Water surface elevation was lowered an average of 1.55 meters.
- Average cross section increased 46%.
- One (1) culvert must be eliminated and eleven (11) bridges and culverts must be replaced, in summary, twelve (12) out of thirteen (13) bridges and culverts must be replaced, 92%.
- Average bridge spans increase of 16.06 meters.
- 7,980 square meters of land must be expropriated.
- 42 residences must be expropriated.
- 2.97% of the total land expropriation cost of the project.
- 54.57% of the total residential/commercial expropriation cost of the project.
- 59.35% of demolition of structures cost of the project.
- 15.39% of the earth movement cost of the project.
- 46.71% of bridge replacement cost of the project.
- 21.17% of reinforced concrete construction cost of the project.

On Quebrada Mariana:

- Water surface elevation was lowered an average of 2.54 meters.
- Average cross section decreased 25%.
- One (1) out of two (2) bridges must be replaced, 50%.
- Average bridge spans increase of 29.83 meters.
- 1,500 square meters of land must be expropriated.
- 34 residences must be expropriated.
- 0.56% of the total land expropriation cost of the project.
- 33.23% of the total residential/commercial expropriation cost of the project.
- 24.52% of demolition of structures cost of the project.
- 11.24% of the earth movement cost of the project
- 8.88% of the bridge replacement cost of the project.
- 24.96% of reinforced concrete construction cost of the project.

The most impacted stream in terms of cross sectional area and inline structures is Quebrada Mabu, which its average cross section area must be increased by 46% and 92% of its inline structures must be replaced. This happens because Quebrada Mabu crosses through downtown Humacao, so it will impact the majority of its adjacent residential and commercial developments which results in 40% of the land/residential/commercial expropriation total cost of the project.

Of the land expropriation total cost, 96% of it is on Rio Humacao, but it's mostly in the floodway area near the river mouth, which mostly this land belongs to Puerto Rico Highway and Transportation Authority (PRHTA).

Of the residential/commercial expropriation cost, 54% of it is on Quebrada Mabu due to the fact that this stream crosses through downtown Humacao, which is highly urbanized. On the other hand, Quebrada Mariana and Rio Humacao doesn't impact excessively because there are no much developments around these streams.

Of the project total cost of $106,454,776.91, 52% of this cost, $54,910,866.67, is for the construction of the reinforced concrete walls on both sides of the channel due to the geometry used for this analysis, rectangular. The construction of reinforced concrete walls is necessary because of the vertical slopes on both sides of the channel, and the length of them, which in total are 18,572 meters combined.

The channelization of the Rio Humacao and its tributaries, Quebrada Mabu and Quebrada Mariana it's not economically viable due to the high cost of the project, $106,454,776.91. If the project total cost is compared to the inflated economical estimated damage cost, $56,315,000.00, of the September 19, 1960 flood, the channelization almost doubles the value of covering the damages of the 1% annual chance flood, or the 100-year peak discharge and it also makes the project not viable.

RECOMMENDATIONS

- This type of study can be performed in other rivers with a similar scenario to evaluate it extent and its economical viability. This type of problem happens in almost every municipality in Puerto Rico were residential, commercial and industrial developments were constructed around rivers in their floodplain before the FEMA FIRM's were adopted by the PR Planning Board on 1984.
- For this type of analysis, minimum of two alternatives should be studied to verify the economical impact and evaluate if it is cost effective. The natural channelization (trapezoidal cross section), $71,789,642.16, is less expensive than the engineered channelization (rectangular cross section), $106,454,776.91, a project cost savings of 33%. Even though, the natural channelization is less expensive, it impacts double the quantity of land and residential/commercial expropriations and the bridges will have longer spans, both alternatives have to be studied. The natural channelization is less expensive because it doesn't involve the use of reinforced concrete. It will also look more attractive as it blends with nature and recreational areas can be created along it, but it will affect many people.
- This type of project where the channelization impacts many of its adjacent residential and commercial developments and its road and utilities infrastructure, as it happens on Quebrada Mabu, should be carefully analyzed and studied because many families would have to be relocated. Also many roads have to be redesigned to accommodate the new span of the bridges and many utilities, water supply, storm sewer, sanitary sewer, electricity, gas (in some places), etc. had to be relocated.
- FEMA and the governmental agencies or organizations that finance these types of projects should make a thorough cost benefit analysis to evaluate if it is beneficial to go ahead with this type of project or not.

REFERENCES

[1] Federal Emergency Management Agency, "*Flood Insurance Study, Commonwealth of Puerto Rico and Municipalities*", November 18, 2009, pp 27.

[2] United States Department of the Interior Geological Survey, "*Floods of September 6, 1960, in Eastern Puerto Rico*", 1961, pp 1.

[3] Federal Emergency Management Agency, "*Flood Insurance Study, Commonwealth of Puerto Rico and Municipalities*", November 18, 2009, pp 5.

[4] Federal Emergency Management Agency, "*Flood Insurance Study, Commonwealth of Puerto Rico and Municipalities*", April 19, 2005, pp 87.

[5] Federal Emergency Management Agency, "*Flood Insurance Study, Commonwealth of Puerto Rico and Municipalities*", November 18, 2009, pp 55.