APENDICE B

Estudio Hidrológico e Hidráulico

Octubre 2010

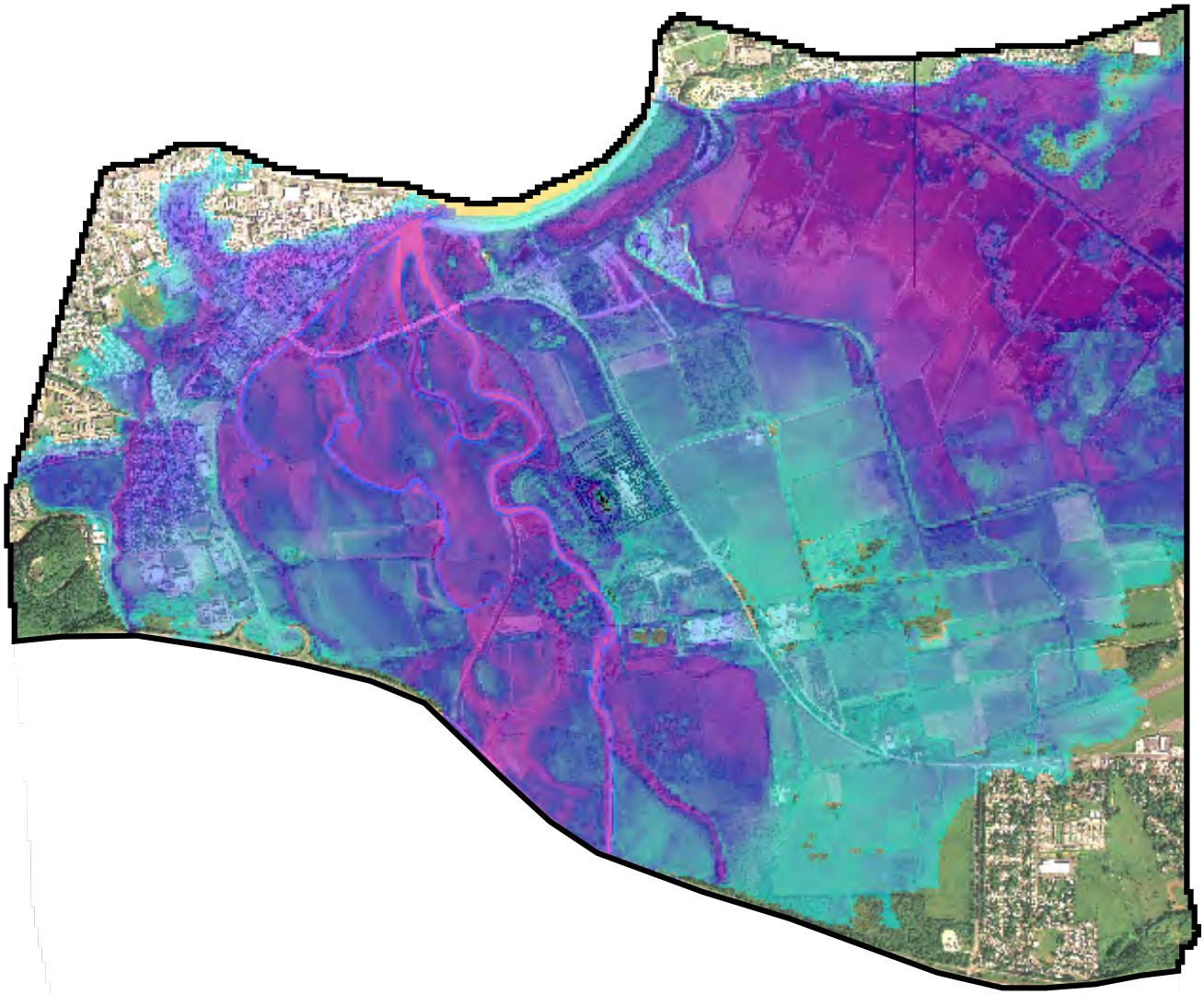
Declaración de Impacto Ambiental – Preliminar

Planta de Generación de Energía Renovable y Recuperación de Recursos

BARRIO CAMBALACHE DE ARECIBO

EnergyAnswers Arecibo

HYDROLOGIC-HYDRAULIC STUDY OF RÍO GRANDE DE ARECIBO, RENEWABLE POWER GENERATION AND RESOURCE RECOVERY FACILITY, ARECIBO, PUERTO RICO



October 5, 2010

Prepared for:

Energy Answers International
79 N Pearl Street
Albany NY, 12207

Prepared by:

GLM MORRIS ENGINEERING
Tanca St. # 250
P.O. BOX 9024157
San Juan, PR 00902
Tel. (787) 723-8005 Fax (787) 721-3196

TABLE OF CONTENTS

1. INTRODUCTION 1
   1.1. Project Description and Location 1
   1.2. Scope and Purpose of Study 1
   1.3. Authorization 1
   1.4. Parties Involved with Project 1

2. STUDY AREA DESCRIPTION 2
   2.1. Study Area Description 2
   2.2. Prior Studies and Floodplain Mapping 3
      2.2.1. Federal Emergency Management Agency (FEMA) 3
      2.2.2. United States Geological Survey (USGS) Flood Atlas 4
      2.2.3. US Army Corps of Engineers (USACE) 5
   2.3. Summary of Peak Discharges 6
   2.4. Field Observations 8
   2.5. Field Survey Data 8

3. STUDY APPROACH AND METHODOLOGY 10
   3.1. Hydrologic Analysis 10
   3.2. Hydraulic Analysis 10

4. HYDROLOGIC ANALYSIS 12
   4.1. Watershed Limits 12
   4.2. Soil Types, Curve Number and Time of Concentration 12
   4.3. Model Calibration 13
      4.3.1. Rainfall Depths 13
      4.3.2. Calibration Results 16
   4.4. Discharge Hydrographs for Design Storms 18
   4.5. Hydrologic Effects of Río Santiago Diversion 20
   4.6. Results of Hydrologic Analysis 21
   4.7. Verification of Hydrology 21

5. HYDRAULIC ANALYSIS 23
   5.1. Hydraulic Model Configuration 23
   5.2. Effective FEMA Tie-in/ Length of Study Reach 24
   5.3. Models Prepared 24
   5.4. Hydraulic Modeling Coefficients 25
   5.5. Downstream Water Surface Elevation 26
   5.6. Results of Duplicate Effective/Existing Condition Model 26
   5.7. Results of Floodway Encroachment/Proposed Condition Model 27
   5.8. Revised FIS Floodway Data Table 28

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS 29

7. CERTIFICATION 30

8. REFERENCES 31

LIST OF FIGURES

Figure 1: Project site location map on USGS topographic quadrangle

Figure 2: Project site location map on recent aerial photography

Figure 3: Flow patterns below highway PR-22 bridge

Figure 4: FEMA FIRM panel 230J, dated November 18, 2009

Figure 5: USGS Historical Flood Atlas, Investigation Report 01-4247

Figure 6: Location of USGS stream gage stations

Figure 7: Army Corps of Engineers' Río Grande de Arecibo Flood Control Project

Figure 8: Analyzed watershed limits

Figure 9: Hydrologic Soil Groups found within analyzed watersheds

Figure 10: Location of the three rainfall stations with 15-minute records for the Hurricane Georges event

Figure 11: Cumulative rainfall for the three stations with 15-minute records for the Hurricane Georges event

Figure 12: Hurricane Georges 24-hour rainfall isohyetal map and location of rainfall stations

Figure 13: Comparison of observed and simulated hydrographs at USGS gage station 50024950, Río Grande de Arecibo below Utuado

Figure 14: Flood Hydrographs at Río Grande de Arecibo before and after Río Santiago diversion

Figure 15: Hydrograph attenuation at Lago Dos Bocas and Caonillas

Figure 16: Layout and extent 2D-grid for Río Grande de Arecibo

Figure 17: Layout and extent of Hydrograph Routing Model

Figure 18: Layout and extent of Duplicate Effective/Existing Condition Model

Figure 19: Comparison of FEMA and Duplicate Effective/Existing Condition 100-year flood profile

Figure 20: Location of bank modification area

Figure 21: Proposed geometry of bank modification area

Figure 22: Proposed 100-year floodway limits

Figure 23: 100-year water surface elevation differences attributable to encroachment

Figure 24: Annotated FIRM panel 230J

LIST OF TABLES

Table 1: FEMA Floodway Data Table for FIS of Río Grande de Arecibo

Table 2: FEMA FIS peak discharge at Río Grande de Arecibo

Table 3: Peak discharge calculated by USGS for Hurricane Georges (September 1998)

Table 4: USACE Peak Discharge at Río Grande de Arecibo and Río Tanamá

Table 5: Comparison of Río Grande de Arecibo peak discharge from previous studies

Table 6: Comparison of Río Tanamá peak discharge from previous studies

Table 7: Calculated hydrologic parameters of analyzed sub-basins

Table 8: Rainfall station data used at each analyzed sub-basin

Table 9: Hurricane Georges Rainfall Depths (September 21 and 22, 1998) used for rainfall distribution calculations

Table 10: 24-hour Rainfall Depths at each sub-basin during Hurricane George

Table 11: Calibrated hydrologic parameters of analyzed sub-basins

Table 12: Runoff Hydrograph Calibration to USGS gage 50024950 for Hurricane Georges, September 21-22 1998

Table 13: Comparison of Peak Discharges as published in "Flood *of September 22, 1998, in Arecibo and Utuado, Puerto Rico. USGS Water Resources Investigations Report 01-4247:"*

Table 14: 100-year NOAA Atlas 14 Rainfall Depths (inches) for each sub-basin

Table 15: 24-hour NOAA Atlas 14 Rainfall Depths for each sub-basin

Table 16: Peak Discharge at Río Grande de Arecibo, at confluence with Río Tanamá

Table 17: Comparison of peak discharges at USGS gage station 50027750, Río Grande de Arecibo above Arecibo

Table 18: Manning's n-value used in Hydraulic Model

Table 19: FEMA Water Surface Elevation (m-msl) at Cross Section "C"

Table 20: Results of Duplicate Effective/Existing Condition Model

Table 21: 10-, 50-, and 500-year flood levels for Duplicate Effective/Existing Condition Model

Table 22: Comparison of 100-yr Existing and Encroached Water Surface Elevations

Table 23: Revised Río Grande de Arecibo Floodway Data Table

LIST OF APPENDIXES

Appendix A: Partial Reproduction of FEMA FIS of Río Grande de Arecibo

Appendix B: Time of Concentration Calculations

Appendix C: Hurricane Georges NCDC Rainfall Data and Rainfall Distribution Calculations

Appendix D: USGS gage 50024950, Río Grande de Arecibo below Utuado, data for Hurricane George

Appendix E: NOAA Atlas-14 Rainfall Data and Rainfall Distribution Calculations

Appendix F: Input Data and Results of HEC-HMS Hydrologic Model

Appendix G: Log-Pearson III Analysis for USGS gage 50027750, Río Grande de Arecibo above Arecibo

Appendix H: FEMA MT-2 forms

HYDROLOGIC-HYDRAULIC STUDY OF RÍO GRANDE DE ARECIBO, RENEWABLE POWER GENERATION AND RESOURCE RECOVERY FACILITY, ARECIBO, PUERTO RICO

1. INTRODUCTION

1.1. Project Description and Location

Energy Answers International proposes the construction of a renewable power generation and resource recovery facility located on state road PR-2, in the municipality of Arecibo. The site is located along the eastern bank of the river channel, downstream of the old Central Cambalache sugar cane mill, approximately 2 kilometers south of highway PR-22. Figure 1 and Figure 2 show the location of the proposed development on the USGS topographic quadrangle and on recent aerial photography, respectively.

1.2. Scope and Purpose of Study

This study has been undertaken to determine 10-, 50-, 100- and 500-year flood levels along Río Grande de Arecibo and revise encroachment limits at the location of the project site, based on recent topographic data and updated modeling. This study provides hydraulic modeling and documentation required to request a regulatory floodway amendment to the Puerto Rico Planning Board and Federal Emergency Management Agency.

1.3. Authorization

Roberto M. León Iglesias, of CSA Architects and Engineers LLP, has authorized preparation of this report through a written agreement with Gregory L. Morris Engineering, P.S.C.

1.4. Parties Involved with Project

The following parties were involved with the preparation of this report:

Owner:	Energy Answers International
Project Designer:	CSA Architects and Engineers, LLP
Report Preparers:	Gregory L. Morris, P.E., Ph.D.
	Luan M. Esteban, P.E., M.E.C.E.
	José D. Miranda, P.E.
	Juan Portalatin, P.E., M.S.C.E

2. STUDY AREA DESCRIPTION

2.1. Study Area Description

Río Grande de Arecibo generally runs south and its watershed begins at the Cordillera Central mountain range, specifically in the Guilarte State Forest, at elevations of approximately 1,200 m-msl. The river begins at the confluence of Río Las Vacas and Río Cidra, immediately upstream of state road PR-135, in the municipality of Adjuntas. Along its upper reaches, Río Grande de Arecibo runs though a narrow, canyon-like valley, in a region characterized by karst formations. The river is moderately entrenched with stable banks, has a riffle dominated channel with infrequently spaced pools, and a river valley that presents colluvial deposition.

The heavily sedimented Lago Adjuntas dam is located 2.3 kilometers downstream of Adjuntas. A smaller diversion dam is also located 7 kilometers downstream of Lago Adjuntas. Neither dam has appreciable storage, and the 100-year flood overflows the uncontrolled crests of both structures. Because of coarse sediment trapping by the Lago Adjuntas reservoir, bed degradation has occurred downstream the dam. Some portions of the riverbed completely lack granular material, exposing bedrock. These in-stream structures are located more than 30 kilometers upstream from the coastal floodplain. Several other in-stream reservoirs are located within the river's watershed (upstream to downstream): Lago Garzas, Lago Pellejas, Lago Caonillas, and Lago Dos Bocas.

Lago Garzas, located on the uppermost portion of the watershed, was built in 1943 and diverts runoff from approximately 6 mi^2 to the south coast of the Island for the production of hydroelectricity and for irrigation of the Lajas Valley. The two major reservoirs within the watershed are Lago Dos Bocas and Lago Caonillas, built in 1942 and 1948, respectively, for hydroelectric production. Even though neither reservoir was designed for flood control purposes, they do offer hydrograph attenuation during large events.

The river enters a wide alluvial floodplain downstream of the PR-22 highway bridge. This coastal floodplain is approximately 4 kilometers wide, and extends from the river mouth at the Atlantic Ocean to approximately 11 kilometers upstream. The primary developed area in the floodplain is the town of Arecibo, located along the western portion of the valley. Three bridges are currently located in the coastal floodplain: 1) the PR-22 highway bridge, 2) state road PR-2 bridge, and 3) PR-680, Victor Rojas Bridge.

Caño Tiburones is an extensive coastal lagoon and wetland system located between Río Grande de Manatí (to the east) and Río Grande de Arecibo (to the west). Caño Tiburones has been historically affected by floodwaters overflowing from Río Grande de Manatí and Río Grande de Arecibo, although inflow from Arecibo is now prevented by a system of dikes along the western portion of the Caño. High floodwaters, however, tend to overtop the dike system.

The project site is located between state road PR-2 and the river channel, along the eastern portion of the Río Grande de Arecibo floodplain, approximately 2 kilometers downstream (north) of highway PR-22. The property is located downstream from the old Central Cambalache sugar mill, approximately 2 kilometers west of Caño Tiburones. Figure 3 shows flow patterns at the floodplain below the highway PR-22 bridge. After flow exits the highway bridge, part runs north towards PR-2, while the other portion runs towards the east, perpendicular to road PR-2.

2.2. Prior Studies and Floodplain Mapping

Several studies have been performed previously for Río Grande de Arecibo.

2.2.1. Federal Emergency Management Agency (FEMA)

Río Grande de Arecibo has been previously studied by FEMA in its Flood Insurance Study (FIS) for the Lower Río Grande de Arecibo Basin published in 1980. The study determined peak discharge, base flood elevations and floodway limits for a reach that extends approximately 17 kilometers upstream from the river mouth. The one-dimensional, unsteady flow, HEC-6 step-backwater model developed by the US Army Corps of Engineers was used by FEMA to model the coastal floodplain. Copy of FEMA's effective model is not available at the FEMA Project Library.

The study limit along the eastern portion of the floodplain was determined by FEMA to be the dike that runs southward from the Caño Tiburones mouth, and parallels state road PR-2 for approximately 11 kilometers, as seen in FEMA Flood Insurance rate Map (FIRM) panel 230J, dated November 18, 2009 (see Figure 4). According to the FIRM panel, the project site is located at FEMA cross section "D", with base flood elevation of 5.2 m-msl. Table 1 presents a portion of FEMA's Floodway Data Table for Río Grande de Arecibo.

Table 1: FEMA Floodway Data Table for FIS of Río Grande de Arecibo

Cross Section	Distance from mouth (km)	Base Flood Elevation (m-msl)		
		without floodway	with floodway	difference
B	0.4	2.7	2.7	0.0
C	0.8	3.6	3.6	0.0
D (site)	2.1	5.2	5.2	0.0
E	2.9	6.6	6.6	0.0
F	3.4	7.1	7.4	0.3
G	4.2	7.8	8.1	0.3
H	5.1	9.1	9.4	0.3
I	6.5	11.5	11.8	0.3
J	6.9	12.8	13.1	0.3

FEMA determined peak discharge using rainfall-runoff modeling, and hydrographs were routed to and through the Dos Bocas Dam. The FIS reports peak discharge along Río Grande de Arecibo downstream of the Dos Bocas Dam, and at the confluence with Río Tanamá, as seen in Table 2. Partial reproduction of FEMA's FIS of Río Grande de Arecibo is included in Appendix A.

Table 2: FEMA FIS peak discharge at Río Grande de Arecibo

Location	Drainage Area (km^2)	Peak Discharge (m^3/s)			
		10-yr	50-yr	100-yr	500-yr
Confluence with Río Tanamá	487	2,890	4,550	5,680	8,640
Downstream Dos Bocas Dam	415	2,520	4,050	4,930	7,650

2.2.2. United States Geological Survey (USGS) Flood Atlas

The USGS prepared the Water-Resources Investigation Report 01-4247 "*Flood of September 22, 1998, in Arecibo and Utuado, Puerto Rico*" (Torres-Sierra, 2002) to document the flood event that occurred in the Río Grande de Arecibo basin due to the passing of Hurricane Georges. The study provides peak discharge and flood levels based on USGS stream gage data and observed flood marks, respectively. Figure 5 shows the Historical Flood Atlas published by the USGS.

Peak discharge was computed by USGS over the spillways at the Caonillas and Dos Bocas Dams using recorded flood stage data and the theoretical spillway discharge rating curve for each reservoir. The computed peak discharge for Río Grande de Arecibo at the Dos Bocas Dam was transferred downstream to station 50027750 Río Grande de Arecibo above Arecibo using the procedure described by López and others (1979). This method was also used to translate the observed peak discharge at station 50028000 Río Tanamá near Utuado to station 50028400 Río Tanamá at Charco Hondo.

The location of USGS stream gage stations is shown in Figure 6. Station 50027750, Río Grande de Arecibo above Arecibo, is located above the confluence with Río Tanamá. USGS station 50027750, and station 50028400, Río Tanamá at Charco Hondo, are both located upstream from the highway PR-22 bridge. Table 3 shows the peak discharge calculated by the USGS for the September 1998 event.

Table 3: Peak discharge calculated by USGS for Hurricane Georges (September 1998)

Location	Drainage Area (km^2)	Peak Discharge (m^3/s)
Río Grande de Arecibo at the Dos Bocas Dam	440	3,260
50027750 Río Grande de Arecibo above Arecibo [a]	451	3,330
50028000 Río Tanamá near Utuado	48	666
50028400 Río Tanamá at Charco Hondo	149	778

[a] does not include discharge from Río Tanamá

2.2.3. US Army Corps of Engineers (USACE)

The USACE prepared a hydrologic-hydraulic study of the lower Río Grande de Arecibo basin for the "*Río Grande de Arecibo Final Feasibility Report and Environmental Impact Statement*" in July 1993. The study analyzed the proposed flood control project for Río Grande de Arecibo and two of its tributaries. The project consists primarily of three major elements, as seen in Figure 7: 1) approximately 4,500 meters of levee and floodwalls around the eastern and southern boundaries of the town of Arecibo, 2) 2,900 meters of a trapezoidal earthen channel to divert flow from the upper Río Santiago basin into the Río Grande de Arecibo floodplain, downstream of highway PR-22, and 3) 1,200 meters of levee north of Río Tanamá, immediately upstream of state road PR-10. Construction of the Río Tanamá levee, the Río Santiago diversion channel and the southern portion of the Río Grande de Arecibo levee has been

completed. The levee along the eastern boundary of the town of Arecibo has not begun.

The USACE study determined peak discharge along Río Grande de Arecibo based on a Log-Pearson III flood frequency analysis, verified through rainfall-runoff modeling performed with HEC-1 and through USGS regional regression equations. The Log-Pearson analysis was performed with data from the abandoned USGS station 50029000 at Central Cambalache, combined with peak data from station 50027750 Río Grande de Arecibo above Arecibo (which does not include discharge from Río Tanamá). Discharge for Río Tanamá was estimated with HEC-1 modeling. Table 4 presents the peak discharges calculated by USACE.

Table 4: USACE Peak Discharge at Río Grande de Arecibo and Río Tanamá

Location	Area (km^2)	100-year Peak Discharge (m^3/s)		
		Log-Pearson III	HEC-1	USGS equations
50028400 Río Tanamá at Charco Hondo	149	N/A	660	N/A
50027750 Río Grande de Arecibo above Arecibo	451	N/A	4,427	N/A
50029000 Río Grande de Arecibo at Central Cambalache	518	4,000	4,870	7,000

2.3. Summary of Peak Discharges

Table 5 and Table 6 compare peak discharge as calculated by previous studies along Río Grande de Arecibo and Río Tanamá, respectively. The FEMA FIS presents the highest, most conservative, peak discharge for Río Grande de Arecibo.

Table 5: Comparison of Río Grande de Arecibo peak discharge from previous studies

Study/Location	Drainage Area (km^2)	Peak Discharge (m^3/s)	Yield (m^3/s / km^2)
USGS Flood Atlas (Torres-Sierra, 2002)			
at Dos Bocas Dam	440	3,260	7.4
USGS 50027750	451	3,330	7.4
USACE (100-YEAR, HEC-1)			
USGS 50027750	451	4,427	9.8
USGS 50029000	518	4,870	9.4
FEMA FIS (100-YEAR)			
Downstream Dos Bocas Dam	415	4,930	11.9
at Confluence with Tanamá	487	5,680	11.7

Table 6: Comparison of Río Tanamá peak discharge from previous studies

Study/Location	Drainage Area (km^2)	Peak Discharge (m^3/s)	Notes
USGS Flood Atlas (Torres-Sierra, 2002)			
USGS 50028000	48	666	Hurricane Georges
USGS 50028400	149	778	Hurricane Georges
USACE			
USGS 50028400	149	660	100-year, HEC-1
100-year event (Ramos-Ginés, 1999)			
USGS 50028400	149	626	Bulletin 17B weighted

2.4. Field Observations

The site was visited on several occasions on February and April 2010. The following observations were made based on these field observations.

- The site is located approximately 200 meters east of the active river channel. Overbanks are heavily vegetated with brush, tress and some bamboo. Bed material consists predominately of sand.
- The project site is located along the eastern bank of Río Grande de Arecibo, in the Global Fibers Paper Mill facilities. Various abandoned structures from the old mill operations can still be found inside the site
- A concrete barrier (Jersey barrier), approximately 1-meter tall, runs along the state road PR-2 median beginning at the intersection of roads PR-681 and PR-2. This barrier is occasionally interrupted along road intersections.

2.5. Field Survey Data

Surveyor Pedro J. Dávila Colón provided river and bridge cross sections of the Río Grande de Arecibo study reach referenced vertically to mean sea level and/or Puerto Rico Vertical Datum of 2002, (MSL, PRVD02) and horizontally referenced to the State Plane Coordinates System for Puerto Rico and the North American Datum of 1983, (SPC, NAD83). The river cross-sections were surveyed during February 2010.

Floodplain elevations and topographic contours are also referenced vertically and horizontally to MSL, PRVD02 and SPC, NAD83, respectively. Elevations were obtained from the Digital Elevation Models for San Juan and Mayagüez, Puerto Rico, prepared for the NOAA Pacific Marine Environmental Laboratory (PMEL), Center for Tsunami Inundation Mapping Efforts (TIME) by the NOAA National Geophysical Data Center (NGDC) on May 5, 2006.

Topographic datasets used in the elevation grids consist of LIDAR collected at 3 meter postings by the USACE, and obtained from the USDA, National Resources Conservation Service for the main island. Topographic LIDAR data were collected by 3001, Inc. for the USACE in 2004 as part of an effort to develop digital orthophoto imagery for administration of the US Department of Agriculture GIS Orthophotography update program. The data cover nearly the entire island of Puerto Rico at 3 meter postings. The grids have an estimated vertical accuracy of 0.1 to 1 meters for topographic areas, and 0.1 meters to 5% of water depth for bathymetric areas. Topographic values are largely derived from USACE LIDAR surveys, which have an estimated vertical accuracy of 0.1 to 0.15 meters.

Three topographic digital elevation grids were built for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Inundation Mapping Efforts (TIME), a 3 arc-second grid covering the whole island of Puerto Rico and two 1/3 arc-second grids centered around Mayagüez and San Juan, Puerto Rico. The best available data from US federal and state agencies and the University of Puerto Rico were obtained for grid compilation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, GMT and MBSystem software.

The published elevation grids were originally tied to the mean high water, (MHW) vertical Datum but were transformed to MSL, PRVD02 by applying the correction provided NOAA.

3. STUDY APPROACH AND METHODOLOGY

3.1. Hydrologic Analysis

The hydrologic analysis has been performed using the US Army Corps of Engineers' HEC-HMS model based on the Unit Hydrograph Methodology developed by the Natural Resources Conservation Services (NRCS). Runoff hydrographs generated by this method are based on rainfall depths and durations, soil type and area, land use, lag times, and Antecedent Moisture Conditions.

Río Grande de Arecibo and its tributaries are partially located on the Puerto Rico karstic area, which is characterized by irregular limestone formations with sinkholes, underground streams, and caverns. In many places, surface runoff seeps underground through the hundreds of sinkholes throughout the watershed and travels an indeterminate length through underground fissures. This indeterminate hydrologic response of the watershed cannot be determined by use of any direct methodology or calculation.

For this reason, the hydrologic model was calibrated using a historical event (Hurricane Georges, September 22, 1998) for which the watershed's rainfall and peak discharge were known. This calibration served to incorporate into the model the uncertainties in the flow pattern caused by the complex surface and subsurface drainage mechanism existing within the watershed.

Discharge along the watershed is also influenced by several in-stream reservoirs, mainly Lago Dos Bocas and Lago Caonillas. These reservoirs were included in the hydrologic model and spillway discharge was calibrated by adjusting weir flow coefficients.

3.2. Hydraulic Analysis

Because of the flat and unconfined topography of the floodplain, the hydraulic analysis was performed using the FLO-2D two-dimensional model; a numerical model nationally-approved by FEMA. FLO-2D is a dynamic flood routing model that simulates channel flow by a one-dimensional model, floodplain flow by a 2-D grid, and by coupling the 1D to every adjacent 2-D element to calculate water exchange between the two. It simulates a flood over complex topography and roughness using the full dynamic wave momentum equation and a central finite difference routing scheme with eight potential flow directions to predict the progression of a flood hydrograph over a system of square grid elements.

Unconfined overland flow is simulated in eight directions (4 compass directions and 4 diagonal directions). One-dimensional channel flow is simulated with rectangular, trapezoidal or natural shaped cross section. When the discharge exceeds the channel capacity, an interactive routine in FLO-2D will compute the overbank discharge onto the floodplain or the return flow to the channel on a grid element basis.

The hydrologic-hydraulic model prepared consists of a flow surface topography represented by a square grid system. The grid system was created from a Digital Elevation Model (DEM) created by precision LIDAR mapping. Inflow hydrographs are used as hydrologic inputs to the model. Channel elements representing the principal stream within the simulation boundary were included as one-dimensional flow paths using irregular channel geometry defined by field survey.

4. HYDROLOGIC ANALYSIS

4.1. Watershed Limits

The Río Grande de Arecibo coastal floodplain drains a total area of approximately 541 squared kilometers. The watershed tributary to the study reach was divided into 9 sub-basins; delimited using the USGS topographic quadrangle, as seen in Figure 8. Although the watersheds were initially delimited using the topographic quadrangle, the drainage area within the karst area that actually contributes surface runoff is indeterminate, and was adjusted during the calibration process. The highest concentration of limestone formations is located between Lago Dos Bocas and the coastal floodplain. The upper watersheds are mainly undeveloped or forested areas with steep terrain. The watershed's coastal floodplain is relatively flat and there is significant ponding of water in some overbank areas near the river.

4.2. Soil Types, Curve Number and Time of Concentration

The Curve Number represents the runoff potential within a watershed and is estimated based on soil type (hydrologic soil group), land use and Antecedent Moisture Condition (AMC). In this study an AMC-II was used. The soil types within the watershed were obtained from Soil Survey Geographic data base (SSURGO), which contains the most detailed level of soil mapping performed by the NRCS. A runoff curve number was assigned to each soil type and land use combination, and a weighted average curve number was then calculated. Figure 9 illustrates the hydrologic soil groups found within the studied watersheds.

The time of concentration is the time required for rainfall in the most distant part of the watershed to influence the discharge from the basin outlet. Time of Concentration was initially calculated with the Soil Conservation Service TR-55 method, but due to the uncertainties associated with subsurface drainage and in-stream reservoirs within the watersheds, the time of concentration for each sub-basin was adjusted through calibration. Table 7 presents the calculated hydrologic parameters of the analyzed sub-basins, prior to calibration. Appendix B shows Time of Concentration calculations. Curve Number Calculations are included in the accompanying DVD.

Table 7: Calculated hydrologic parameters of analyzed sub-basins

Sub-basin	Area (km^2)	CN	TC (min)
Lago Caonillas	125	76	173
Río Viví	43	68	172
Río Grande de Arecibo at Utuado	125	72	135
Río Limón	98	80	167
Río Caonillas	22	72	56
Río Grande de Arecibo at Dos Bocas	40	72	100
Río Tanamá at Esperanza	127	74	204
Río Grande de Arecibo above Arecibo	36	70	143
Río Tanamá at Charco Hondo	15	74	37
Río Grande de Arecibo at Cambalache	12	76	140
Río Santiago	11	76	74

4.3. Model Calibration

The calibration process was undertaken to determine uncertain hydrological characteristics of the watershed such as time of concentration, travel lag times, and drainage area using an historical event where rainfall and peak discharges were known to produce a simulated hydrograph with characteristics similar to the observed one for the same rainfall. The calibration was performed using the rainfall event associated with the passing of Hurricane Georges during September 21-22, 1998. Calibration focused on matching the peak discharge and flow volumes, while producing a hydrograph shape as similar to the observed hydrograph as possible.

4.3.1. Rainfall Depths

The 15-minute rainfall data used for calibration was obtained from the National Climatic Data Center, Summary of the Day, for three stations within the Río Grande de Arecibo watershed: 1) Cerro Maravilla, 2) Adjuntas Substation, and 3) Dos Bocas. These are the only stations in the area with 15-minute records for the Hurricane Georges event. Other stations in the area provide only daily rainfall data.

Figure 10 shows the location of the three rainfall stations with 15-minute records for the Hurricane Georges event, and Figure 11 presents the cumulative rainfall for the three stations. As seen on the figure, each station had different rainfall distributions. Table 8 lists which rainfall station data (and rainfall distribution) was used at each of the analyzed sub-basins based on proximity to the station.

Table 8: Rainfall station data used at each analyzed sub-basin

Sub-basin	Rainfall Station/Rainfall Distribution
Lago Caonillas	Cerro Maravilla
Río Viví	Cerro Maravilla
Río Grande de Arecibo at Utuado	Adjuntas Substation
Río Limón	Cerro Maravilla
Río Caonillas	Dos Bocas
Río Grande de Arecibo at Dos Bocas	Dos Bocas
Río Tanamá at Esperanza	Adjuntas Substation
Río Grande de Arecibo above Arecibo	Dos Bocas
Río Tanamá at Charco Hondo	Dos Bocas
Río Grande de Arecibo at Cambalache	Dos Bocas
Río Santiago	Dos Bocas

Hyetographs were constructed using rainfall depths obtained from the rainfall stations listed in Table 8, for different durations, as seen in Table 9. The 24-hour rainfall depth seen in Table 9 corresponds to the most intense 24-hour period during the event that occurred between September 21 and 22, 1998, the 12-hour depths corresponds to the most intense 12-hour period, and so on. NCDC rainfall data obtained for the Hurricane George event, as well as Hurricane Georges rainfall distribution calculations, are included in Appendix C.

Table 9: Hurricane Georges Rainfall Depths (September 21 and 22, 1998) used for rainfall distribution calculations

Duration (hr)	Rainfall Depth (in)		
	Adjuntas Substation	Cerro Maravilla	Dos Bocas
0.25	1.2	1.0	0.6
0.5	2.3	1.7	1.1
1	4.3	2.8	1.9
2	7.0	4.8	3.2
3	8.9	6.6	4.1
6	12.8	10.7	5.7
12	16.5	15.8	8.1
24	18.1	18.8	9.6

Since rainfall depths varied greatly from watershed to watershed, an isohyetal map was constructed using 24-hour rainfall depth for a total of 17 stations in the area to estimate the 24-hour rainfall depth at each individual sub-basin during the Hurricane Georges event. The data used to generate the isohyetal map corresponds to the three stations that have 15-minute data (Cerro Maravilla, Adjuntas Substation, and Dos Bocas), plus daily data from 14 other stations.

Figure 12 presents the isohyetal map generated from Hurricane Georges precipitation data and the location of the rainfall stations used to generate the map. The 24-hour rainfall depth at each sub-basin (shown in Table 10) was applied to their corresponding hyetograph.

Table 10: 24-hour Rainfall Depths at each sub-basin during Hurricane George

Sub-basin	24-hour Rainfall Depth	
	inches	millimeters
Lago Caonillas	21.1	536
Río Viví	18.5	470
Río Grande de Arecibo at Utuado	18.5	470
Río Limón	14.0	356
Río Caonillas	11.8	300
Río Grande de Arecibo at Dos Bocas	12.0	305
Río Tanamá at Esperanza	12.3	312
Río Grande de Arecibo above Arecibo	7.1	180
Río Tanamá at Charco Hondo	6.6	168
Río Grande de Arecibo at Cambalache	5.8	147
Río Santiago	5.8	147

4.3.2. Calibration Results

Hydrologic parameters, particularly within the karst area, were calibrated to match observed and calculated peak discharges. Table 11 shows calibrated hydrologic parameters for the analyzed sub-basins.

Table 11: Calibrated hydrologic parameters of analyzed sub-basins

Sub-basin	Area (km^2)	CN	TC (min)
Lago Caonillas	125	76	125
Río Viví	43	63	100
Río Grande de Arecibo at Utuado	125	65	250
Río Limón	90	72	83
Río Caonillas	18	66	67
Río Grande de Arecibo at Dos Bocas	35	66	100
Río Tanamá at Esperanza	80	72	242

Sub-basin	Area (km^2)	CN	TC (min)
Río Grande de Arecibo above Arecibo	26	73	100
Río Tanamá at Charco Hondo	11	74	67
Río Grande de Arecibo at Cambalache	12	76	140
Río Santiago	11	76	74

Lago Dos Bocas and Lago Caonillas were both included in the hydrologic model as storage nodes. Stage volume relationships and spillway lengths from the Dos Bocas and Caonillas Dams were obtained from the USGS Scientific Investigations Report 2007-5053 "*Sedimentation History of Lago Dos Bocas, Puerto Rico, 1942-2005*" (Soler-López, 2007), and Water Resources Investigation Report 01-4043 "*Sedimentation Survey of Lago Caonillas, Puerto Rico, February 2000*" (Soler-López, 2007), respectively.

The 15-minute runoff hydrograph observed at USGS stream gage station number 50024950, Río Grande de Arecibo below Utuado, was obtained from the US Geological Survey (see data in Appendix D). The gage is located 6 kilometers above Lago Dos Bocas, as seen in Figure 6, and has a drainage area of approximately 170 km^2. Hydrologic parameters were calibrated to produce a simulated hydrograph at the location of station 50024950 with characteristics similar to the observed hydrograph, for the same rainfall event. This station was chosen for hydrograph comparison because it is the only station with available storm runoff hydrograph for Hurricane Georges. Peak discharge, as computed by USGS, was compared at all other points along the watershed.

Comparison of the observed and simulated hydrographs at USGS gage 50024950 is presented in Figure 13. The peak discharges and runoff volume for each of the two hydrographs are compared in Table 12.

Table 12: Runoff Hydrograph Calibration to USGS gage 50024950 for Hurricane Georges, September 21-22 1998

Parameter	Hydrograph at USGS gage 50024950		Difference
	Observed	Calculated	
Peak Discharge (m^3/s)	2,160	2,110	-2.3 %
Runoff Volume (Mm^3)	48.6	57.2	15%

The USGS study "*Flood of September 22, 1998, in Arecibo and Utuado, Puerto Rico. USGS Water Resources Investigations Report 01-4247*" provides peak discharge at various locations along the watershed that include: 1) Lago Dos Bocas spillway, 2) Lago Caonillas spillway, 3) at USGS gage station 50027750 on Río Grande de Arecibo above Arecibo, and 4) at USGS gage station 50028400 on Río Tanamá at Charco Hondo. Table 13 compares the peak discharges calculated by USGS and those obtained with our calibrated hydrologic model.

Table 13: Comparison of Peak Discharges as published in "*Flood of September 22, 1998, in Arecibo and Utuado, Puerto Rico. USGS Water Resources Investigations Report 01-4247:*"

Location	Peak discharge (m^3/s)		Difference
	USGS	HEC-HMS	
Río Grande de Arecibo above Arecibo	3,330	3,312	0.5 %
Río Tanamá at Charco Hondo	778	811	4.2 %
Lago Caonillas spillway	1,330	1,343	1.0 %
Lago Dos Bocas spillway	3,260	3,280	0.6 %

4.4. Discharge Hydrographs for Design Storms

Design hyetographs were constructed for each sub-basin using the 100-year rainfall depths reported in National Oceanic and Atmospheric Administration (NOAA) Atlas 14 published October 26, 2006. Table 14 presents the rainfall depth, for different durations, used to generate the design storm rainfall distribution for each sub-basin. NOAA rainfall data and rainfall distribution calculations are included in Appendix E.

Table 14: 100-year NOAA Atlas 14 Rainfall Depths (inches) for each sub-basin

Sub-basin	Duration (hr)							
	0.25	0.5	1	2	3	6	12	24
Lago Caonillas	1.78	2.84	4.22	6.14	7.16	9.67	13.55	18.92
Río Viví	1.69	2.71	4.02	5.95	6.86	9.43	13.13	17.38
RGA at Utuado	1.92	3.07	4.55	6.87	7.99	11.06	15.45	20.49
Río Limón	1.72	2.75	4.08	5.61	6.44	8.79	12.17	16.54
Río Caonillas	1.54	2.46	3.65	4.92	5.57	7.30	10.07	14.04
RGA at Dos Bocas	1.57	2.51	3.73	4.97	5.61	7.30	10.09	14.32
Río Tanamá at Esperanza	1.68	2.68	3.98	5.45	6.29	8.39	11.62	15.95
RGA above Arecibo	1.38	2.21	3.28	4.45	5.09	6.73	9.32	12.61
RGA at Cambalache	1.10	1.76	2.61	3.55	4.01	5.26	7.33	9.83
Río Santiago	1.10	1.76	2.61	3.55	4.01	5.26	7.33	9.83

The 10-, 50-, 100-, and 500-year 24-hour rainfall depths were applied to dimensionless hyetograph generated for each sub-basin. Rainfall depths used in the hydrologic analysis are presented in Table 15.

Table 15: 24-hour NOAA Atlas 14 Rainfall Depths for each sub-basin

Sub-basin	24-hour Rainfall depth (in)			
	10-yr	50-yr	100-yr	500-yr
Lago Caonillas	9.42	15.61	18.92	28.40
Río Viví	8.98	14.48	17.38	25.60
RGA at Utuado	10.09	16.85	20.49	31.00
Río Limón	8.72	13.86	16.54	24.07
Río Caonillas	7.92	10.13	14.04	19.63
RGA at Dos Bocas	7.98	12.19	14.32	20.18
Río Tanamá at Esperanza	8.67	13.47	15.95	22.90
RGA above Arecibo	7.39	10.90	12.61	17.15
RGA at Cambalache	6.32	8.75	9.83	12.45
Río Santiago	6.32	8.75	9.83	12.45

4.5. Hydrologic Effects of Río Santiago Diversion

As seen in Figure 7, the upper Río Santiago watershed has been diverted as part of the USACE Río Grande de Arecibo Flood Control Project. Prior to the flood control project, the river flowed north across the town of Arecibo before discharging into Río Grande de Arecibo approximately 400 meters upstream from the river mouth. The river has now been redirected under the highway bridge opening, and it now discharges into Río Grande de Arecibo approximately 2 kilometers downstream of the highway bridge.

We have generated flood hydrographs along Río Grande de Arecibo under two conditions to assess the effects of the Río Santiago diversion: 1) with Río Santiago's original discharge point upstream of the river mouth, and 2) with the current diversion under highway PR-22, and discharge point 2 kilometers downstream of the highway.

The diverted Río Santiago upper watershed represents less than 2% of the total drainage area tributary to the Arecibo coastal floodplain. This river drains into the valley before discharge along the Río Grande de Arecibo reaches the floodplain, having little-to-no effects on the flood hydrograph. Figure 14 compares flood hydrographs along Río Grande de Arecibo with and without the Río Santiago diversion. As seen graphically on Figure 14, the impacts of the Río Santiago

diversion are negligible. The flood hydrograph used in the hydraulic analysis corresponds to current conditions; with the diversion of Río Santiago.

4.6. Results of Hydrologic Analysis

The initial pool level at the Dos Bocas and Caonillas Dams was obtained from the average water level from 19 years of daily data at the dam sites. Even though the reservoirs were not designed for flood control, Lago Dos Bocas attenuates peak discharge approximately 19%, while Lago Caonillas reduces discharge approximately 45%, as seen graphically in Figure 15.

Table 16 compares the peak discharges obtained with the UH methodology with the FEMA discharge downstream of the confluence of Río Tanamá. Peak discharges calculated are similar, but lower, than those obtained by FEMA, with the exception of the 500-year discharge which is higher. Input data and results of all hydrologic models are included in Appendix F.

Table 16: Peak Discharge at Río Grande de Arecibo, at confluence with Río Tanamá

Study	Peak Discharge (m^3/s)			
	10-yr	50-yr	100-yr	500-yr
GME	1,615	4,014	5,469	9,797
FEMA	2,890	4,550	5,680	8,640

4.7. Verification of Hydrology

Peak discharges were verified by applying a Log Pearson Type III statistical distribution to the annual peak discharge series at USGS gage 50027750, Río Grande de Arecibo above Arecibo. Peak discharge data were available for the water years of 1982-2002. The frequency analysis data and results are given in Appendix G. Table 17 compares the Log Pearson peak discharges against those computed with the HEC-HMS model. This discharge corresponds to Río Grande de Arecibo upstream of the confluence with Río Tanamá. The 100-year discharge obtained with hydrologic modeling is higher, more conservative, than those obtained with Log Pearson. Our hydraulic analysis will use the higher peak discharge that better matches the regulatory FEMA discharge.

Table 17: Comparison of peak discharges at USGS gage station 50027750, Río Grande de Arecibo above Arecibo

Return Interval (years)	Peak discharge (m^3/s)	
	Log-Pearson III	GME
10	861	1,615
50	2,657	4,014
100	4,051	5,469

5. HYDRAULIC ANALYSIS

5.1. Hydraulic Model Configuration

As mentioned earlier, the hydraulic analysis was performed using the FEMA-approved FLO-2D two-dimensional hydraulic model. The model grid extends upstream from the Atlantic Ocean to a distance of approximately 10 kilometers. The flow system was represented by more than 100,000 square grid elements, 20 X 20 meters. Ground elevation of the grid elements were obtained from LIDAR topographic data. A small grid size was required to analyze the complex hydraulic system in the study area with the desired level of accuracy.

The hydraulic system used the following boundary conditions:

- **River Grid Elements.** River grid elements simulate flow in channels as one-dimensional. Average flow velocity and depth define the discharge between adjacent channel grid elements. Secondary currents, dispersion and super elevation in channel bends are not modeled with the 1-D channel component. The average flow path length between two channel elements is on the order of the length of the grid element and this precludes the simulation of hydraulic jumps over a short distance. The flow transition between subcritical and supercritical flow is based on the average conditions between two channel elements. The flow along each grid element is routed using the dynamic wave approximation to the momentum equation.

  The surveyed river sections were interpolated to represent each river grid element. The CHAN.DAT input file included for each model in accompanying DVD presents the river grid elements as well as the cross section geometry that defines the thalweg and bank elevations, average cross section roughness, and the length of channel within the grid element. Channel slope is computed as the difference between the channel element thalweg elevation divided by the half the sum of the channel lengths within the channel elements.

- **Inflow Elements.** Channel inflow hydrographs were used to represent the flood discharges from Río Tanamá and Río Grande de Arecibo that enter the model. The INFLOW.DAT input file included in the accompanying DVD presents the inflow elements used in the model.

- **Outflow Elements.** Both floodplain and channel outflow grid elements were used to remove water from the system. The discharge from outflow elements is equal to the sum of the inflows, and a flow depth is then assigned to the

outflow element based on a weighted average of the upstream flow depths. In this manner flow is approximated at each outflow element. The outflow discharge is completely removed from the system, and is accounted as outflow volume. These outflow elements correspond to the elements that are located at the downstream of the model, and along the eastern limit of the study, which represents flow that enters Caño Tiburones.

5.2. Effective FEMA Tie-in/ Length of Study Reach

Effective FEMA tie-in is required at both the downstream and upstream ends of the submitted models. Base flood elevations must "tie-in" within 0.5 feet to current FEMA flood elevations at both downstream and upstream ends of the revised river reach.

The downstream tie-in will be located at FEMA cross section "C" (PR-2 road), 800 meters upstream from the river mouth, and the upstream tie-in will be located at FEMA cross section "E", 2.9 kilometers upstream of the river mouth. The study reach to be revised has a length of 2.1 kilometers.

5.3. Models Prepared

The combination of large peak discharge and small grid size (20 X 20 m) produce an extremely slow computational time steps, requiring a model running time of more than 24 hours. To reduce the computational time, the hydraulic model was divided into two areas separated by PR-22 highway, as seen in Figure 16.

The area upstream of PR-22 was analyzed to perform hydraulic routing of the calculated discharge hydrograph along a distance of 7 kilometers upstream from the PR-22 highway bridge. The area downstream of PR-22, which corresponds to our revision area, was calibrated to match FEMA's flood profile and perform the floodway encroachment analysis.

The following FLOD-2D two-dimensional models were prepared:

1. Hydrograph Routing Model (HR). This model was prepared to perform hydraulic routing of the calculated discharge hydrograph along a distance of 7 kilometers upstream from highway PR-22 (FEMA cross section "G"). The model includes two types of boundaries, inflow hydrograph and free outflow nodes. Discharge at each outflow node in the Hydrograph Routing Model was used as hydrologic input at the upstream end of the Existing Condition and Floodway Encroachment Models. The location of the boundary nodes, as well as the extents of the HR Model, is presented in Figure 17. Input data and

results of the Hydrograph Routing Model are included in the accompanying DVD.

2. Duplicate Effective/Existing Condition Model (DE/EC). Since FEMA's Effective Model used to prepare the FIS of Río Grande de Arecibo is not available, this model was constructed within the FLO-2D environment to simulate the FEMA 100-year flow and match the FEMA effective flood profile. The model covers the revision distance of 2.1 kilometers, extending from FEMA cross section "C" to FEMA cross section "E". The model was run for the 10-, 50-, 100-, and 500-year events.

   The discharge hydrographs calculated at the outflow elements in the HR model were used as inflow boundary nodes in the DE/EC Model. The extents and location of boundary nodes for the DE/EC Model are presented in Figure 18. The model includes levee grid elements to represent the concrete barrier that runs along the PR-2 median (Jersey barrier).

   This model also includes the Río Santiago diversion channel that was dug out of the valley floor for the COE flood control project. The model was run with the flood hydrograph generated at the floodplain with the Río Santiago diversion, as seen in Figure 14. Input data and results of the Duplicate Effective/Existing Condition Model are included in the accompanying DVD.

3. Floodway Encroachment/Proposed Condition Model (FE/PC). This model was performed for the 100-year event to simulate regulatory limits, plus new floodway limits surrounding the project site, based on the Existing Condition Model. This model includes proposed river bank modifications between the project site and the channel to provide additional hydraulic conveyance capacity and compensate for the proposed encroachment around the site.

   Floodway encroachment limits were determined along Río Grande de Arecibo based on a maximum allowable increase in water surface elevation of 0.3 meters. Encroachment limits were determined using a similar procedure to the Type-1 method implemented in the CoE HEC-RAS model. The method consists on applying frictionless vertical walls along the flood boundaries to manually define encroachment limits, based on trial and error. Input data and results of the Floodway Encroachment/Proposed Condition Model are included in the accompanying DVD.

5.4. Hydraulic Modeling Coefficients

Manning's roughness coefficients are used to represent friction losses of the hydraulic system, and are a function of ground cover. The hydraulic roughness

coefficients (n-values) used in the 2-D model, and modified through calibration, are presented in Table 18.

Table 18: Manning's n-value used in Hydraulic Model

Location	Manning's N-value
Main Channel	0.03 - 0.04
Overbanks	0.05 - 0.06

5.5. Downstream Water Surface Elevation

Free outflow nodes are used as downstream boundary condition under the FLO-2D environment. As mentioned previously, water level at the outflow elements are determined by a weighted average of the upstream flow depths. Hydraulic coefficients were modified during the calibration process to match water levels at the model boundary with those presented in the FIS at FEMA cross section "C" (Table 19).

Table 19: FEMA Water Surface Elevation (m-msl) at Cross Section "C"

10-year	50-year	100-year	500-year
2.7	3.0	3.6	4.2

5.6. Results of Duplicate Effective/Existing Condition Model

A calibration process, which consisted of modifying hydraulic coefficients, was undertaken to match FEMA effective 100-yr water levels within the acceptable 0.15 meter (0.5 feet) difference. The DE/EC Model produces base flood elevations within the acceptable limits, as seen in Figure 19 and Table 20. Table 21 shows 10-, 50-, and 500-year flood levels for the Duplicate Effective/Existing Condition Model.

Table 20: Results of Duplicate Effective/Existing Condition Model

FEMA Cross Section	FLO-2D River Grid Element	Distance U/S River Mouth (km)	100-yr Water Surface Elevation (m-msl)		Diff (m)
			FEMA	DE/EC Model	
C	29,630	0.8	3.60	3.61	0.01
D (site)	34,346	2.1	5.20	5.29	0.09
E	43,355	2.9	6.60	6.61	0.01

Table 21: 10-, 50-, and 500-year flood levels for Duplicate Effective/Existing Condition Model

FEMA Cross Section	Distance U/S River Mouth (km)	Water Surface Elevation (m-msl)		
		10-year	50-year	500-year
C	0.8	2.63	3.31	4.68
D (site)	2.1	4.09	5.03	6.19
E	2.9	5.23	6.33	7.65

5.7. Results of Floodway Encroachment/Proposed Condition Model

This model, based on the calibrated DE/EC Model, incorporates existing regulatory floodway limits, plus the additional encroachment of the proposed site. The encroachment consists on applying frictionless vertical walls along the flood boundaries to manually define encroachment limits by trial and error.

To achieve the desired floodway limits around the project site, excavation of higher ground on the floodplain between the project site and the river channel was simulated to provide additional hydraulic conveyance capacity, and compensate for the proposed encroachment. Elevations within the area shown in Figure 20 will be lowered to a maximum of 3.5 m-msl, while areas that are already lower than 3.5 m will not be altered. Figure 21 shows a schematic design of the proposed bank modification area.

Figure 22 shows the proposed 100-year floodway limits for the study reach. Figure 23 shows maximum 100-yr water surface elevation increase attributable to encroachment. Since 100- and 500-yr flood levels have not been revised, floodplain limits will not altered. Table 22 compares 100-year Existing and Floodway Encroached water surface elevations. The increases presented on this table correspond to the average increase per model cell within the cross section.

Table 22: Comparison of 100-yr Existing and Encroached Water Surface Elevations

FEMA Cross Section	Water Surface Elevations (m-msl)		Difference (m)
	Existing	Encroachment	
C	3.61	3.65	0.04
D	5.29	5.35	0.06
E	6.61	6.61	0.00

5.8. Revised FIS Floodway Data Table

Table 23 presents the revised Río Grande de Arecibo Floodway Data Table. The proposed floodway limits do not increase base flood elevations more than 0.3 meters along any point throughout the floodplain, in compliance with federal and state regulations. Figure 24 shows the annotated FIRM panel 230 which includes the proposed floodway limits.

Table 23: Revised Río Grande de Arecibo Floodway Data Table

Cross Section	Distance from mouth (km)	Base Flood Elevation (m-msl)		
		without floodway	with floodway	difference
B	0.4	2.7	2.7	0.00
C	0.8	3.6	3.7	0.10
D (site)	2.1	5.3	5.4	0.10
E	2.9	6.6	6.6	0.00
F	3.4	7.1	7.4	0.30
G	4.2	7.8	8.1	0.30
H	5.1	9.1	9.4	0.30
I	6.5	11.5	11.8	0.30
J	6.9	12.8	13.1	0.30

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

1. Hydrology was based on model calibration to the Hurricane Georges event which occurred in September 22, 1998. Peak discharges were calibrated to values obtained and reported by USGS on its Water Resources Investigation 01-4247 "*Flood of September 22, 1998, in Arecibo and Utuado, Puerto Rico*" (Torres-Sierra, 2022).
2. FEMA's Effective Model is not available. A two-dimensional model was constructed within the FLO-2D environment to simulate FEMA's 100-year flow and match FEMA's effective flood profile. The revised study reach covers a distance of 2.9 kilometers, extending from FEMA cross section "C" to FEMA cross section "E".
3. The Floodway Encroachment/Proposed Condition Model was prepared for the 100-year event to simulate regulatory limits, plus new floodway limits surrounding the project site, based on the Duplicate Effective/Existing Condition Model. Floodway encroachment limits were determined along Río Grande de Arecibo based on a maximum allowable increase in water surface elevation of 0.3 meters.
4. This Floodway Encroachment/Proposed Condition Model includes the proposed excavation of higher ground on the floodplain between the project site and the river channel (see Figure 20) to provide additional hydraulic conveyance capacity, and compensate for the proposed encroachment around the site. Proposed river bank modifications consist of lowering field elevations to a maximum of 3.5 m-msl, as seen schematically in Figure 21. Proposed floodway limits are shown in Figure 22. The annotated flood map is shown in Figure 24.
5. The 100- and 500-year flood levels have not been altered, and therefore, floodplain limits have not been revised.

7. CERTIFICATION

I hereby certify that the document "Hydrologic and Hydraulic, Río Grande de Arecibo, Renewable Power Generation and Resource Recovery Facility, Arecibo, Puerto Rico" has been prepared in accordance with the best hydrologic and hydraulic practices as described in this document and that, based on the studies and field measurements provided by other parties, results are true and correct.

Certified today October 4, 2010

José D. Miranda, P.E.

JOSÉ D. MIRANDA RODRÍGUEZ
INGENIERO LICENCIADO
LIC.#18045 P.E.
PUERTO RICO

8. REFERENCES

Barnes, Harry H. 1967. "Roughness Characteristics of Natural Channels". U.S. Geological Survey Water Supply Paper 1849. U.S. Govt. Printing Office, Washington, D.C.

Chow, Ven Te. 1959. "Open Channel Hydraulics". McGraw Hill Book Company, New York.

Federal Emergency Management Agency. April 2005. "Flood Insurance Study (FIS), Volume 1 of 5", Commonwealth of Puerto Rico.

NOAA. 2006. "Precipitation-Frequency Atlas of the United States." National Oceanic and Atmospheric Administration Atlas 14, Washington DC.

Singhofen P.J., and L.M. Eaglin. 1995. "ICPR Advanced: User's Manual". Streamline Technologies Inc., Winter Park, FL.

Torres-Sierra, H. 2002."Flood of September 22, 1998, in Arecibo and Utuado, Puerto Rico". US Geological Survey Hydrologic Investigations Report 01-4247.

US Department of Agriculture, Soil Conservation Service. 1986. "Technical Release 55 (Urban Hydrology for Small Watersheds)". Washington DC.

Puerto Rico

HYDROLOGIC-HYDRAULIC STUDY
RÍO GRANDE DE ARECIBO,
RENEWABLE POWER GENERATION AND
RESOURCE RECOVERY FACILITY,
ARECIBO, PUERTO RICO

FIGURES

GLM MORRIS ENGINEERING

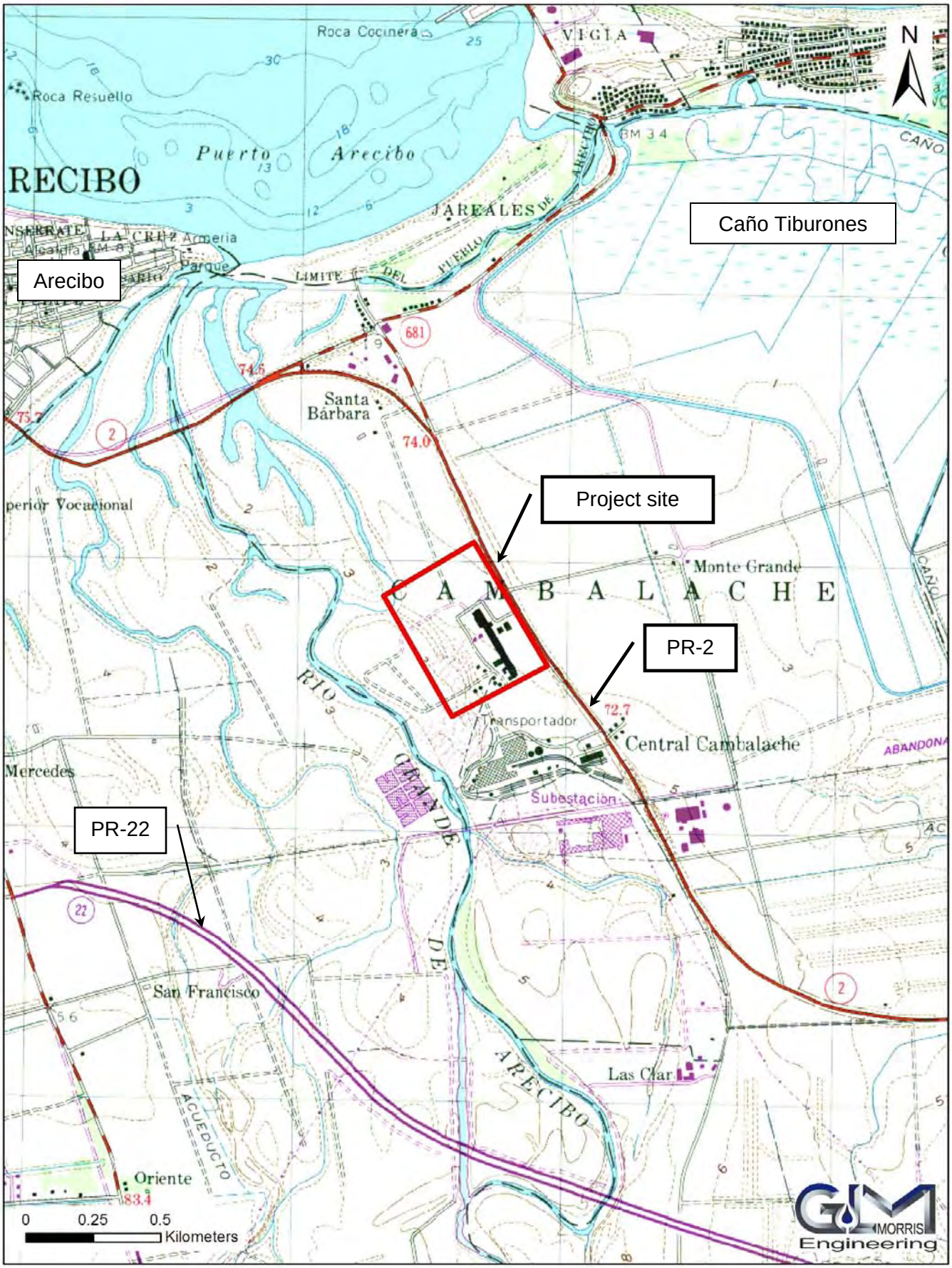


Figure 1: Project Site Location Map on USGS Topographic Quadrangle.

Figure 2: Project Site Location Map on Recent Aerial Photography.

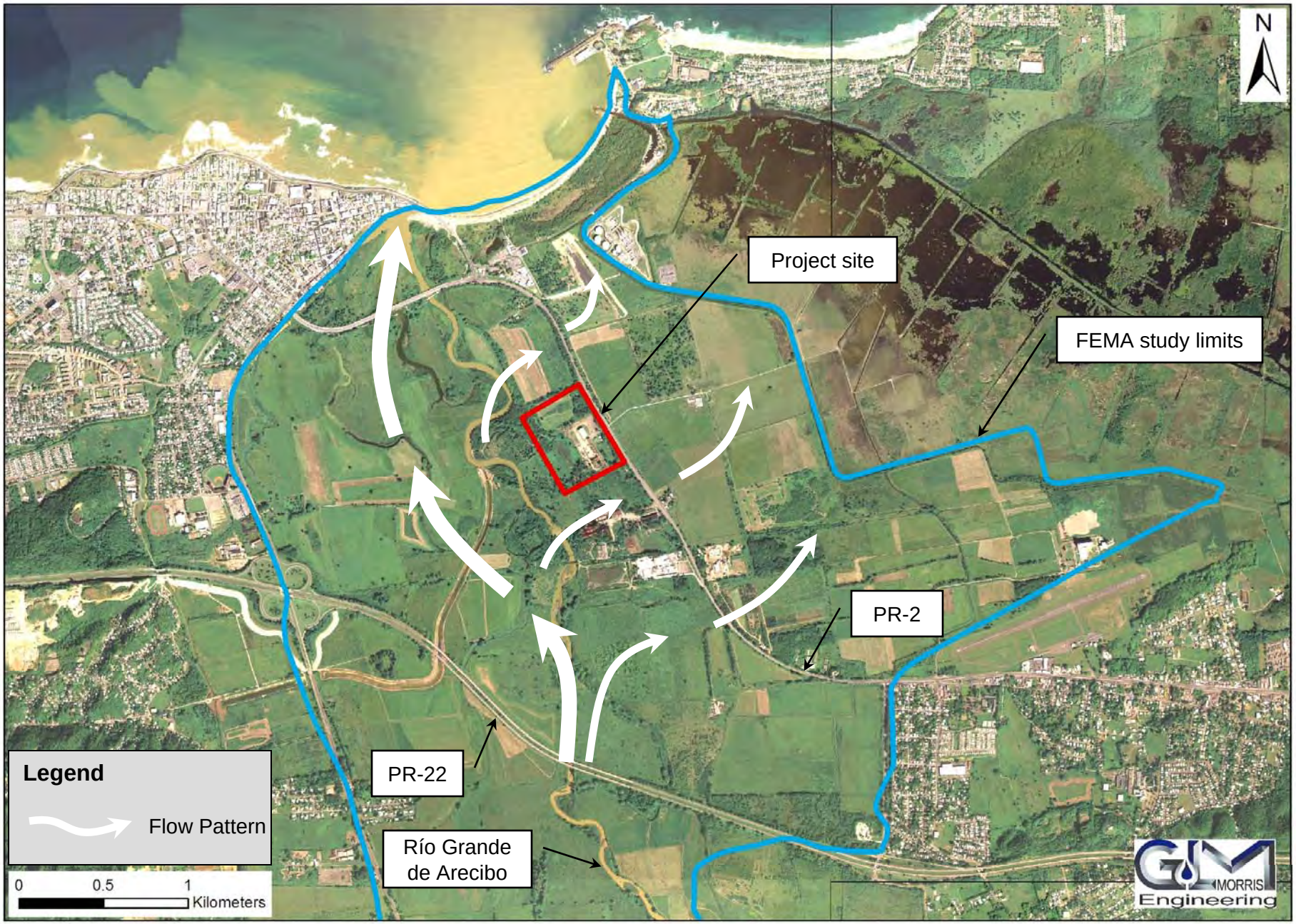


Figure 3: Flow Patterns below Highway PR-22 Bridge.

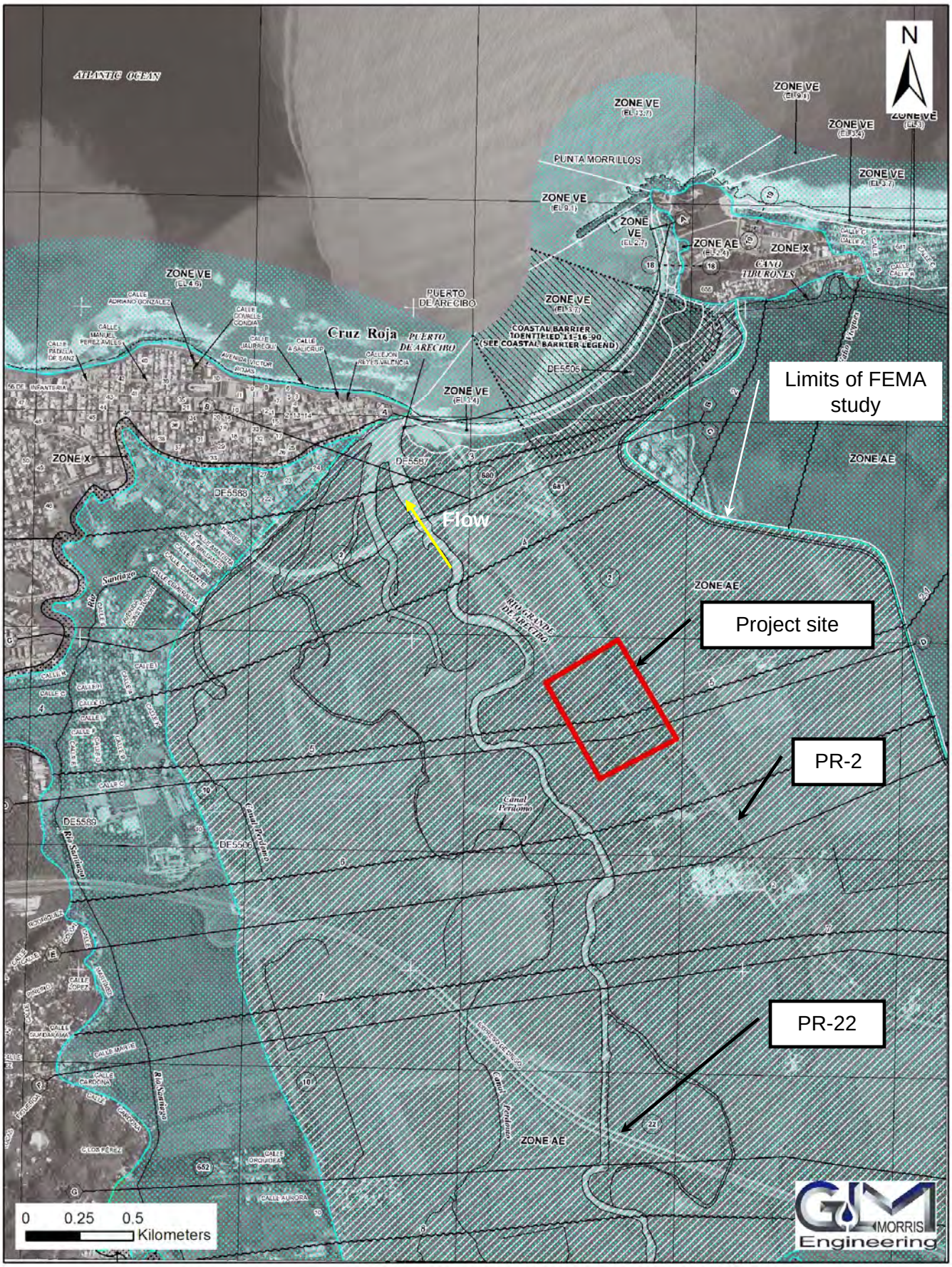


Figure 4: FEMA FIRM Panel 230J, Dated November 18, 2009

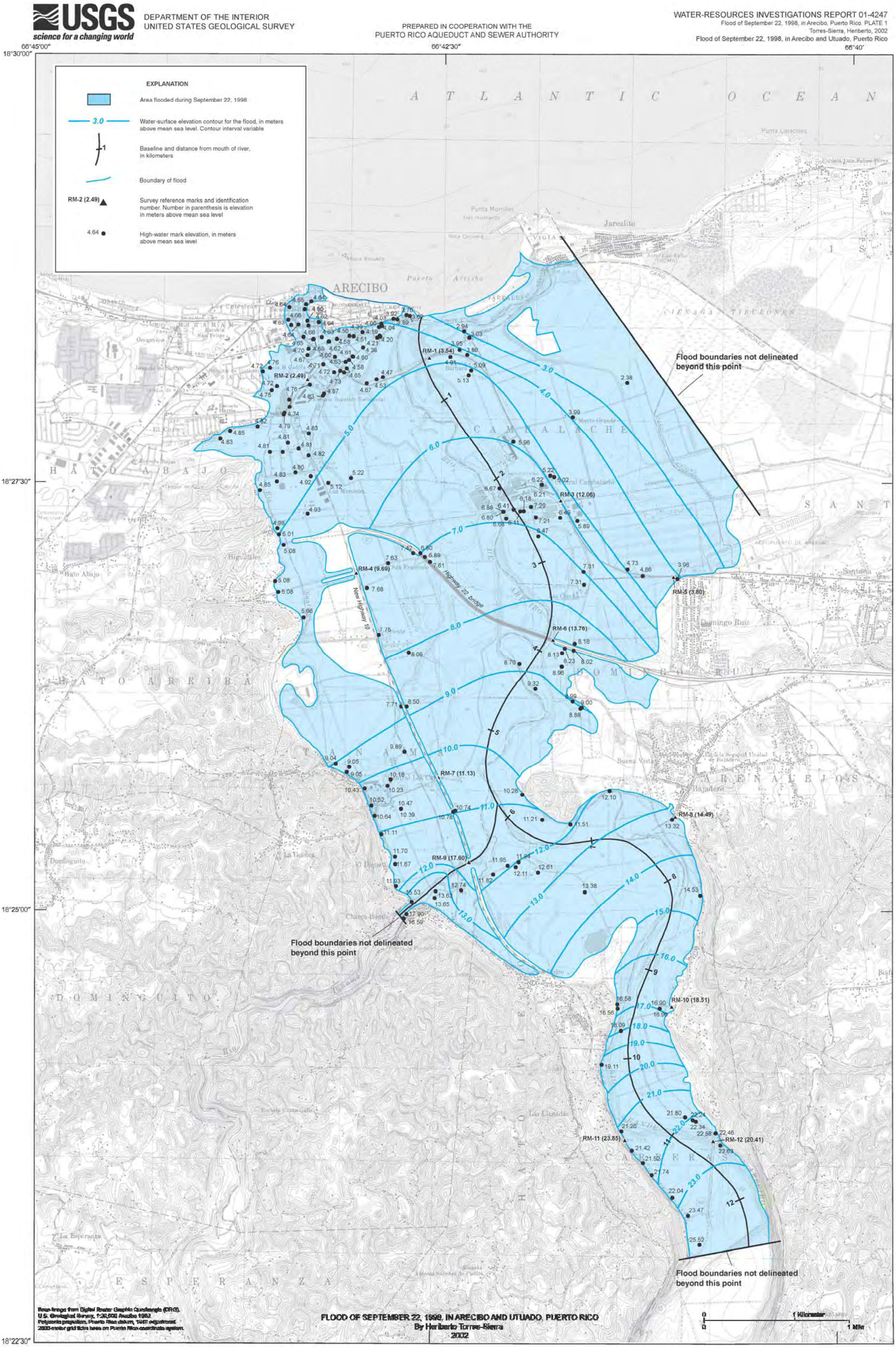


Figure 5: USGS Historical Flood Atlas, Investigation Report 01-4247.

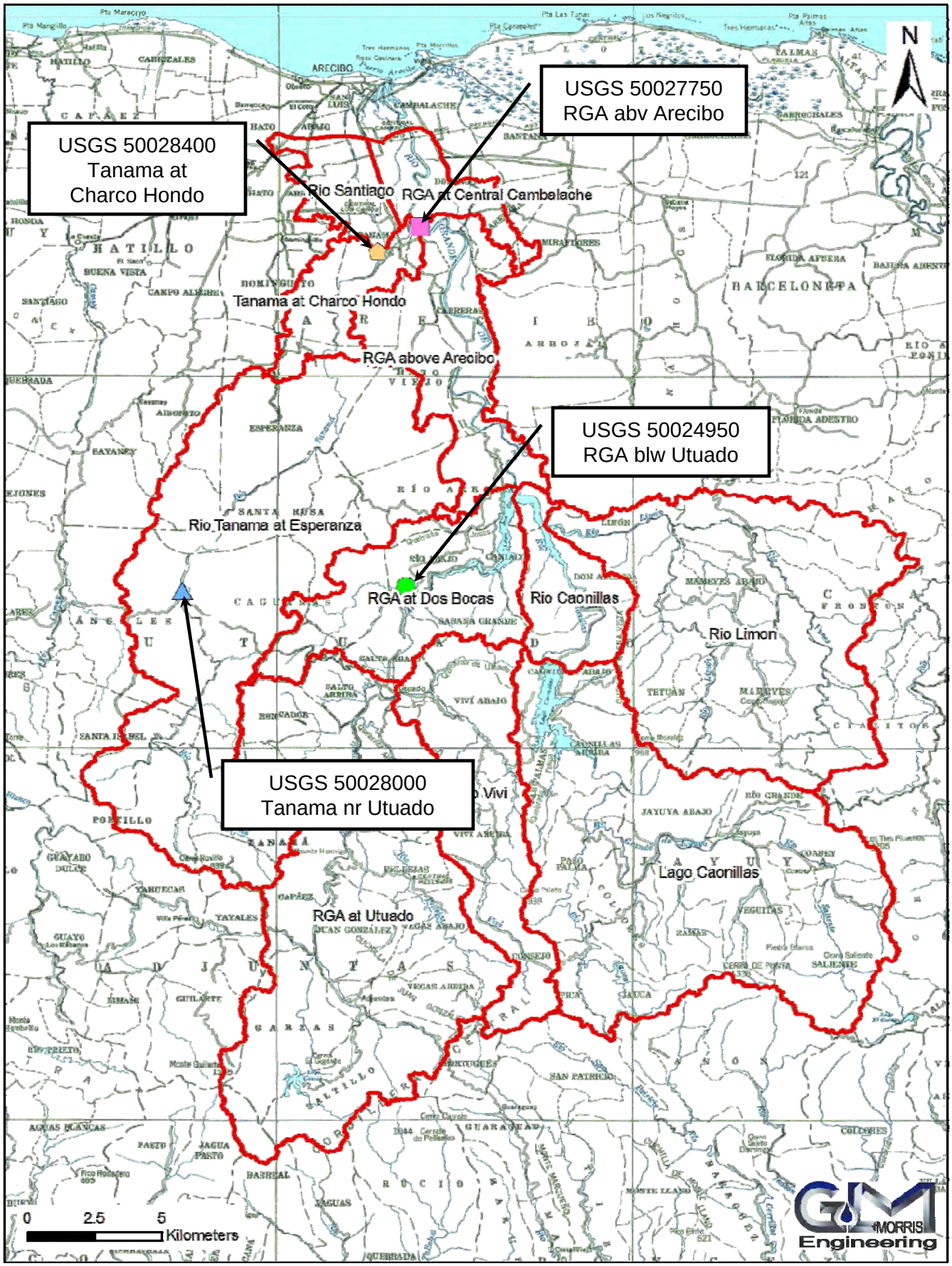


Figure 6: Location of USGS Streamgage Stations

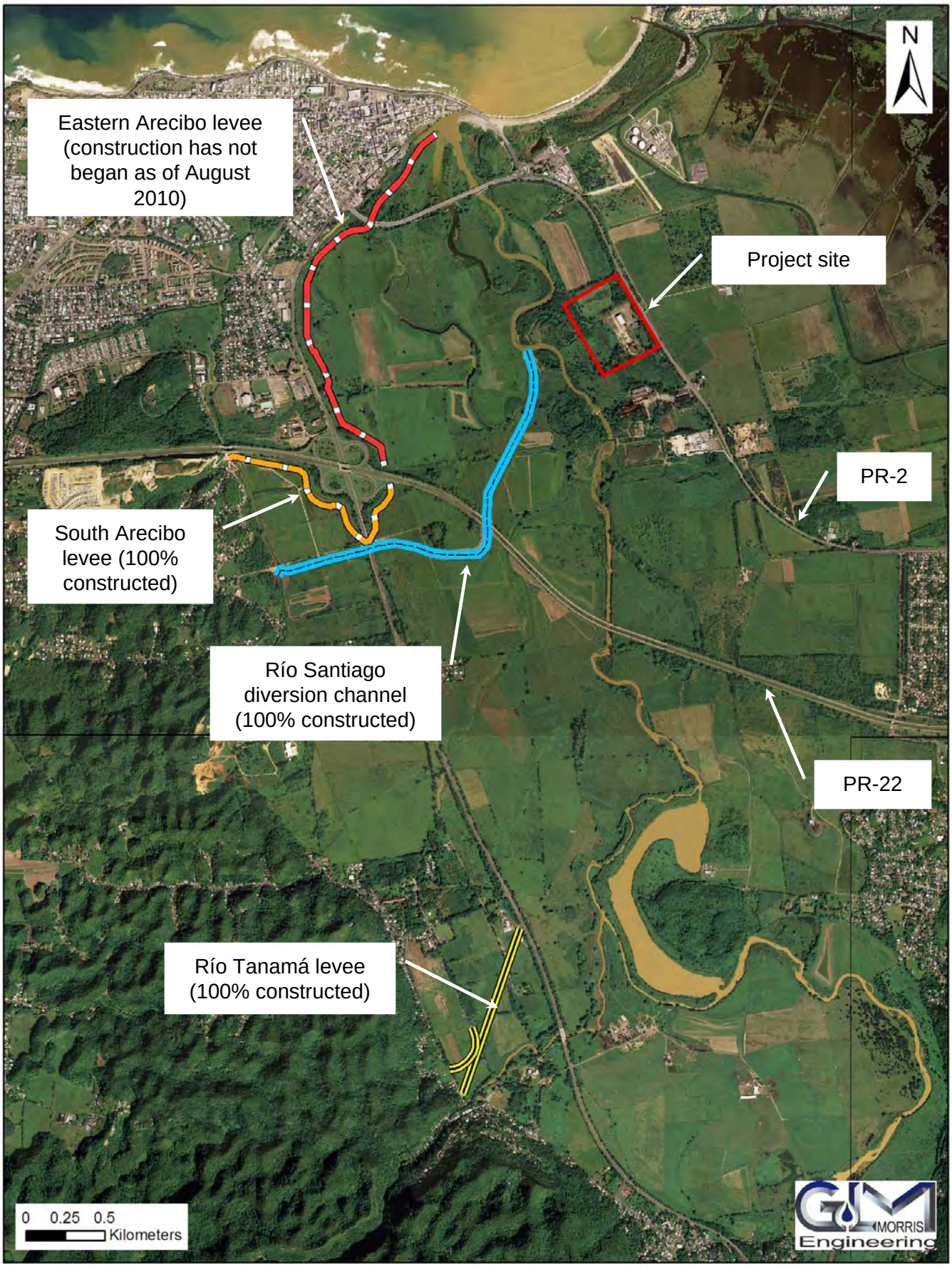


Figure 7: Army Corps of Engineers Río Grande de Arecibo Flood Control Project

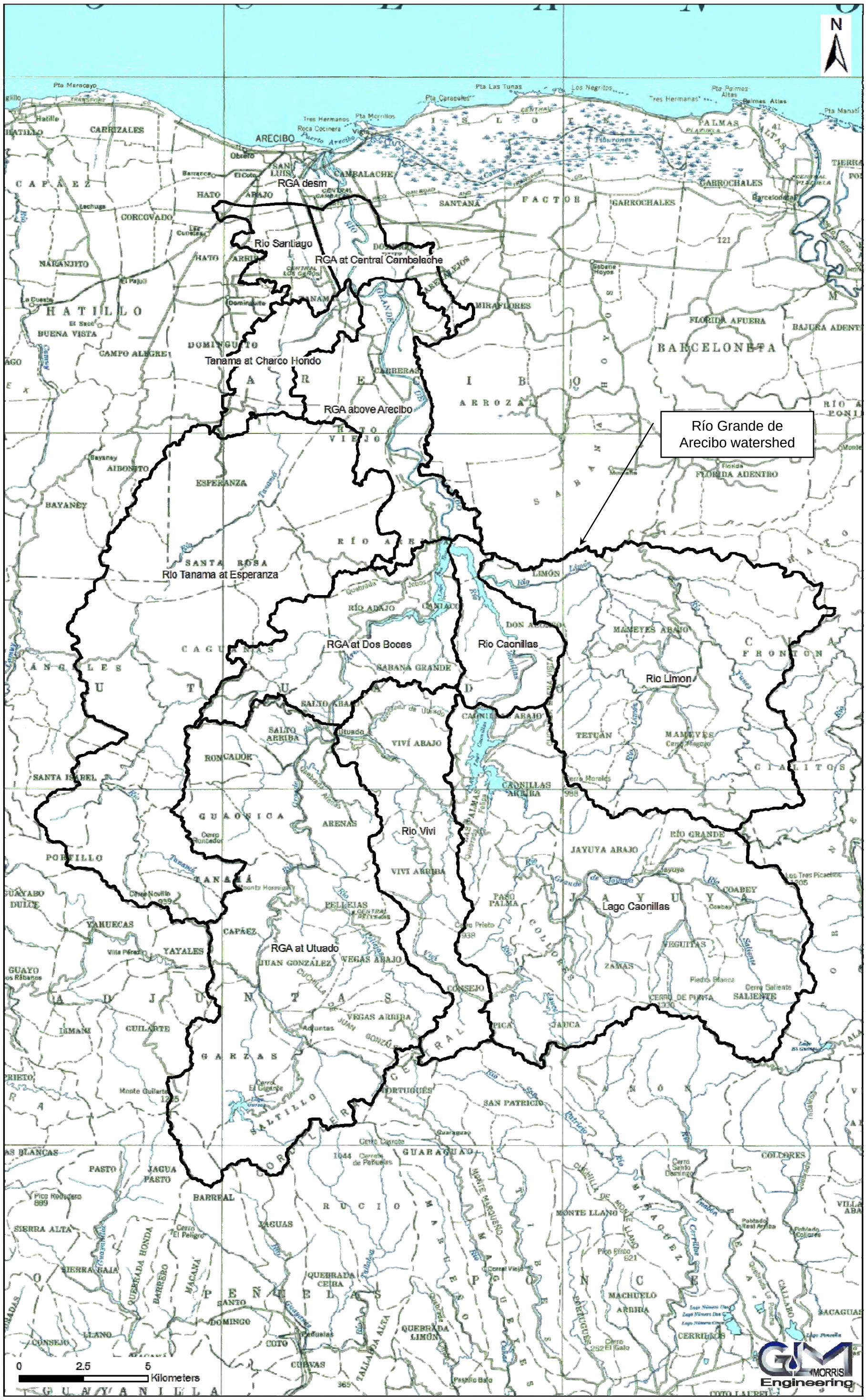


Figure 8: Analyzed Watershed Limits.

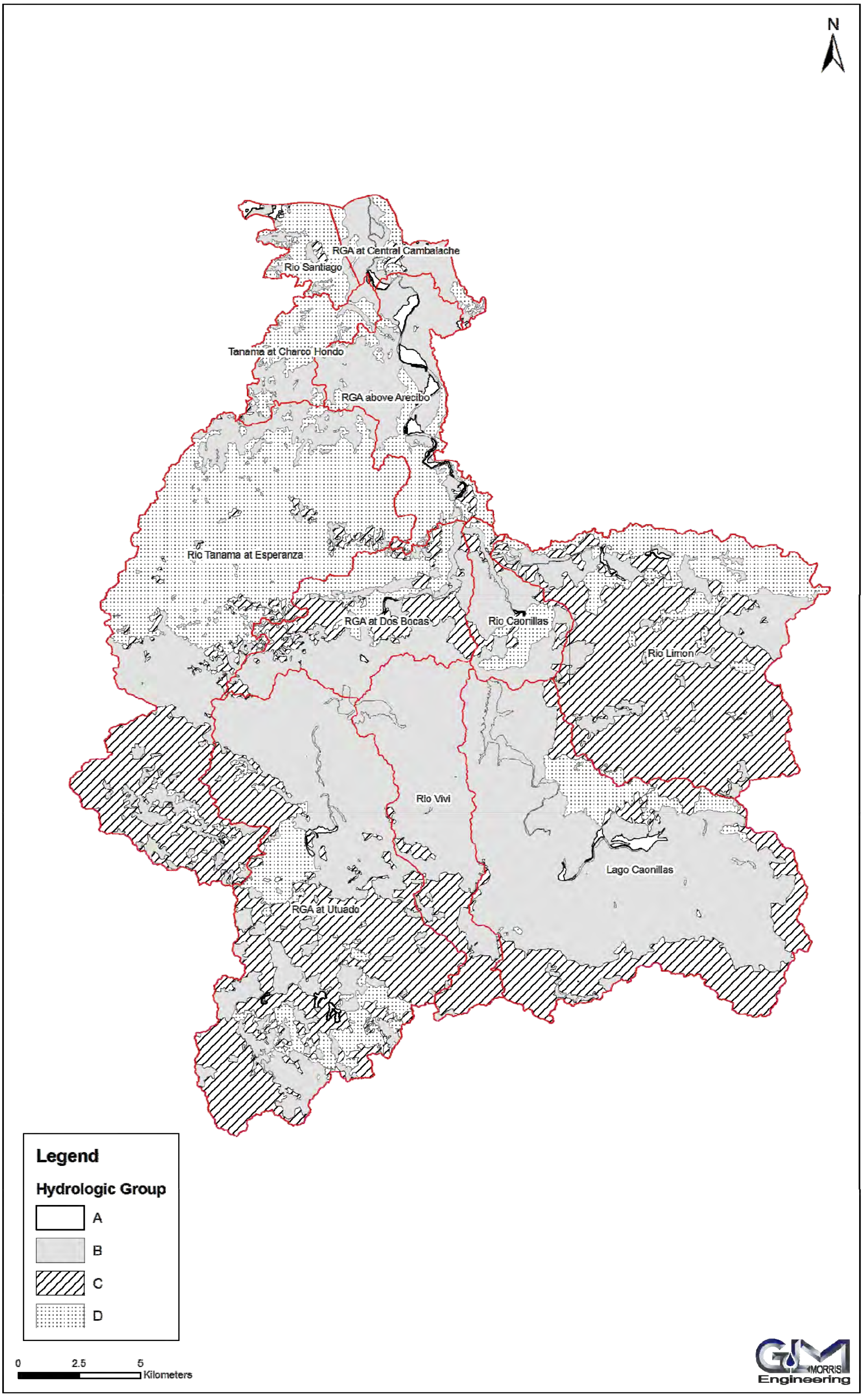


Figure 9: Hydrologic Soil Groups Found within Analyzed Watersheds.

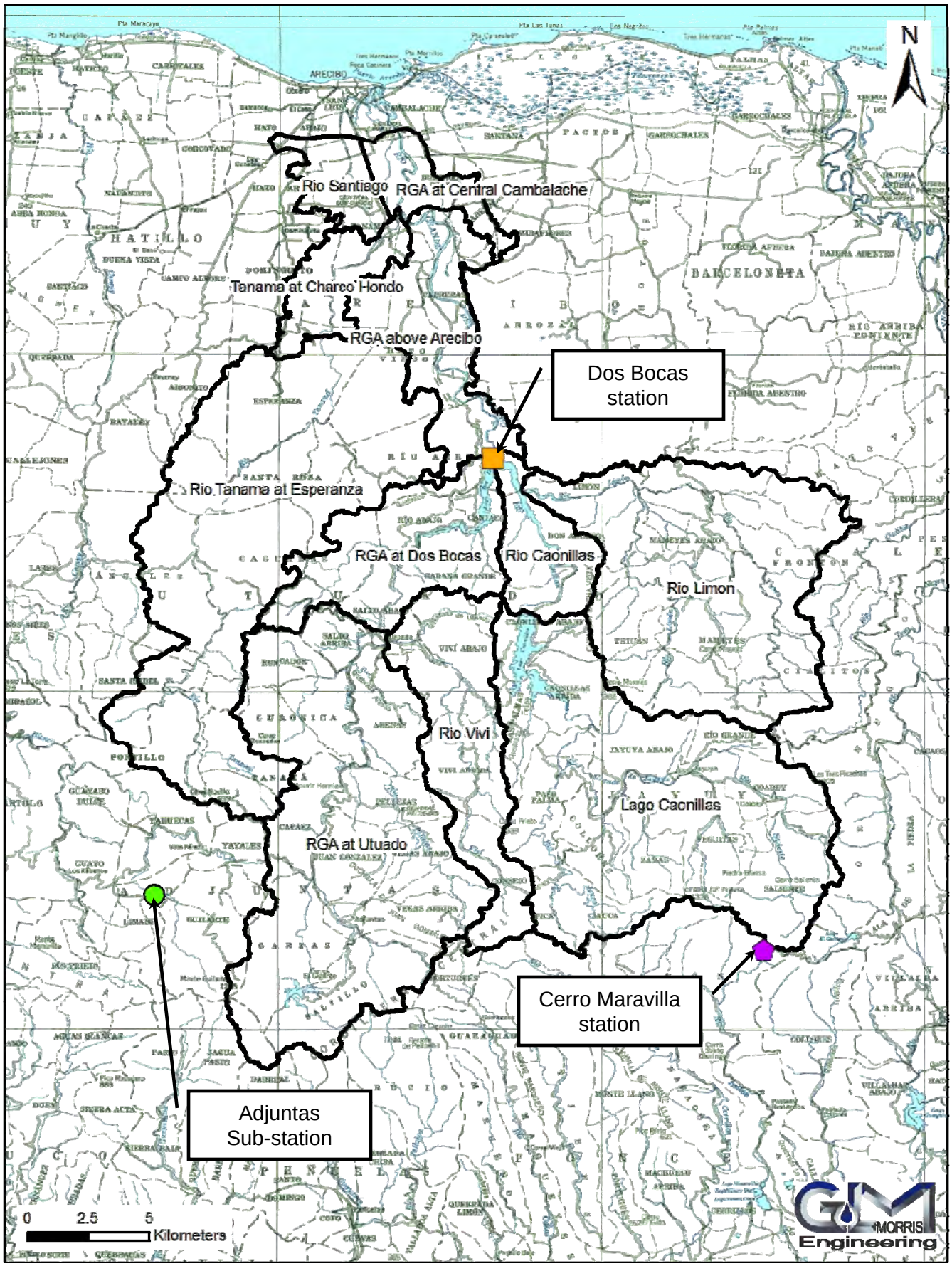


Figure 10: Location of the Three Stations with 15-minute Records for the Hurricane Georges Event.

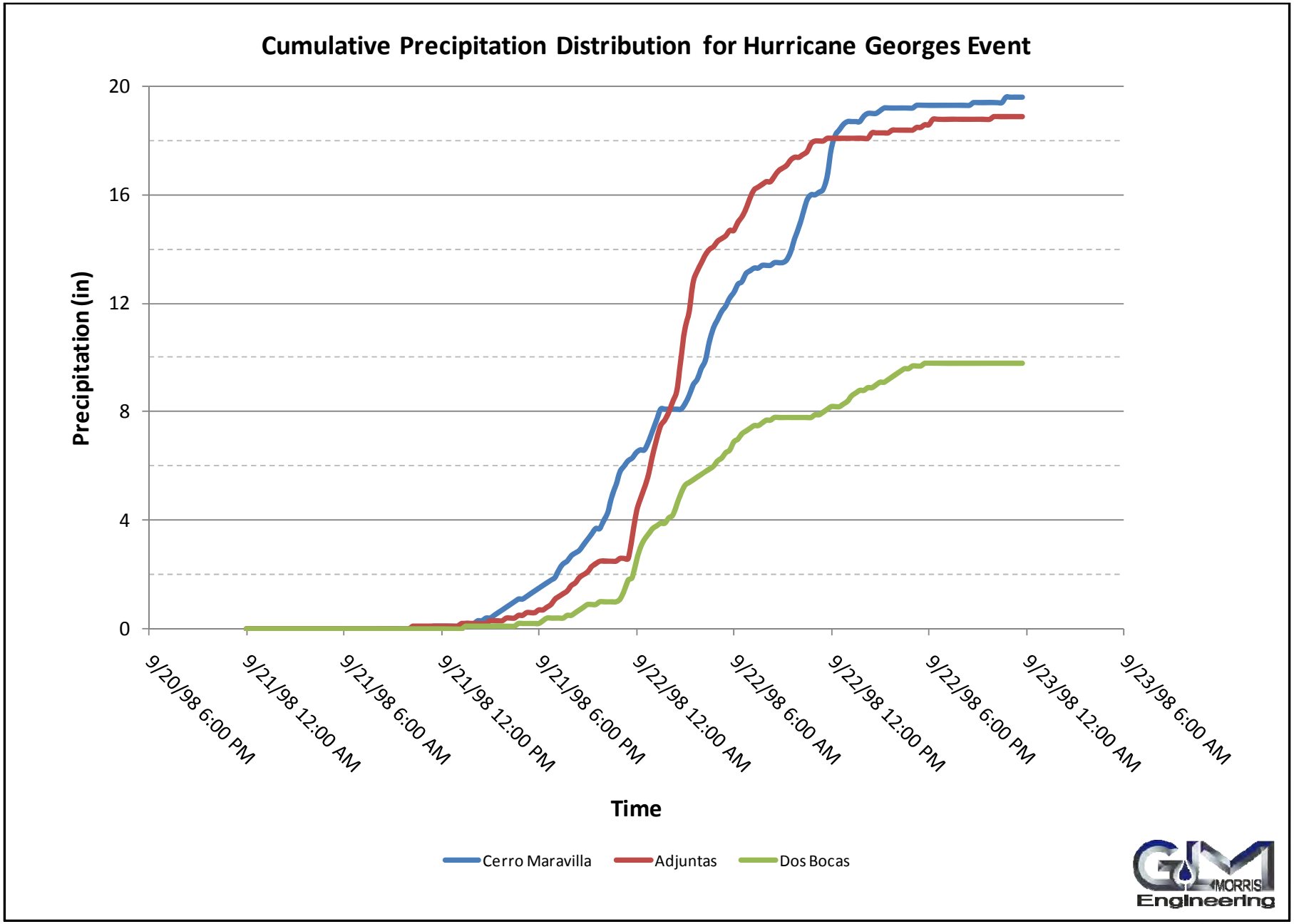


Figure 11: Cumulative Rainfall for the Three Stations with 15-minute Records for the Hurricane Georges Event

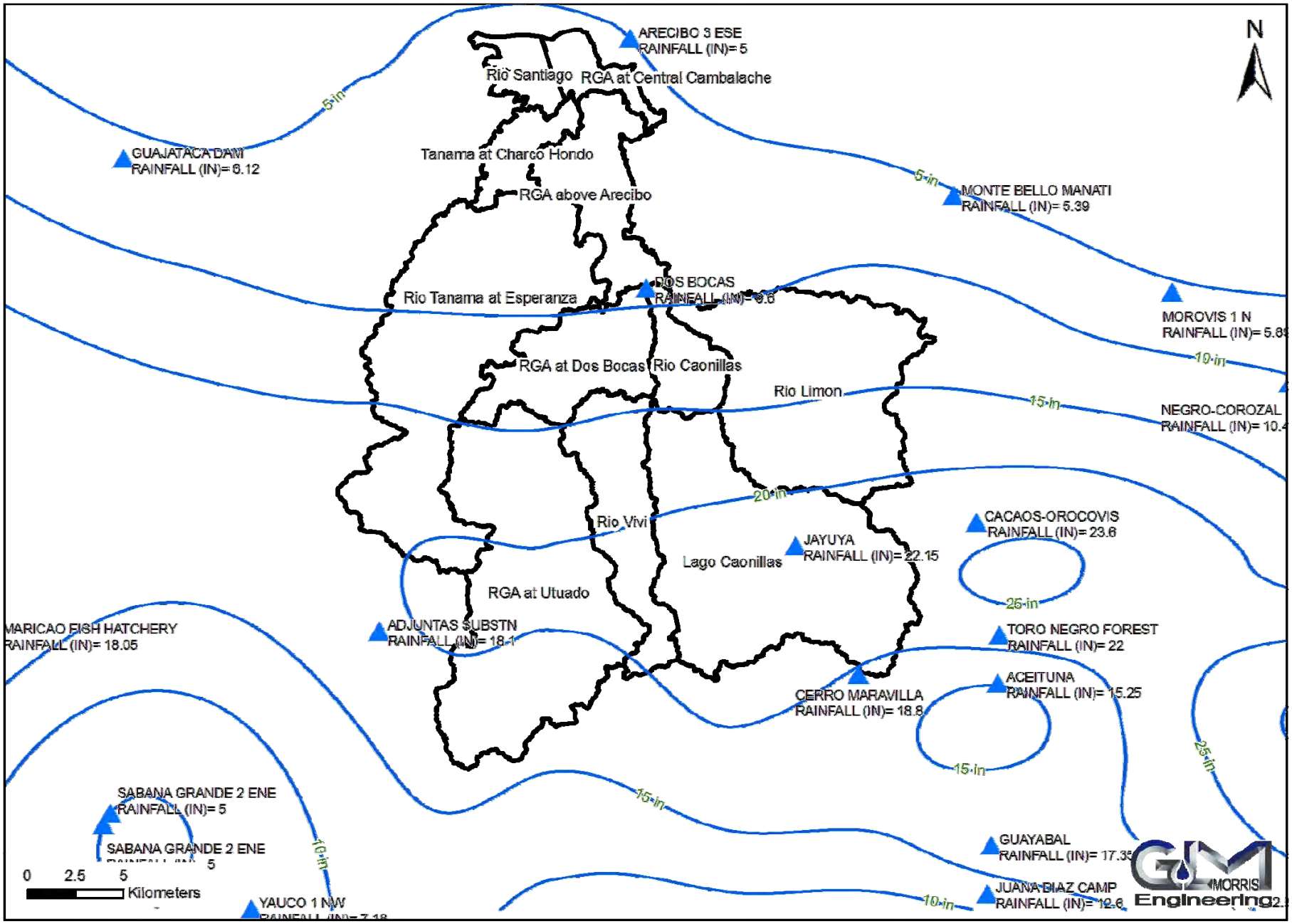


Figure 12: Hurricane Georges 24-hour Rainfall Isohyetal Map and Location of Rainfall Stations.

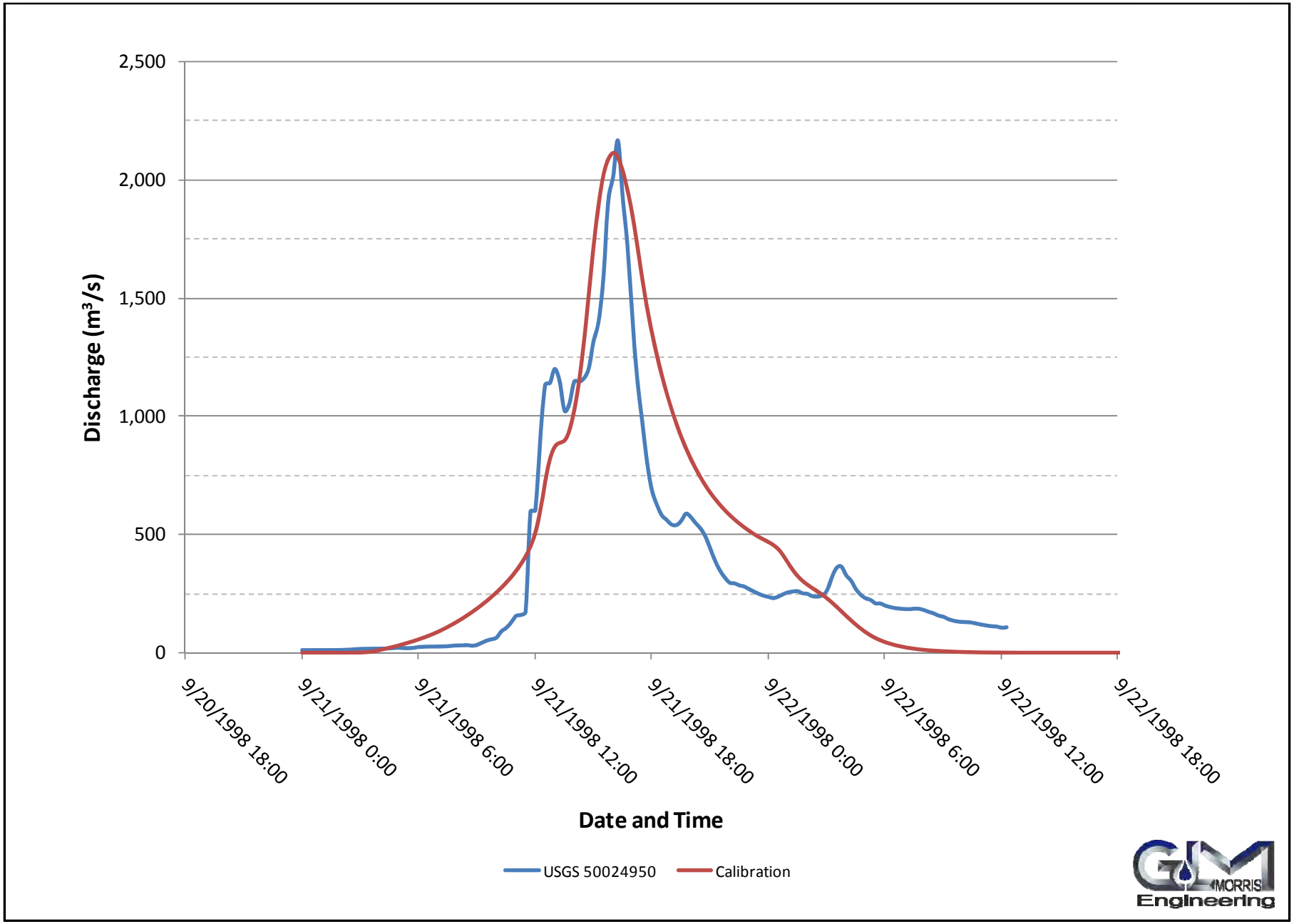


Figure 13: Comparison of Observed and Simulated Hydrographs at USGS Gage Sstation 50024950, Río Grande de Arecibo below Utuado

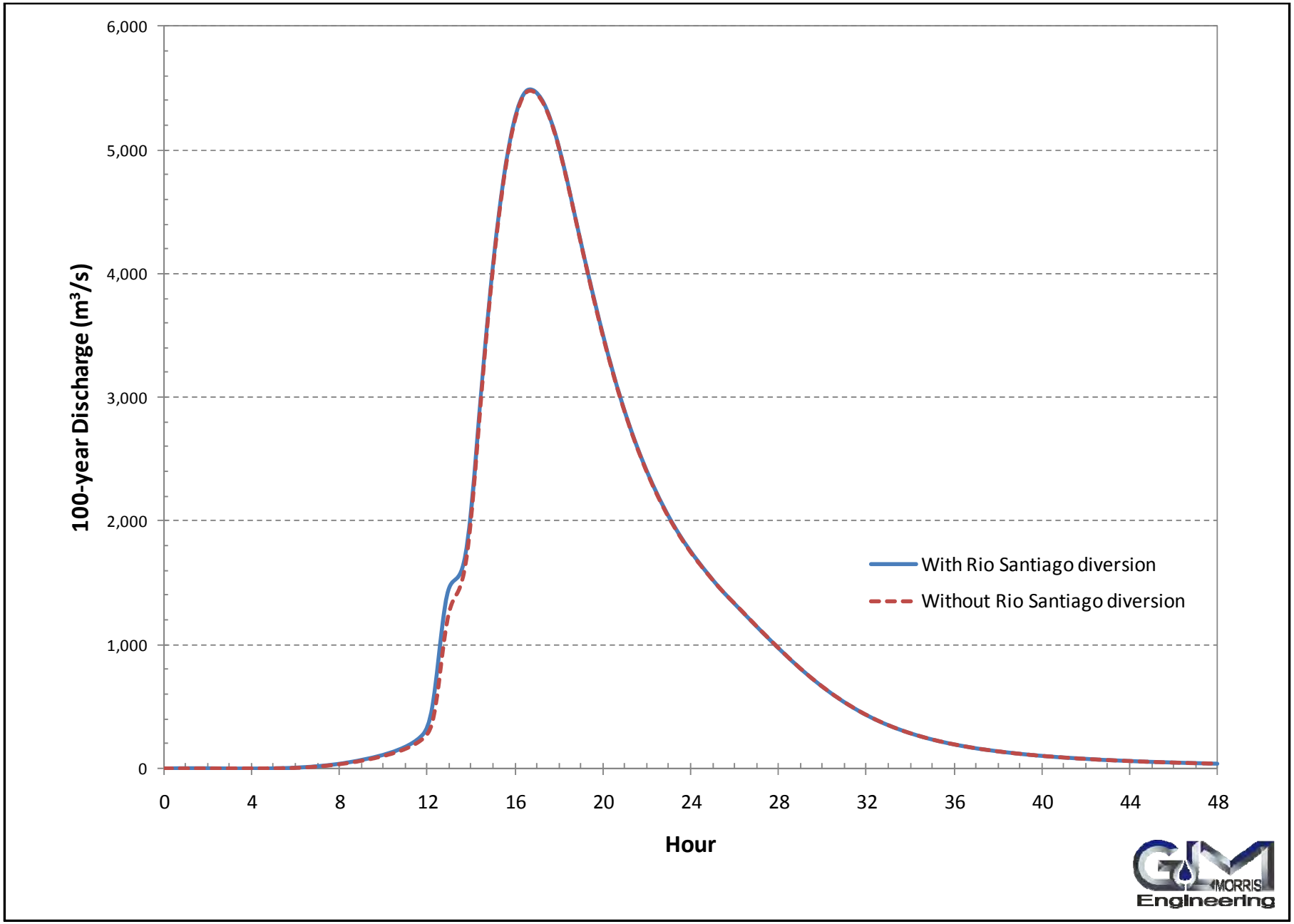


Figure 14: Flood Hydrographs at Río Grande de Arecibo before and after Río Santiago Diversion

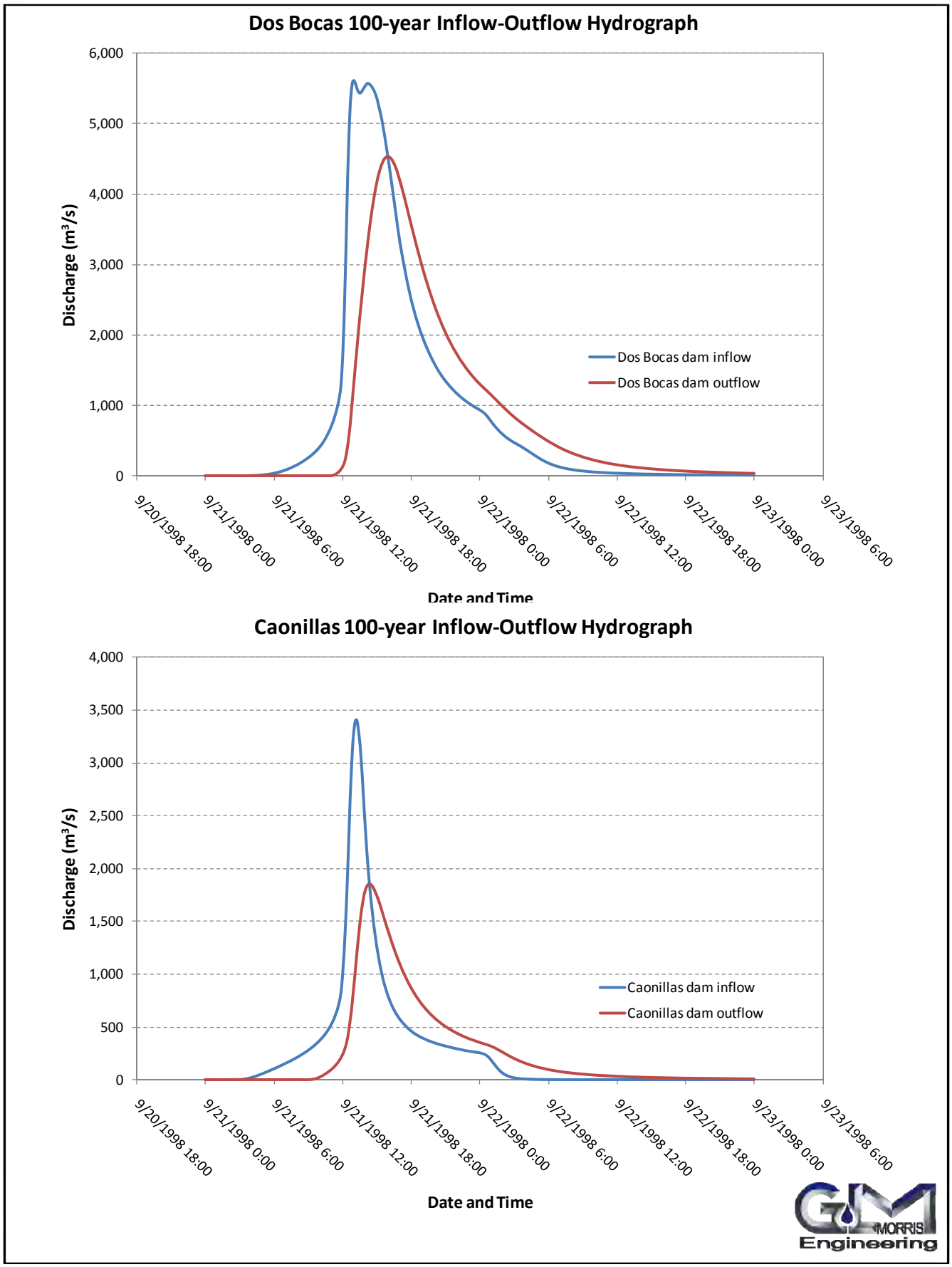


Figure 15: Hydrograph Attenuation at Lago Dos Bocas and Lago Caonillas for 100-year Event

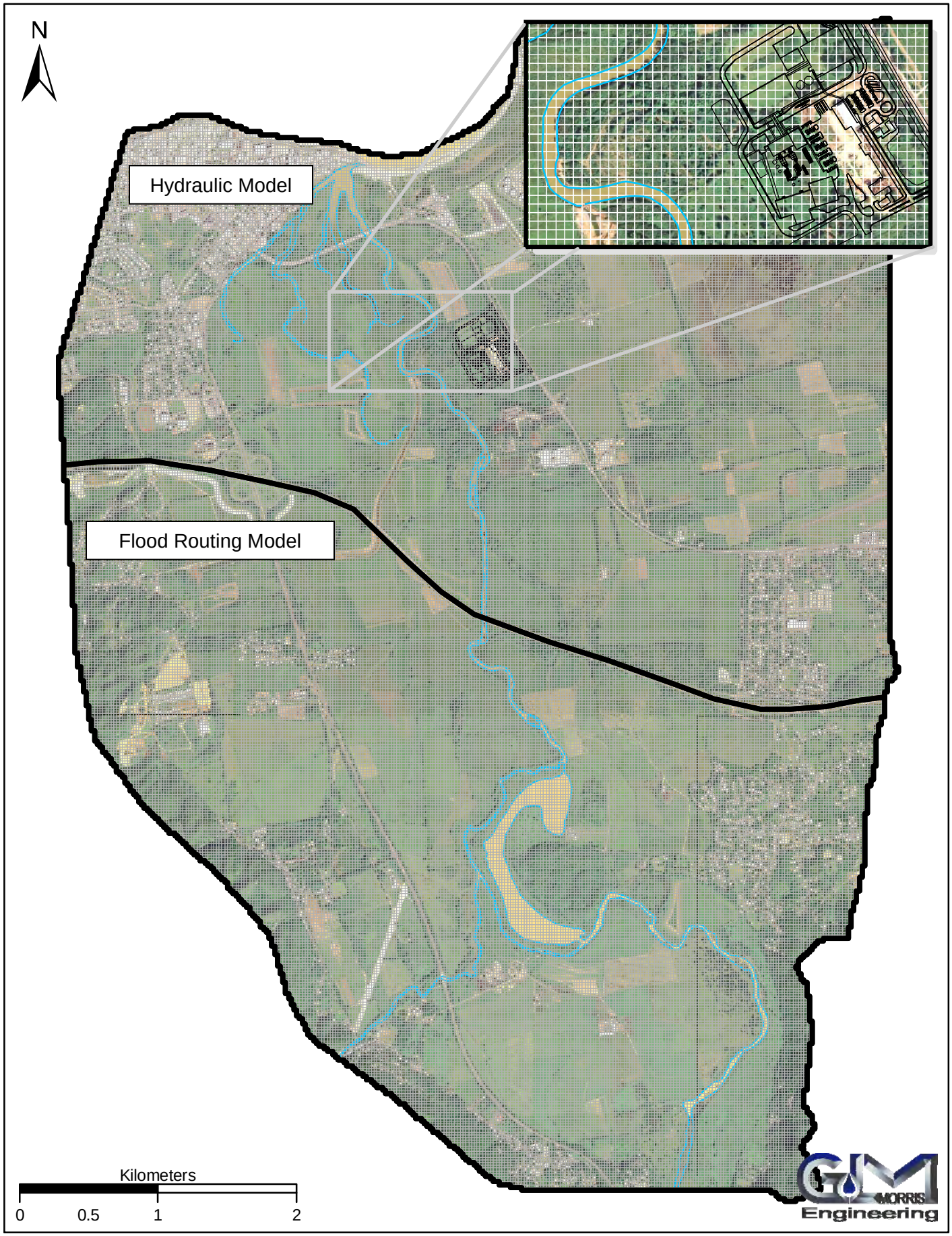


Figure 16: Layout and Extent of 2-D grid for Rio Grande de Arecibo.

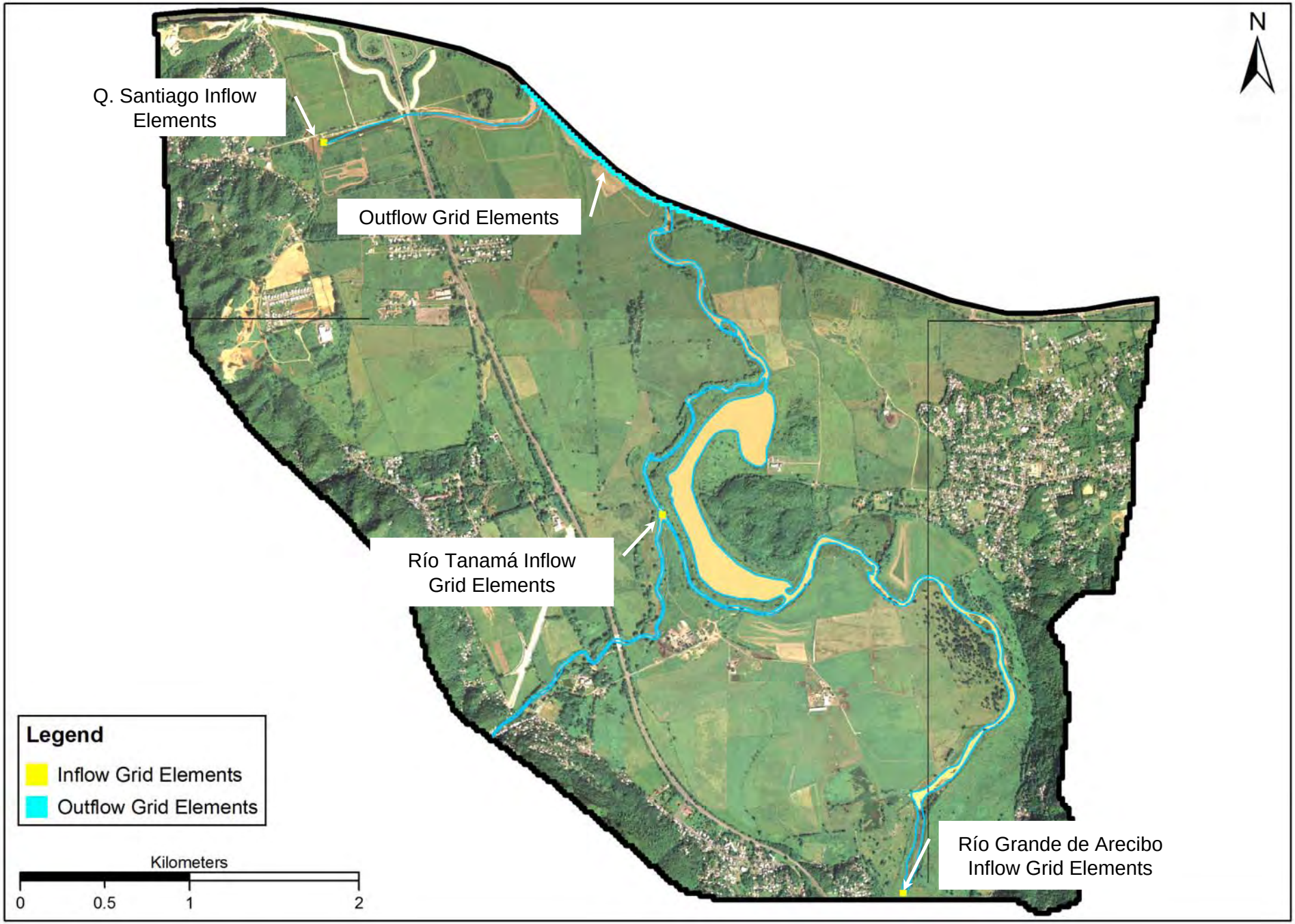


Figure 17: Layout and Extend of Hydrograph Routing Model

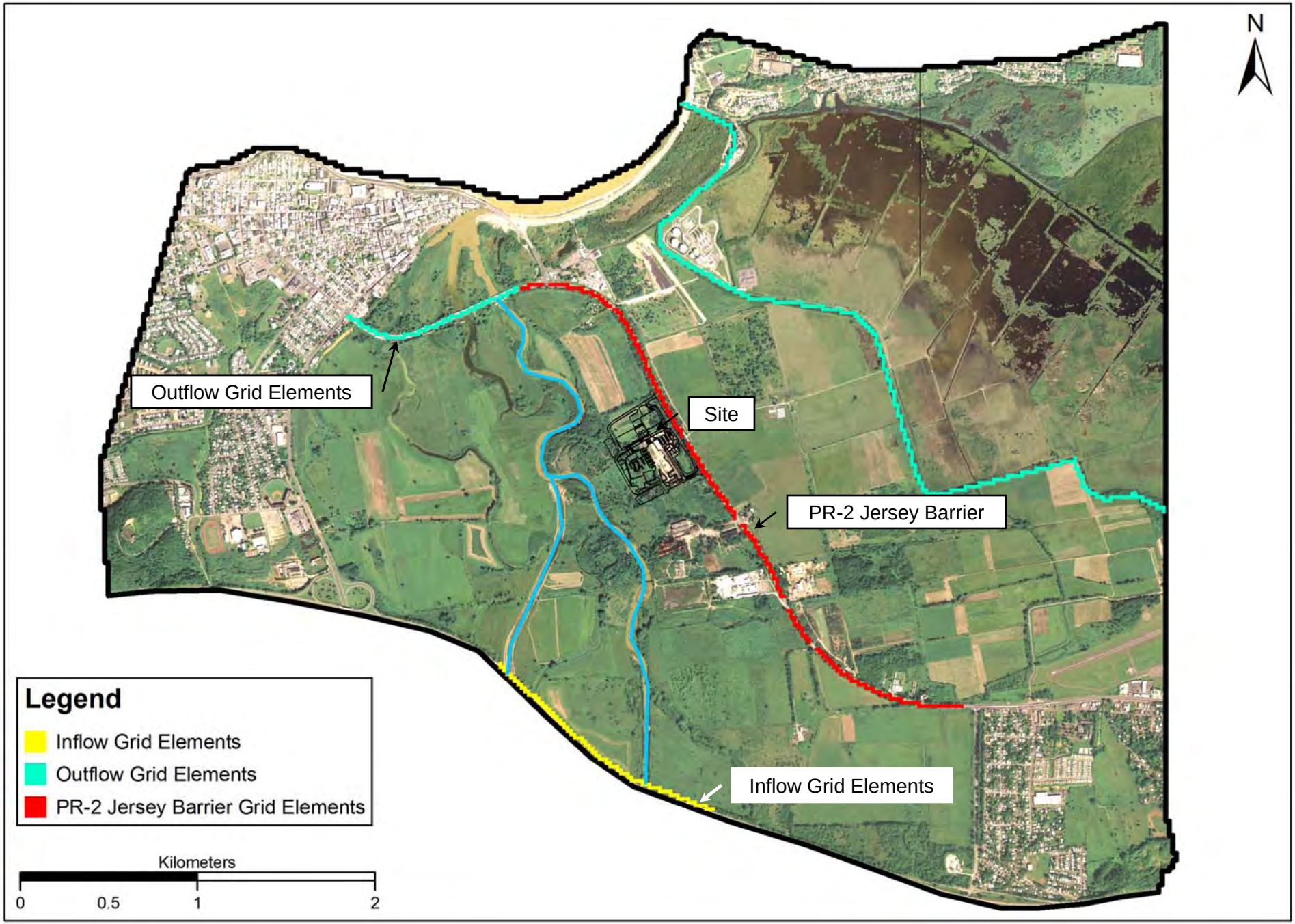


Figure 18: Layout and Extent of Duplicate Effective/Exisitng Condition Model.

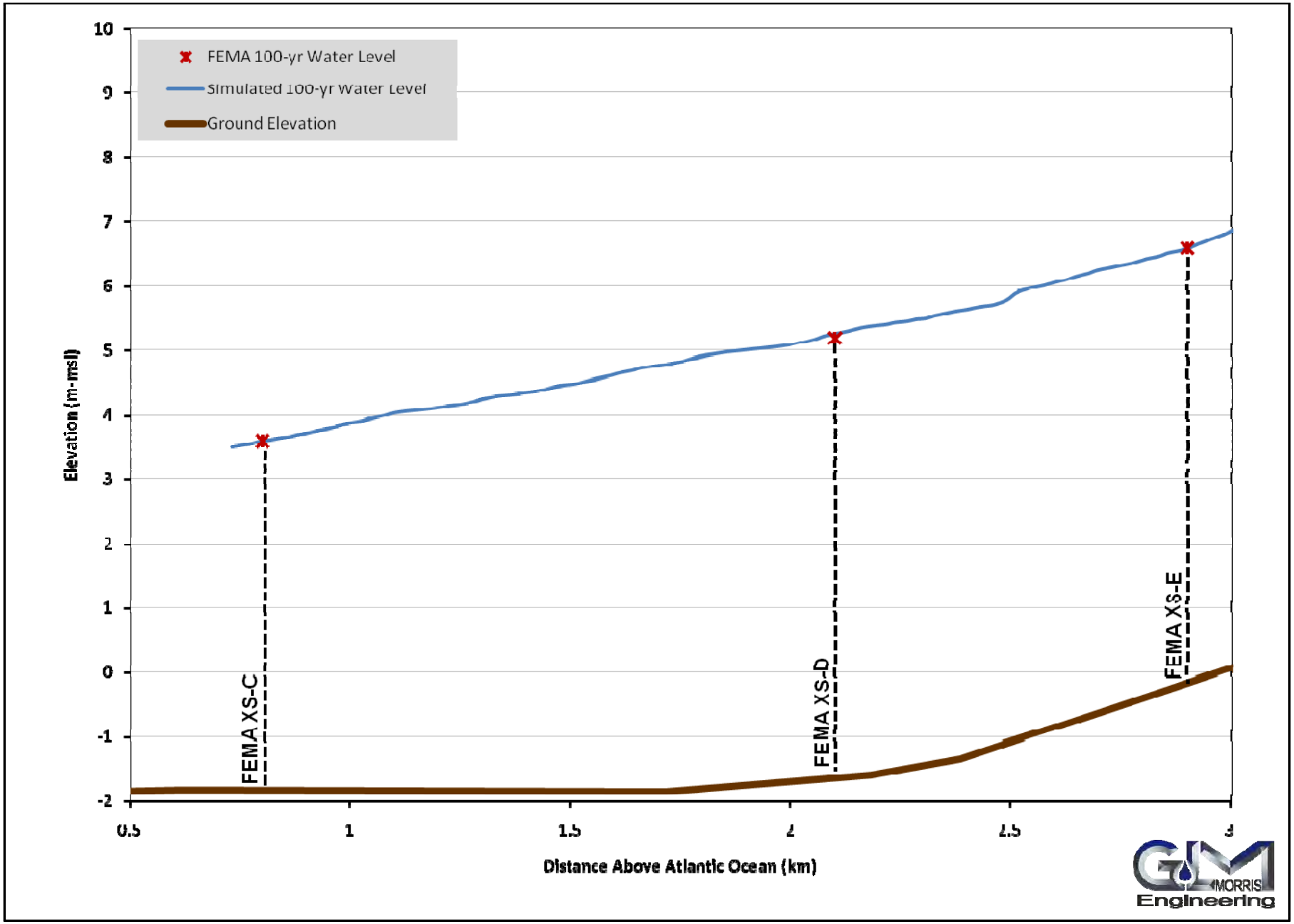


Figure 19: Comparison of FEMA and Duplicate Effective/Existing Condition 100-year Flood Profile.

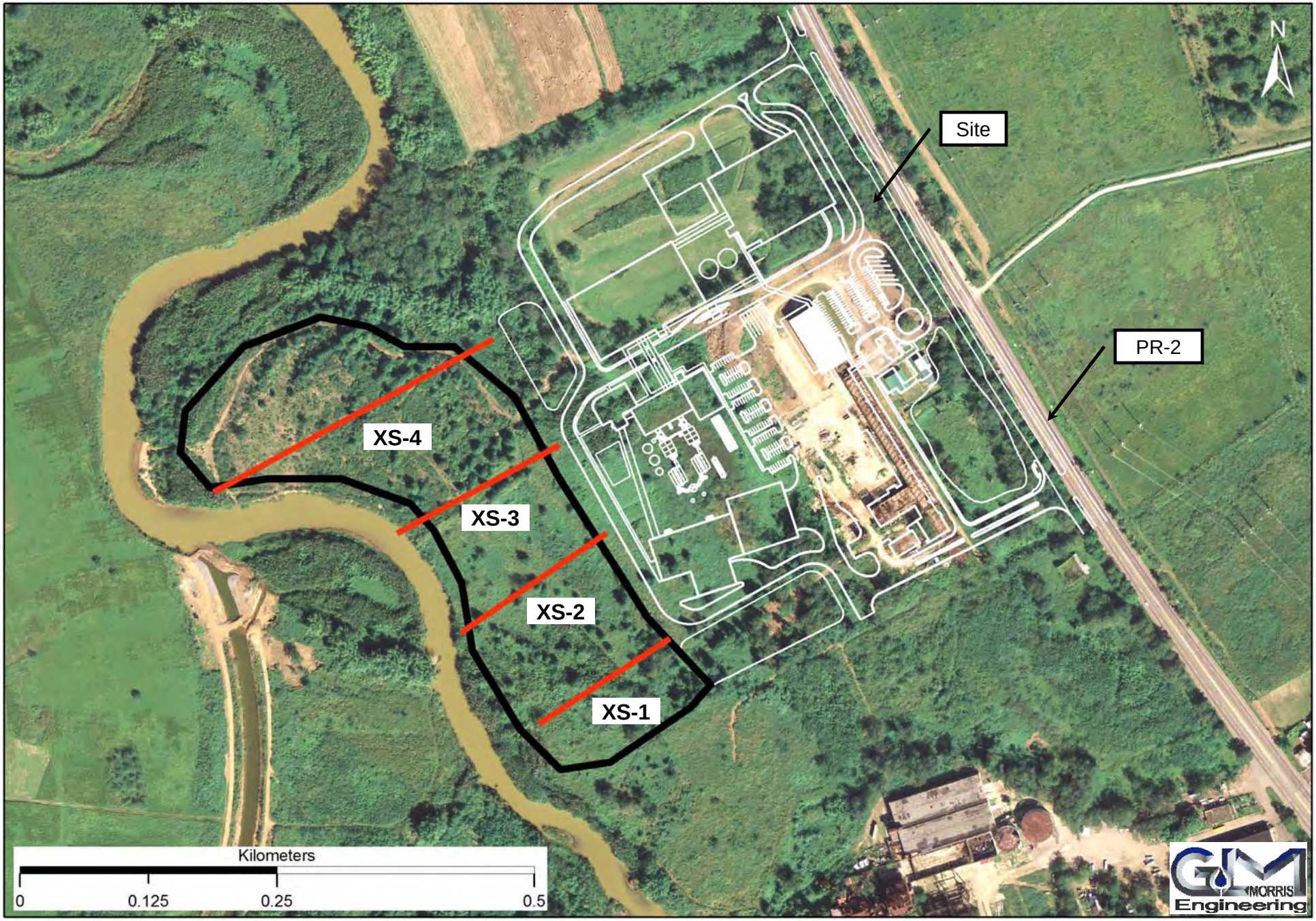


Figure 20: Location of Bank Modification Area.

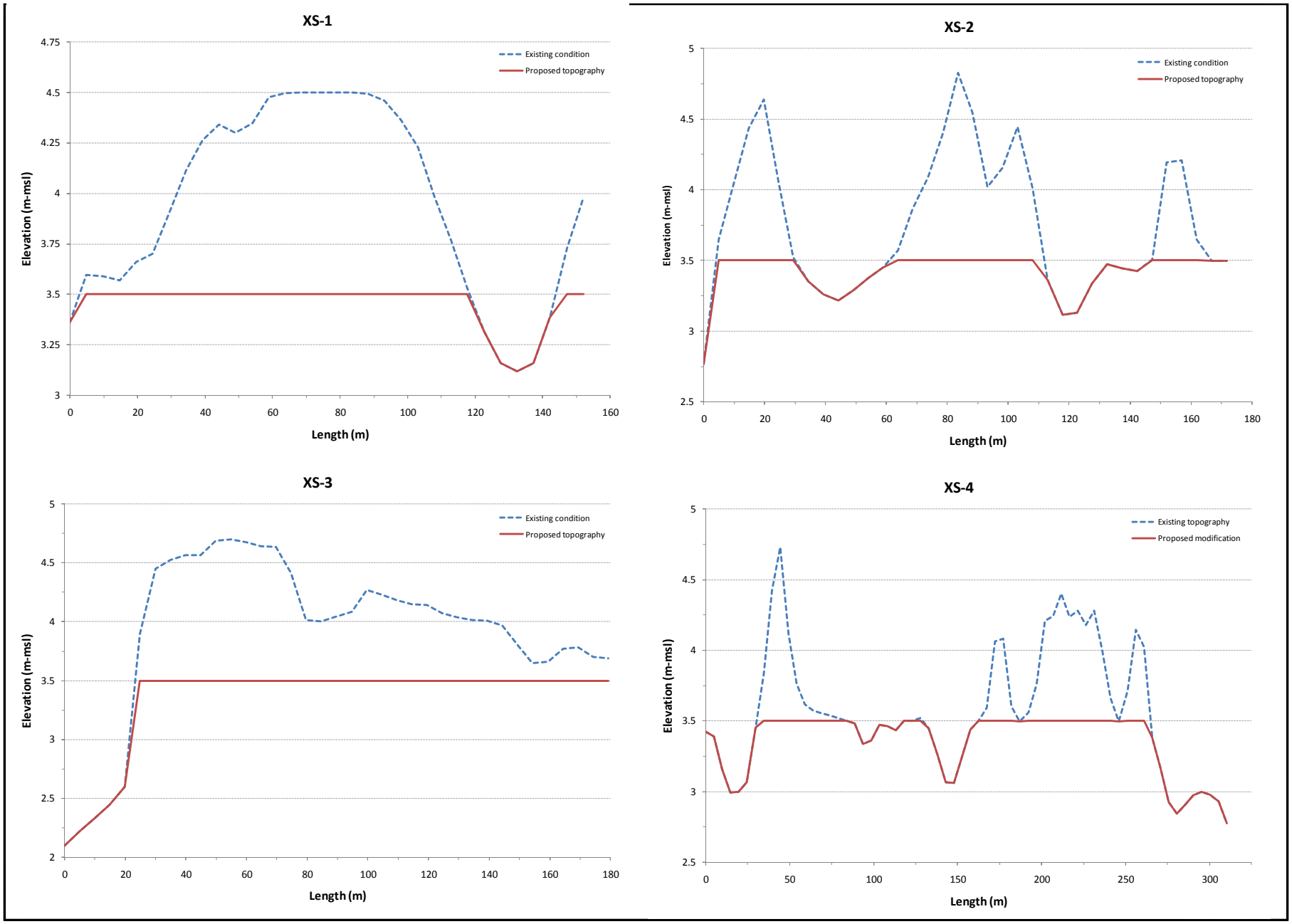


Figure 21: Proposed Geometry of Bank Modification Area

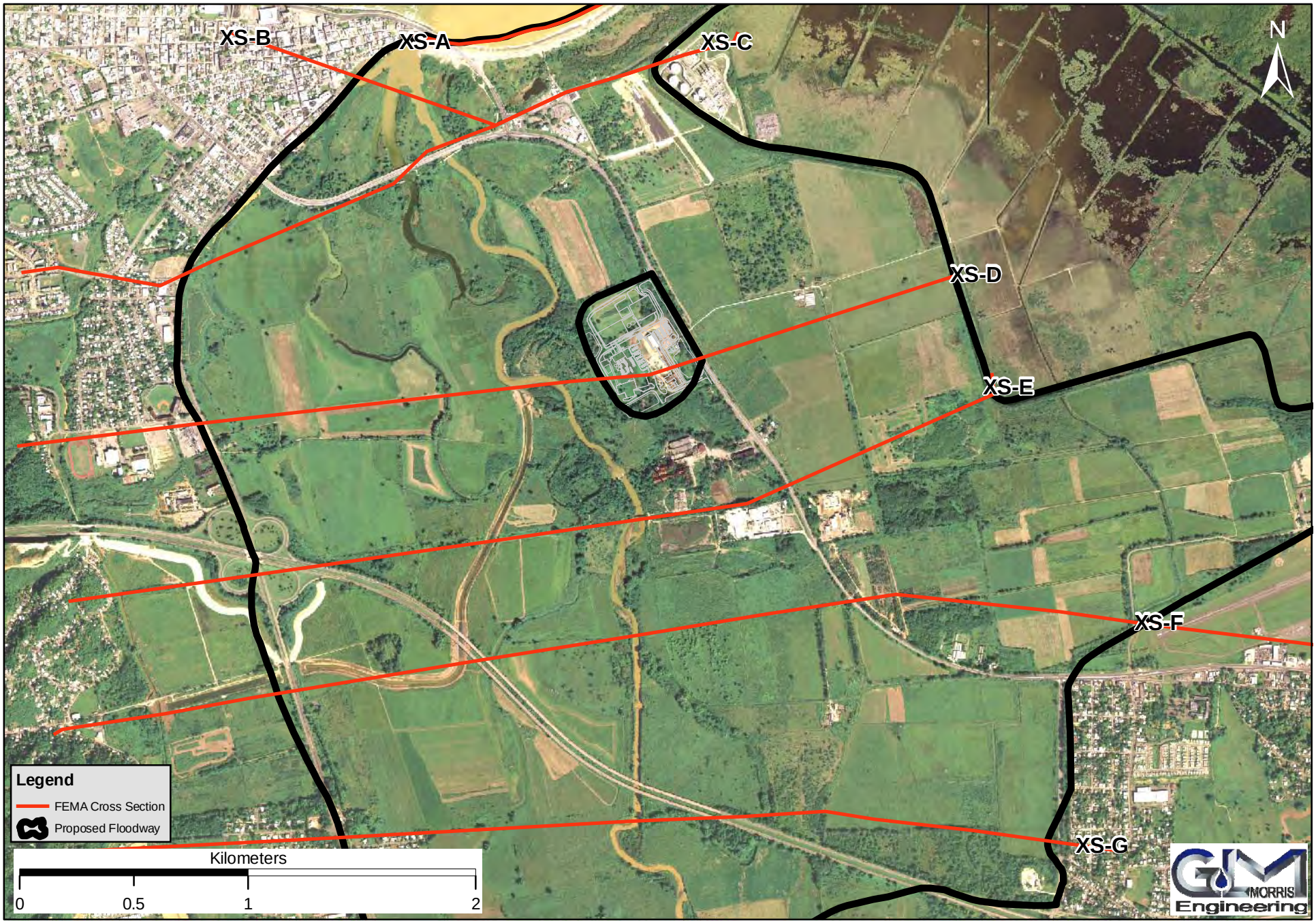


Figure 22: Proposed 100-year Floodway Limits.

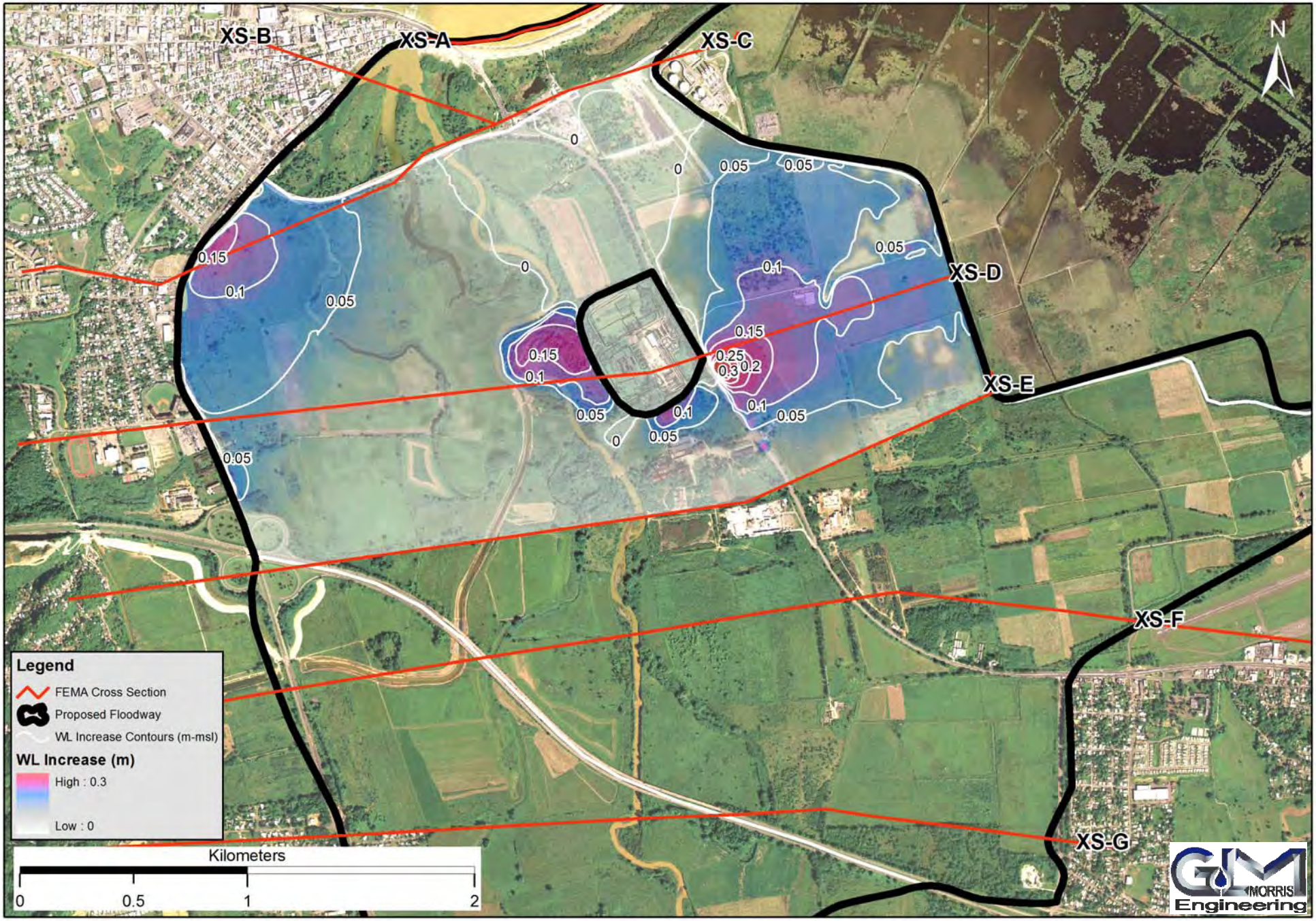


Figure 23: 100-year Water Surface Elevation Differences Attributable to Encroachment.

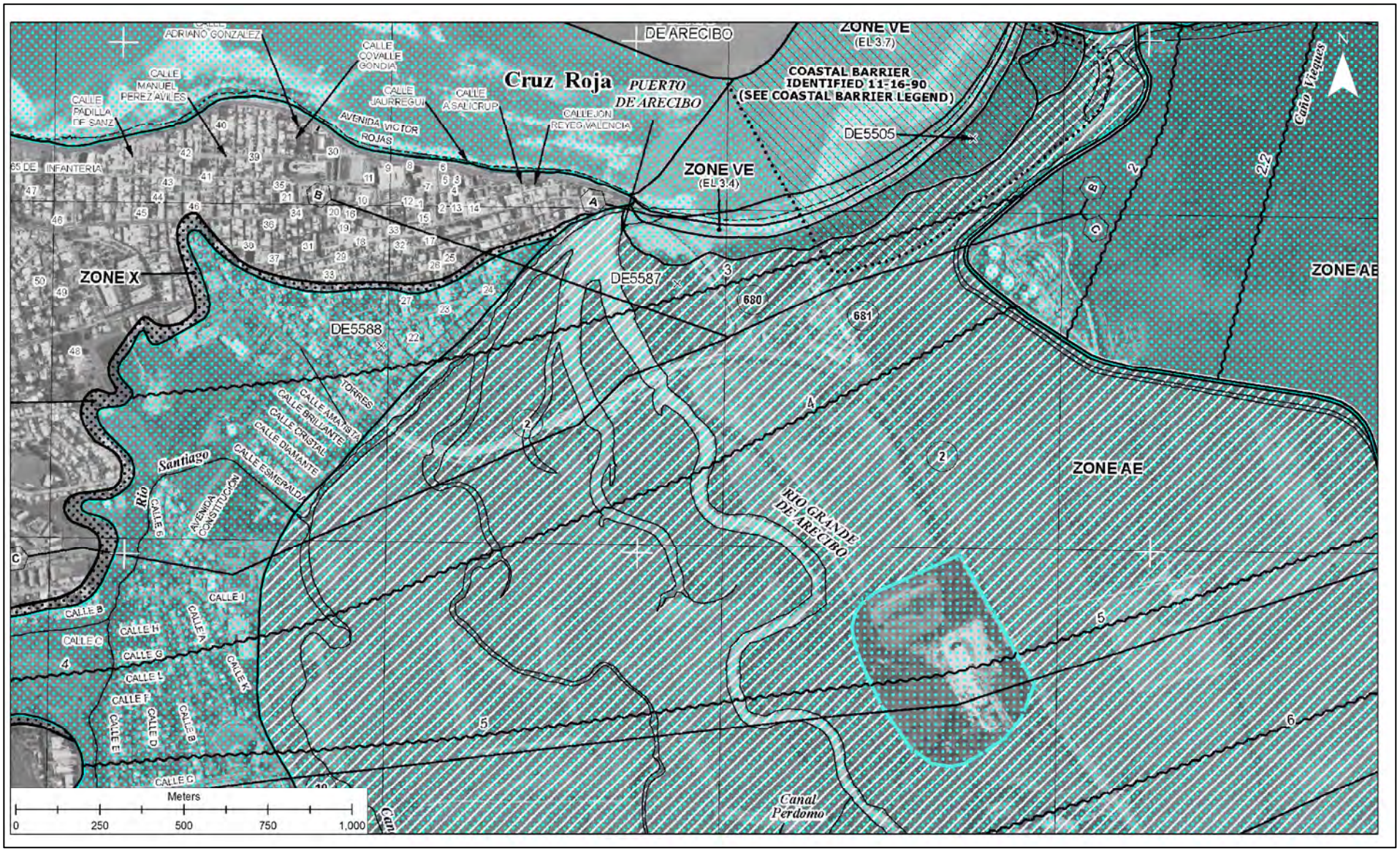


Figure 24: Annotated FIRM panel 230