APPENDIX B: HYDROLOGY AND HYDRAULICS

for

RIO GUAYANILLA, GUAYANILLA, PR

2018 SUPPLEMENTAL APPROPRIATIONS

FLOOD RISK MANAGEMENT STUDY

March 2020

DRNA

US Army Corps of Engineers.
Chicago District

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1.0   Introduction

1.1   Watershed Description

The study area is located in the Rio Guayanilla watershed, including the Municipality of Guayanilla, on the southwestern coast of Puerto Rico. The watershed area, as depicted in Figure 1, is approximately 96 square kilometers (37 square miles). The watershed is bordered on the west by the Rio Yauco, on the east by the Rio Tallaboa, on the northwest by the Rio Grande de Anasco, on the northeast by the upper Rio Grande de Arecibo, and on the south by the Caribbean Sea. There is potential for the river system to the east, the Rio Macana, to overflow into the Rio Guayanilla lower basin during floods in that watershed (USACE, 1990).
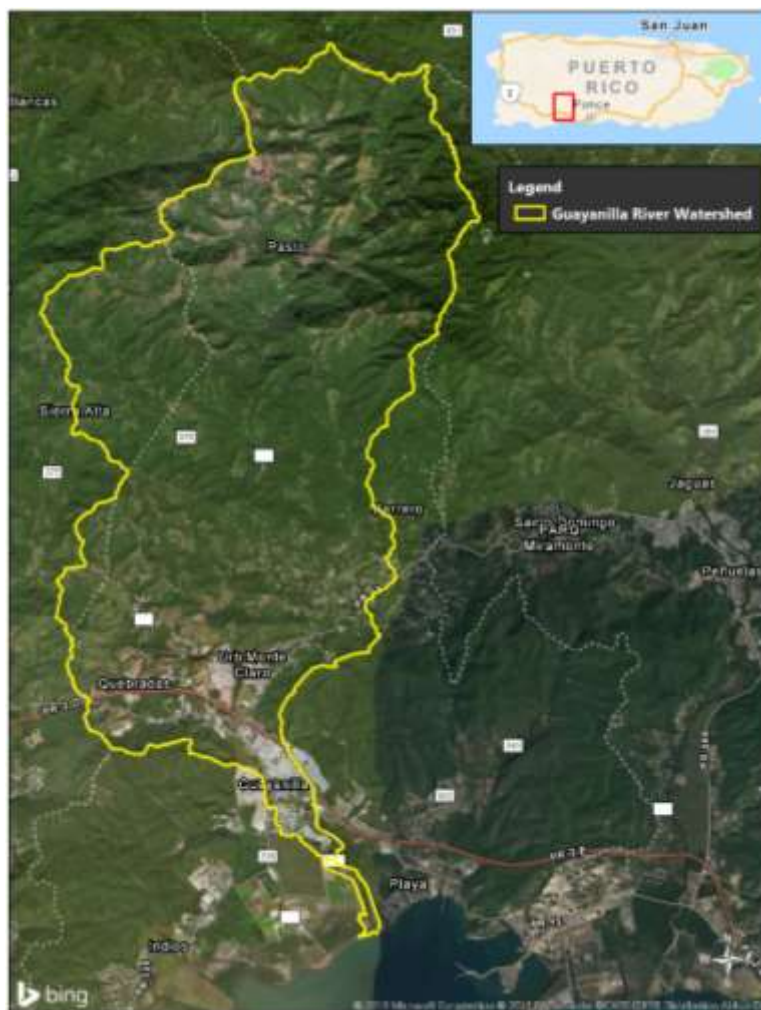
Figure 1: Rio Guayanilla Watershed

The Rio Guayanilla originates at a point near the central mountain range at an elevation of about 1,000 meters (3,280 feet) above mean sea level. The river flows in a southerly direction via a winding, well-defined channel. It flows through steep slopes in the upper part of the watershed, producing fast runoff velocities and allowing minimal infiltration. The total length of the river channel is approximately 23 kilometers (13.9 miles). There is one stream gaging station, 50124200, within the watershed that has been operated continually by the United States Geological Survey (USGS) on the Rio Guayanilla since 1981, refer to Figure 2. The hydraulic capacity of the Rio Guayanilla channel in the lower flood plain is

estimated to be about 3,800 cubic feet per second (cfs) (USACE, 1990). This discharge is equivalent to a recurrence interval of about two years.
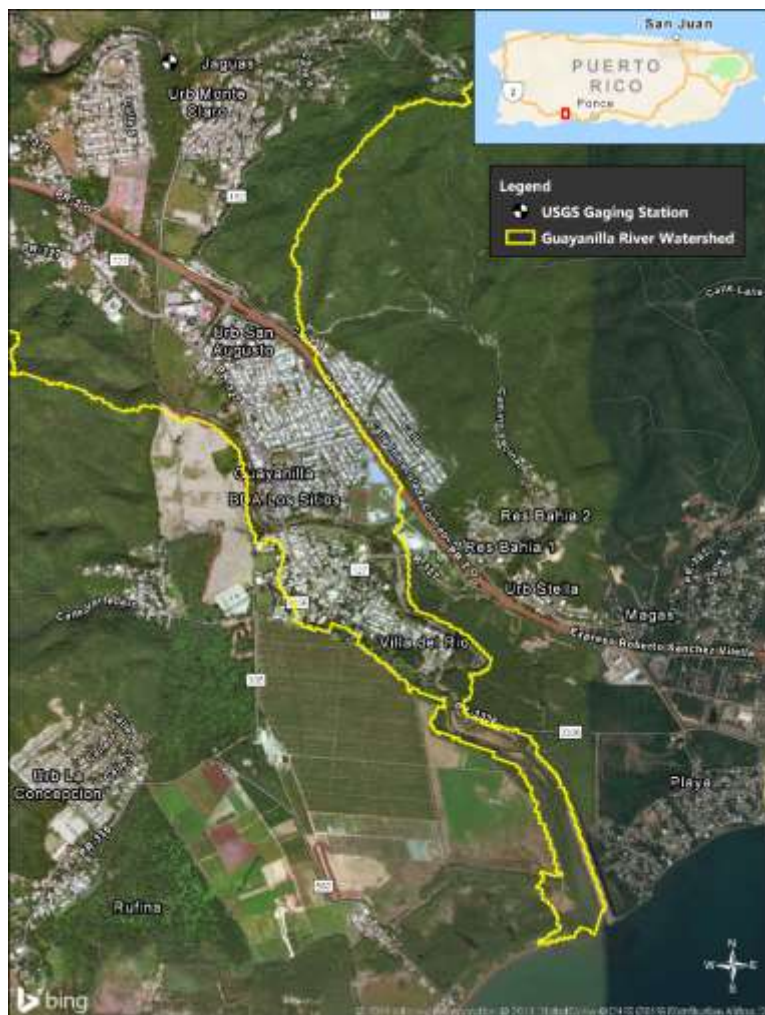
Figure 2: Project Study Area with USGS Gage Location

1.1.1 Flood History

During flood seasons, which is generally May through December, the Rio Guayanilla is a source of frequent flood damages to the town and residents of Guayanilla. Heavy rainfall and very steep slopes in the upper catchment can produce high peak discharges in a relatively short period of time. The 0.01 Annual Exceedance Probability (AEP) flood can inundate over eight square kilometers of land within the study area.

There have been at least 12 damaging floods on the Rio Guayanilla, listed in Table 1. The USGS has not yet published the peak flow during Hurricane Maria in September 2017, therefore data from this event was not utilized in the development of the recommend plan. However, based on discussion with USGS and with the local community, if the data were available it would not change the analysis completed.

Table 1: Damaging Historic Floods Recorded on the Rio Guayanilla

Historic Event	Date of Flood	Discharge (cfs)
Okeechobee Hurricane "San Felipe II Hurricane"	September 13, 1928	23,000
Tropical Storm One	May 7, 1932	28,000
Hurricane Hazel	October 13, 1954	18,000
	May 6, 1958	11,600
Hurricane Eloise	September 16, 1975	22,400
Hurricane David & Hurricane Frederic	August 31, 1979	16,000
Hurricane Debby	September 12, 1982	14,700
Tropical Storm Isabel "1985 Flood Disaster in PR"	October 7, 1985	11,900
Hurricane Georges	September 22, 1998	18,700
	May 6, 2001	18,700
Hurricane Ike	September 22, 2008	14,500
Hurricane Sandy	October 26, 2012	23,800

1.1.2 Phase 1

In 1990, the United States Army Corps of Engineers (USACE) published the *Reconnaissance Report, Rio Guayanilla at Guayanilla.* This study was conducted under the authority of Section 722 of PL 99-662 of the Water Resources Development Act of 1986. The purpose was to investigate flooding problems associated with the overflow of Rio Guayanilla, in the Town of Guayanilla, and identify measures within the federal interest. Although a federal interest was determined, the non-federal sponsor opted out of moving into the Feasibility Phase and implemented a portion of the plan recommended in the Recon Study (USACE, 1990).

In September 2003, the Puerto Rico Department of Natural and Environmental Resources (DNER) began construction of a portion of the USACE's recommended plan from the 1990 Recon Report. The project consisted of channelization of the downstream portion of the Rio Guayanilla for the control of flooding in the Guayanilla floodplain. This Phase I of a greater project was terminated in June 2006.

1.2 Project Description

The focus of this feasibility study is to improve life safety conditions and reduce damages to structures and infrastructure induced by flooding. The objective is to inform the public on the flood hazard and reduce the depth, duration and likelihood of flooding, with emphasis on residential and commercial structures, utilities, transportation infrastructure, and agricultural fields, within the identified area of study.

The focused study area includes the floodplain of the lower Rio Guayanilla, from upstream of highway PR-2 though the river's confluence with the Caribbean Sea. Impacts from portions of the Karst Mountains, to the west, and the marine/estuarine coastline, are also included. Preliminary analysis shows that flooding overtops the existing natural river channel of Rio Guayanilla, in the study area at the 0.5 annual exceedance probability (AEP) storm event (which corresponds to the two-year storm event).

2.0   Data Collection

2.1   Topographic Data

The topography of Puerto Rico is extremely varied, but most of the island is hilly to mountainous, with very steep slopes and narrow valleys in the interior. The south coast of the island is a low alluvial plain that fringes the foot of the steep-sloped upland, except for the western part, which consists of low limestone hills and the eastern end, which is mountainous (Kaye, 1959). The coastal plains are nearly flat areas that slope very gently upward from the shore to the foothills and grade into the alluvial plains of the larger rivers. The mountainous areas are deeply eroded by streams, and valley sides consist of steep slopes of 30° to 45° granitic rock (Monroe, 1980).

Two through-going fault zones, the Great Northern Fault Zone and the Great Southern Fault Zone, divide Puerto Rico into the northeastern, central and southwestern blocks. Puerto Rico is presently bound on the north by the Puerto Rico trench and on the south by the Muertos trough (Larue, 1988). In southern Puerto Rico, the altitudes are much more irregular and much steeper, ranging from a few degrees to as much as 30°, and the direction of dip is generally south but is influenced by the faulting commonly present in that area (Monroe, 1980).

2.2   Field Investigation

Three site visits, in which the Hydraulic Engineer of the Project Delivery Team (PDT) was present for, were conducted in September 2018, November 2018 and April 2019. For the September 2018 visit, Chicago District (LRC) staff, Jacksonville District (SAJ) staff and Mayor Torres Yordán and his staff participated in a site visit of Guayanilla including key locations that were identified in the prior studies. The site visit started at PR-2, the upstream portion of the study area. Stops were made at each of the bridges that could be affected by the recommended plan, including the PR-127 bridges and the PR-3336 Bridge. Additional stops included the downtown area, where the existing channel would become the low flow channel under the recommended plan (1990 Recon); the agricultural fields, where the diversion channel could be sited; and the upstream portion of the constructed Phase I (of the recommended plan in the Recon Report). The final leg of the site visit included a drive down the Phase I levee crest to the outlet at Guayanilla Bay.

The November 2018 site visit was conducted in conjunction with the public meetings, as part of the National Environmental Policy Act (NEPA) and Feasibility Study process. Similar to the previous visit, a site overview visit was conducted by the LRC staff that was not present in September. In addition to the site overview visit, different discipline teams (i.e. economics, geotechnical, hazardous, toxic and radioactive waste (HTRW), etc.) investigated specific site features and areas.

The April 2019 site visit was conducted by LRC staff about six weeks prior to the Tentatively Selected Plant (TSP) milestone. The purpose of the visit was to look at specific site features that would be presented as part of the recommended plan. This included exploring overflow routes in the El Faro neighborhood, adjacent to the downstream portion of the study area; visiting the USGS gage location; reviewing site conditions at the first PR-127 Bridge crossing; and exploring alternate route options, due to the possible road closure between PR-2 and the PR-127 bridges.

Based on the site visits and existing information, topographic survey data was collected for the study in April 2019. The survey data included 47 cross sections, five bridges, and the existing levee. Cross section data was acquired by real-time kinematic (RTK) global positioning system (GPS) and conventional survey methods. At least 17 survey shots were taken at each cross section, extending 25 feet from the existing top of bank. Elevations were collected at points at ¼, ½, and ¾ of the channel width, as well (Javier E. Bidot & Assoc., 2019). This data was later incorporated into the hydraulic model.

2.3   Previous Reports

The 1990 USACE *Reconnaissance Report, Rio Guayanilla at Guayanilla* investigated flooding problems associated with the overflow of Rio Guayanilla, in the Town of Guayanilla. The report included historical flood information, watershed and land use details, and hydrologic and hydraulic analysis. The report presented five potential structural solutions and determined that a flood control project would be economically feasible (USACE, 1990).

In 2002, as part of the design and construction efforts of Phase I, the DNER had a study completed to design a structure to divert Rio Guayanilla flood waters west of the Town of Guayanilla. The objective of the study was to design a diversion structure that would maintain bankfull flow through the existing natural channel. The study included hydrologic and hydraulic analysis using Hydrologic Engineering Center 2 (HEC-2) software (Quinones, Diez, Silva y Asociados Consulting Engineers [QDSA], 2002). Since Phase II and III of the recommended plan from the Reconnaissance Report was never constructed, nothing further was done with the design of the diversion structure.

3.0   Hydrology

3.1   Model Development

The hydrologic modeling was completed using Hydrologic Engineering Center-Hydrologic Modeling System (HMS) 4.3. The pre-processing portions were completed using GeoHMS 10.4 with ArcMap. The hydrologic model utilized 1/3 arc-sec (approximately 10 meters) resolution National Elevation Dataset (NED) from the 3D Elevation Program (3DEP). Seamless 3DEP data were derived from diverse source data that were processed to a common coordinate system and unit of vertical measure. The horizontal coordinate system used for this model was North Atlantic Datum (NAD) 1983 StatePlane Puerto Rico Virgin Islands Federal Information Processing Standards (FIPS) 5200 feet. The vertical coordinate system used is referenced to the Puerto Rico Vertical Datum of 2002 (PRVD02) feet. Basic geographic information systems (GIS) functions were utilized to calculate the curve number (CN), define the longest flow path, and to determine basin slope and length.

3.2   Model Parameters

3.2.1   Basin Delineation

The first step in doing any kind of hydrologic modeling involves delineating streams and watersheds, and getting basic watershed properties such as area, slope, flow length, etc. Using the tools in GeoHMS, the entire watershed was subdivided into subbasins ranging from approximately 32 acres to 2055 acres in size, see Figure 3. These subbasins form the basis of the hydrologic model and were modeled assuming a unified response to rainfall based on land use characteristics and soil type. Elevation data described above, was the principal data source used for subbasin delineation. Subbasin boundaries were modified to encompass areas with similar development patterns. Finally, boundaries were defined to most accurately represent the area tributary to specific modeled elements, such as constrictions caused by crossings.

Figure 3: HEC-HMS Subbasin Delineation Map

3.2.2   Loss Method

The Soil Conservation Service (SCS) Curve Number loss model uses the empirical CN parameter to calculate runoff volumes based on landscape characteristics such as soil type, land cover, imperviousness, and land use development. Areas characterized by saturated or poorly infiltrating soils, or impervious development, have higher CN values, converting a greater portion of rainfall volume into runoff. The SCS methodology uses the below equation to compute stormwater runoff volume for each time step:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

Where:

Q = runoff volume (in.)
P = precipitation (in.)
S = storage coefficient (in.)
I_a = initial abstractions (in.)

Rainfall abstractions due to ponding and evapotranspiration can be simulated using an initial abstractions (I_a) parameter. Greater discussion on how this variable was estimated and utilized in the model is discussed in Section 3.4 below.

Specific combinations of land use and soil type were linked to CN values using a lookup table, refer to Table 2, based on values recommended from Technical Report 55 (TR-55): Urban Hydrology for Small Watersheds (U.S. Department of Agriculture [USDA], 1986). Land use descriptions were taken from the 2001 National Land Cover Database and the Soil Survey Geographic Database (SSURGO) data was used for the soils. The CN matrix includes assumptions about the imperviousness of land use classes, and therefore, percent impervious does not need to be explicitly considered as the SCS runoff volume calculation.

Table 2: SCS Curve Number Values used in the HEC-HMS Model

Land Cover Description	Hydrologic Soil Group			
	A	B	C	D
Forest & Woodland	30	55	70	77
Shrubland & Grassland	39	61	74	80
Agricultural vegetation	67	78	85	89
Developed	77	85	90	92
Open Water	100	100	100	100

3.2.3   Transform Method

The runoff volume produced for a subbasin is converted into a basin-specific hydrograph by using a standard unit hydrograph and an estimate of basin time of concentration. The time of concentration is the time it takes for a drop of water to travel from the hydraulically furthest point in a watershed to the outlet. The time of concentration calculations were performed using the TR-55 method developed for GeoHMS. The lag time is what is entered into HEC-HMS. The standard lag is defined as the length of time between the centroid of precipitation mass and the peak flow of the resulting hydrograph. Generally, lag time is equal to 60 percent of the time of concentration. The time of concentration for subbasins varied from 0.1 to 2.19 hours. The calculated times of concentration were then modified, as needed, for calibration.

3.3   Meteorology

The Jacksonville District has extensive experience with doing hydrologic analysis on the island of Puerto Rico and is familiar with data sources that are available. LRC closely coordinated with SAJ to assure that the methodology used for this study were similar to those used on previous and ongoing studies and projects on the island so that analyses were consistent. Much of the described meteorology methodology, below, was taken from SAJ and modified so that it can be applied to the Rio Guayanilla watershed.

The frequency-based hypothetical design storms were developed using point precipitation from National Oceanic and Atmospheric Administration (NOAA) Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 3 Version 4.0. The following NOAA Atlas 14 rainfall depths, refer to Table 3, were taken at the centroid of the watershed and used in the hydrologic analysis.

Table 3: Precipitation Frequency Estimates at Watershed Centroid (NOAA Atlas 14)

	5-min	10-min	15-min	30-min	60-min	2-hr	3-hr	6-hr	12-hr	24-hr
1-Yr	0.6	0.8	1.1	1.7	2.6	3.1	3.2	3.5	3.7	4.4
2-yr	0.7	1	1.3	2	3	3.7	3.9	4.4	4.8	5.8
5-yr	0.8	1.1	1.4	2.3	3.4	4.3	4.7	5.6	6.6	8.2
10-yr	0.9	1.2	1.6	2.5	3.7	4.9	5.4	6.7	8.2	10.5
25-yr	1	1.4	1.8	2.8	4.2	5.7	6.4	8.3	10.7	14.1
50-yr	1.1	1.5	1.9	3.1	4.6	6.3	7.3	9.7	12.8	17.3
100-yr	1.2	1.6	2.1	3.4	5	7	8.2	11.1	15.2	20.8
200-yr	1.3	1.8	2.3	3.6	5.4	7.7	9.1	12.6	17.9	24.9
500-yr	1.4	2	2.5	4	6	8.6	10.4	14.8	21.8	31

The SCS temporal distributions, Figure 4, were standard synthetic rainfall distributions used throughout the United States and Puerto Rico, since their publication in Technical Paper 149 (TP-149) (SCS, 1973). Specifically, the SCS Type II distribution has historically been applied to Puerto Rico design storms (SCS, 1973). However, since the advent of Atlas 14 rainfall-frequency data, the National Resources Conservation Service (NRCS) specifically recommends not using SCS temporal distributions in conjunction with Atlas 14 rainfall data. Per section 630.0403 Temporal Distribution of Rainfall of Chapter 4 of the NRCS National Engineering Handbook:

> *"To use a Type II or other legacy rainfall distribution with the updated NOAA Atlas 14 data could introduce errors by application of inaccurate rainfall intensities during the storm."*

Therefore, the SCS method is not considered best practices and generally too conservative when applied to the Rio Guayanilla basin.
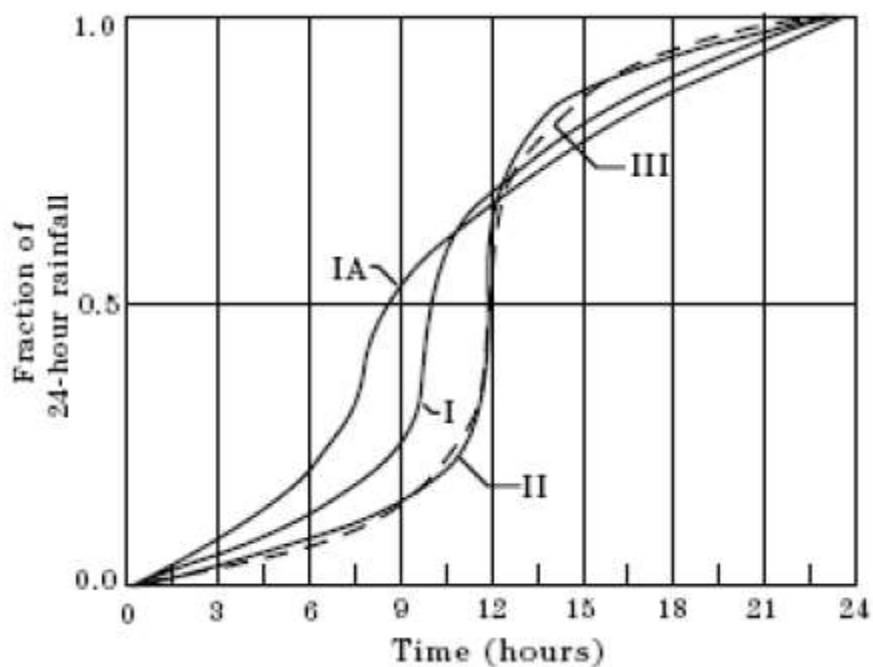
Figure 4: Plot of Types I, IA, II, and III synthetic rainfall distributions (SCS, 1973)

The NRCS Incremental Intensity with Smoothed Atlas 14 Data is explicitly described in Chapter 4 of the National Engineering Handbook (NRCS, 2015). The primary assumption of NRCS storm distributions is that the maximum precipitation of all storm durations from 5-minutes to 24-hours occurs within the same design storm, so that all precipitation intensities are represented in a single storm distribution. The process for creating the temporal distributions is explained below.

A total of ten durations (5-min, 10-min, 15-min, 30-min, 60-min, 2-hr, 3-hr, 6-hr, 12-hr, & 24-hr) for each return interval (1 & 500-year) were used to calculate a unique temporal distribution for each return interval. To create the entire suite of temporal distributions for all intervals, the centroid for the entire basin was used as a reference to extract the Atlas 14 data.

The relationship of intensity and duration is based on a factor defined as incremental intensity. Incremental intensity is defined as the difference in precipitation divided by the difference in duration. The incremental intensity for the 5-minute duration is equal to the 5-minute precipitation divided by 1/12 and has the units of inches per hour. The incremental intensity for the 10-minute duration is the 10-minute precipitation minus the 5-minute precipitation divided by 1/12 (the difference between 5 and 10 minutes in units of hours). Incremental intensity is calculated and smoothed for each return period independently. Plotting this relationship on a log-log scale, it may be a straight line, have slight curvature, or have several dips or waves. Using the Atlas 14 web tool (https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_pr.html), rainfall depths, shown in Table 3, for each duration and return interval were downloaded. This data is conveniently output in a comma-separated value format that can be easily imported into the NRCS WinTR-20 software. The WinTR-20 software program automatically calculates the incremental intensities as part of the import process.

The next step in processing the sequential rainfall durations was smoothing the data. The incremental intensities were smoothed by adjusting the Atlas 14 rainfall depths. Smoothing the data was necessary to limit any potential irregularities from the raw NOAA Atlas 14 data in the distribution such that any bumps, sharp rises or drops that might occur to the resulting hydrograph. The smoothing algorithm is built in to the NRCS WinTR-20 software program whereby the NOAA Atlas 14 non-smooth rainfall data is imported and smoothed automatically as part of the import process. Table 4 show the differences between the non-smooth vs. smooth data for the return intervals.

Table 4: Percent Difference between Smoothed vs Non-Smoothed Rainfall Depths

	5-min	10-min	15-min	30-min	60-min	2-hr	3-hr	6-hr	12-hr	24-hr
1-Yr	18%	-5%	-2%	-2%	0%	-4%	-12%	-13%	-14%	0%
2-yr	16%	0%	-2%	-1%	0%	-3%	-10%	-11%	-12%	0%
5-yr	18%	-2%	-7%	0%	0%	-4%	-10%	-11%	-9%	0%
10-yr	18%	-4%	-4%	-1%	0%	-1%	-9%	-9%	-8%	0%
25-yr	17%	-1%	-4%	-2%	0%	-1%	-8%	-8%	-6%	0%
50-yr	19%	-1%	-6%	0%	0%	-2%	-7%	-7%	-5%	0%
100-yr	18%	-4%	-6%	1%	0%	-1%	-6%	-6%	-3%	0%
200-yr	18%	-1%	-5%	-2%	0%	0%	-5%	-5%	-2%	0%
500-yr	17%	1%	-6%	-1%	0%	-2%	-5%	-5%	-1%	0%

After the data had been smoothed, the smoothed durations were input into a temporal distribution spreadsheet that built the final shapes of the temporal distributions for each return interval, Figure 5.
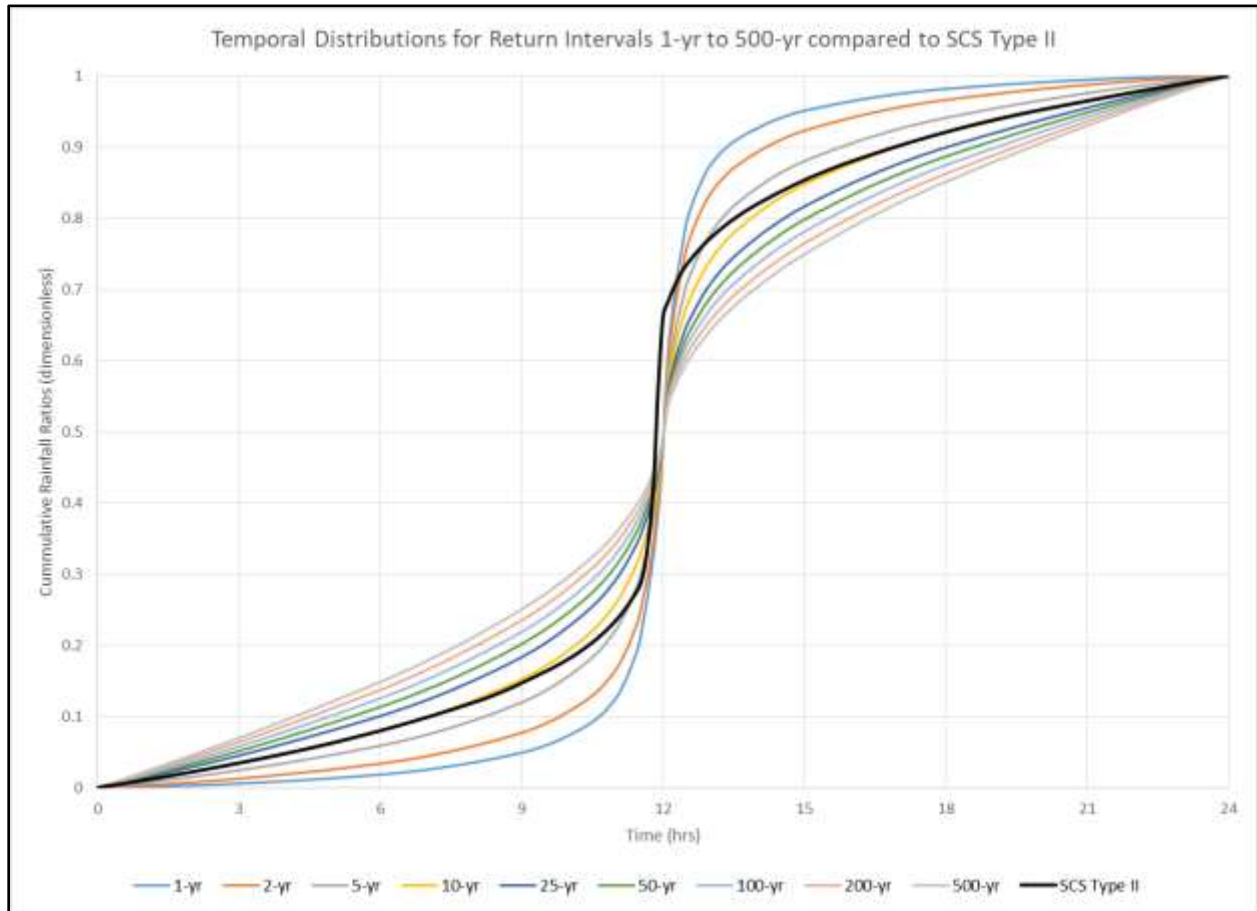
Figure 5: Final Temporal Distributions Developed for Design Storms vs. SCS Type II

As seen in Figure 5, the SCS Type II distribution, when plotted against the site specific NOAA Atlas 14 derived distributions, most closely resembles the 10-year return interval distribution. The design condition for the Rio Guayanilla recommneded plan is the 0.01 AEP. The SCS methodology for Puerto Rico is potentially too conservative, cost prohibitive relative to design, and not best practices when applying NOAA Atlas 14 rainfall depths to a distribution. Ultimately, the NRCS incremental intensity with smoothed NOAA Atlas 14 data methodology was selected as the temporal distribution.

NOAA Atlas 14 data is point-precipitation data. An underlying physical phenomenon with any rainfall event is that the rainfall is inversely proportional to the distance away from the center of the rainfall location, or point. The NOAA Atlas 14 study did not include an areal reduction analysis, nor was it part of the study scope. Therefore, the most recent areal reduction factor analysis will be applied to this study, TP-42 (NWS, 1961). Using the 24-hour curve and a basin area of 37 square miles, an areal reduction factor of 0.98 was applied to the rainfall depths, Figure 6. It was these depths that were then inputted into the HEC-HMS model.

FIGURE 3-13 —Depth-area curves for hurricane PMP for use with figures 3-6 to 3-11.
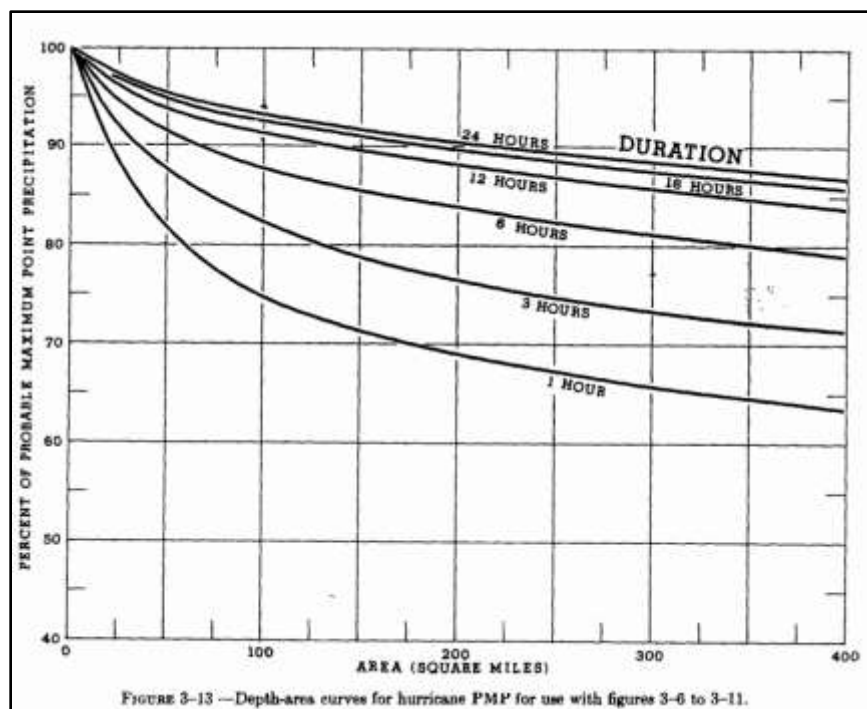
Figure 6: Depth-Area Curves Developed from TP-42

3.4   Model Calibration

Calibration is a critical activity in hydrologic modeling: in order for a model to be useful the modeler must be confident that the model is representing the rainfall-runoff response appropriately. The calibration procedure involves selecting a rainfall event, entering precipitation data into the model, and then comparing the computed hydrographs at one or more locations to measured discharges collected at existing river gages. Initial abstraction, baseflow and time of concentration values can be adjusted to cause the HEC-HMS model to produce hydrographs with similar shape, peak flow, and total runoff volume as measured data.

Calibration for the Rio Guayanilla watershed was difficult as precipitation data for the basin is not readily available. A review of the National Weather Service (NWS) rain gages was completed, however there were no gages in close proximity to the Rio Guayanilla watershed with the precipitation data available that would be required for calibration. The best available data, which was used for calibration, was hourly gridded precipitation data that SAJ obtained from NOAA Southeast River Forecast Center. SAJ had past experience with using this data, and while it was the only data available, SAJ cautioned that it is not always accurate; particularly in the northern part of the watershed which is very mountainous. In addition to the Next Generation Weather Radar (NEXRAD) data, there is one USGS stream gage (50124200) located about 0.5 mile upstream of the study area that has a long period of record.

After reviewing the NEXRAD data and performing sensitivity analysis on routing reaches, which had no effect to model results since the river is extremely flashy, lag times and curve numbers, there were two storm events from the model that compared fairly well to the precipitation data. These were the September 2008 event with a peak flow of 14,500 cfs and October 2010 event with a peak flow of 6,150 cfs. Refer to Figure 7 and Figure 8 below for actual versus simulated model comparison at the location of the USGS stream gage.
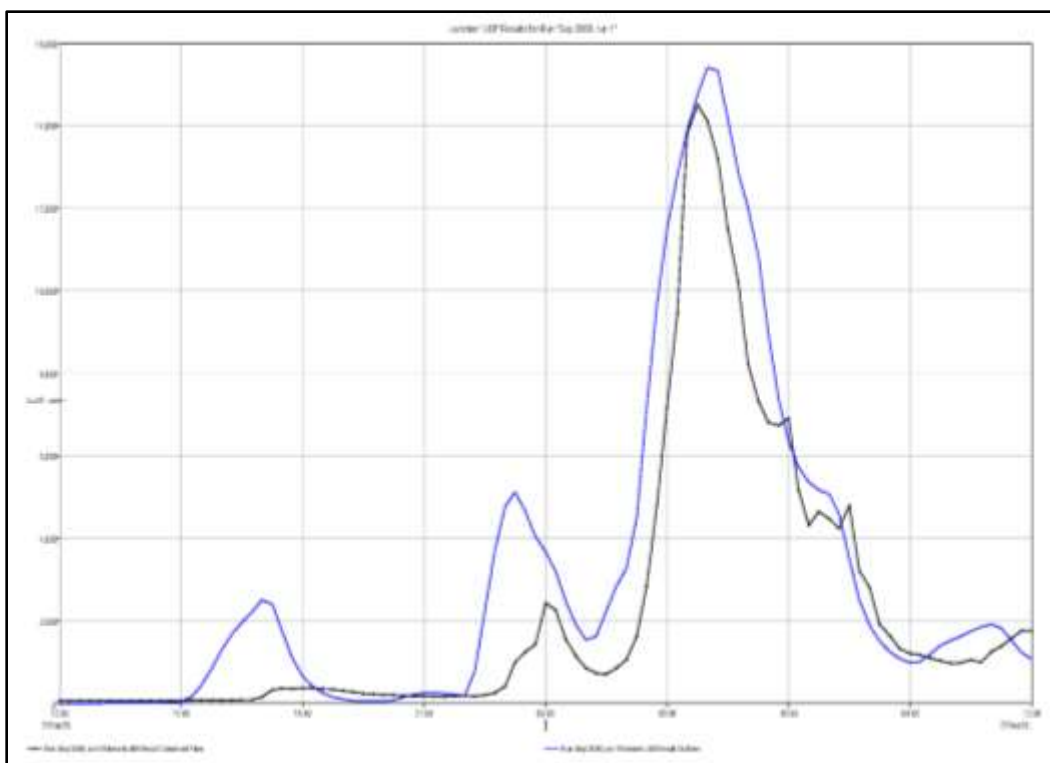
Figure 7: Simulated versus Observed Flow at USGS Stream Gage, September 2008
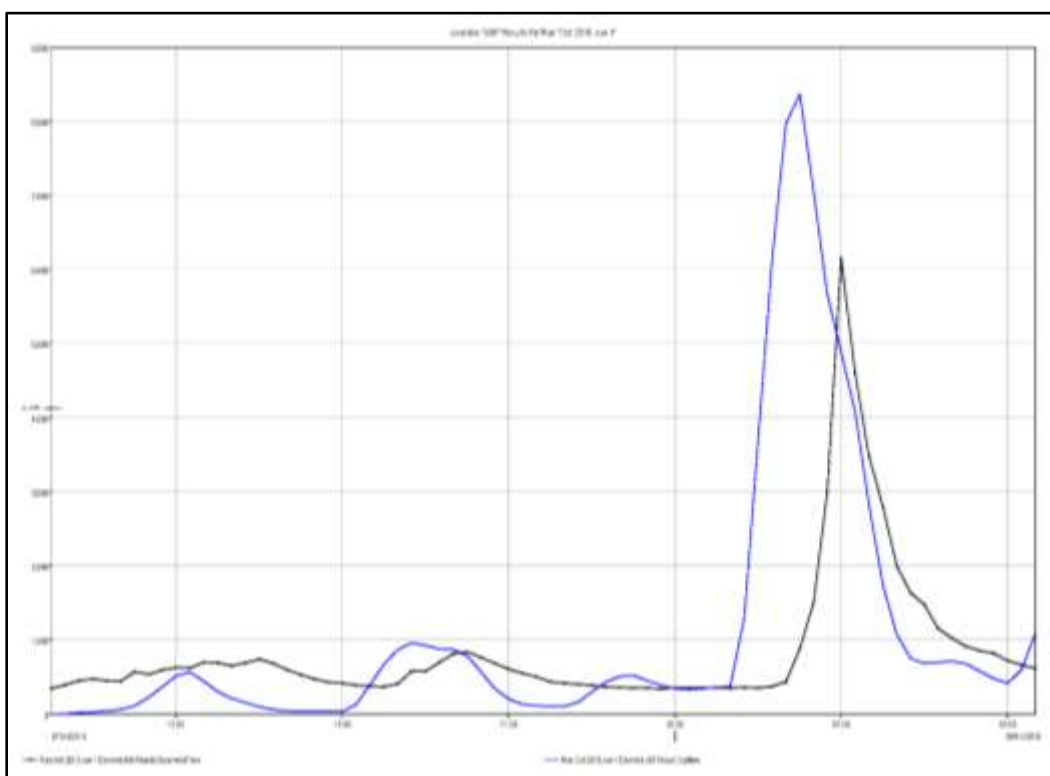
Figure 8: Simulated versus Observed Flow at USGS Stream Gage, October 2010

Once calibration of the above two events was complete, the synthetic design storms were computed in the HEC-HMS model. A Bulletin 17c gage analysis was completed for the Rio Guayanilla USGS stream gage. The regional skew and mean squared error (MSE) values used in this analysis were similar to those used in the 1990 Reconnaissance Report. After the initial model results of the design storms were compared to the Bulletin 17c analysis, it was determined that additional adjustments to the model were needed.

As stated above, parameters such as the routing reaches, lag time and curve number had minimal effect to model results. The only parameter that did have a significant effect on model results was the initial abstraction (I_a). Initial abstraction is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration (USDA, 1986). The commonly used default value of I_a, is estimated as 0.2S, where S is the storage coefficient for soil in the subbasin. S is related to the curve number (CN) through the following equation

$$S = \frac{1000}{CN} - 10$$
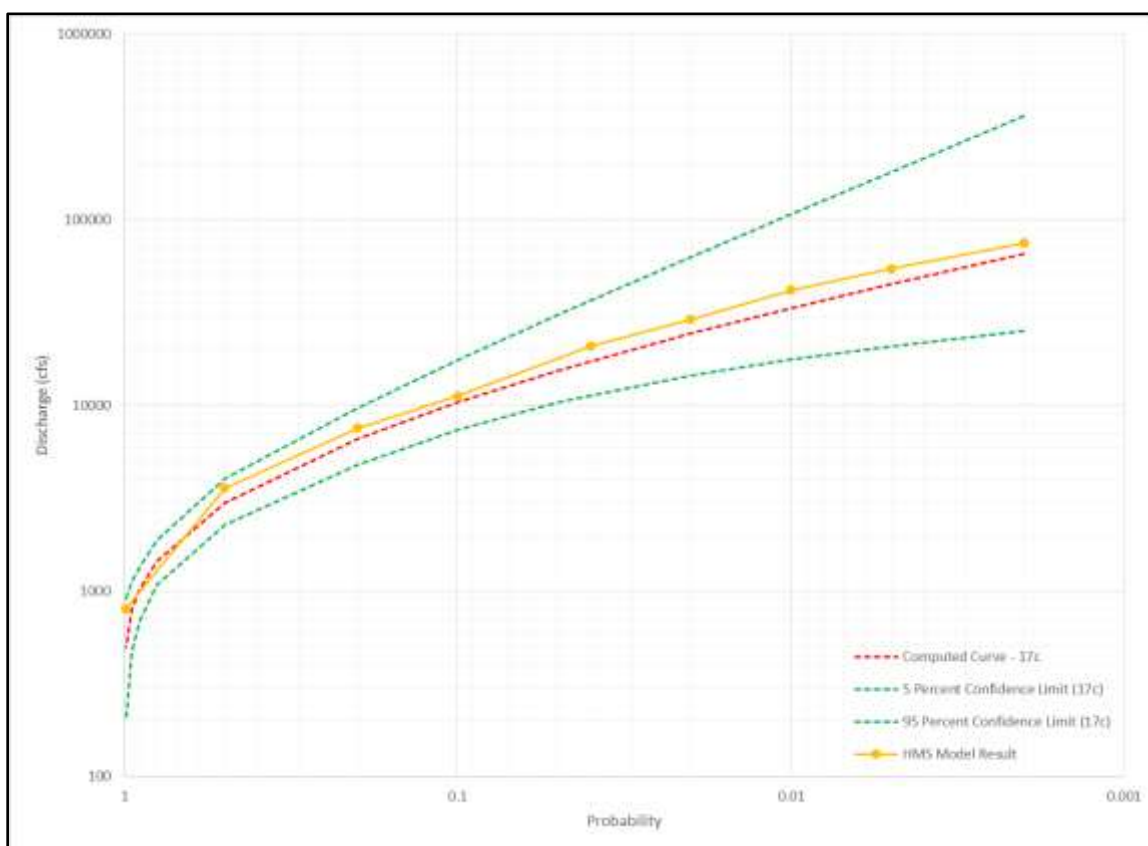
Where:
    CN = curve number (dimensionless)
    S = storage coefficient (in,)

Through an iterative process, the I_a was varied based on the design event until the computed discharge values (yellow line) were within the tolerances of the Bulletin 17c analysis, refer to Figure 9. The I_a values ranged from 5 to 9.

Figure 9: Comparison of Design Storms to Bulletin 17c Analysis

3.5   Model Results

After final calibration, Hydrologic Engineering Center Data Storage System (HEC-DSS) files for each design storm frequency were produced from the HEC-HMS model. These files were then used as the upstream boundary conditions for the Hydrologic Engineering Center River Analysis System (HEC-RAS) model discussed in Section 6.0.

4.0   Tides and Storm Surge

The National Oceanic and Atmospheric Agency (NOAA) operates a tide gage (Magueyes Island, PR Station ID 975911) approximately 18 miles west of the Rio Guayanilla outlet. This tide gage is the closest to the project, and had been operated since 1989. The tidal information can be found on the NOAA webpage at https://tidesandcurrents.noaa.gov/stationhome.html?id=9759110. Figure 10 below shows the tidal datums for the gage. Information specifically referenced in following sections of text is outlined in blue. Note that according to SAJ Coastal Design, Mean Sea Level (MSL) is equal to PRVD02. Based on their experience, conversions for other NOAA Puerto Rico tide gages have ranged from 0.00 – 0.02 feet differences (i.e. negligible). Figure 10 indicates a 0.05 foot difference at the Magueyes Island gage site.

Figure 10: Tidal Datums, 9759110 Magueyes Island, PR

Figure 11 displays the high and low annual exceedance probability levels in meters relative to the mean sea level datum. This figure is found on the above NOAA website under the tide/water levels tab. The plots show the monthly highest and lowest water levels with the 1%, 10%, 50%, and 99% annual

exceedance probability levels in red, orange, green, and blue. Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Lower Low Water (MLLW) and Mean Low Water (MLW) values are displayed in black. The MHHW/MHW and MLLW/MLW values in Figure 11 are consistent with the values reported in Figure 10 (0.10 m = 0.33 ft). On the left are the exceedance probability levels for the mid-year of the tidal epoch currently in effect for the station (consistent with the values in Figure 10). On the right are projected exceedance probability levels and tidal datums for 2018 assuming continuation of the linear historic trend.
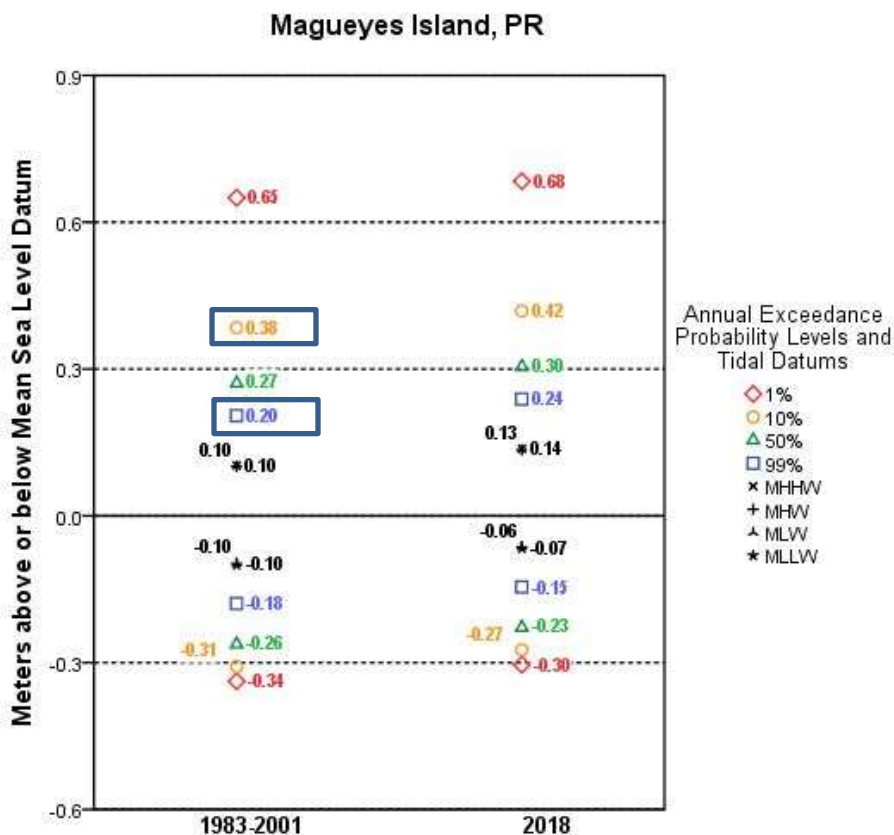
Figure 11: Exceedance Probability Levels and Tidal Datums: 9759110 Magueyes Island, PR

Based on discussions with SAJ staff, with experience working on the island, rather than use the Mean High Water (MHW) or MSL, a return period stage was used due to the fact that the fluvial peak flows are correlated with tropical events which would have higher surges than normal maximum astronomical tides. Using the data in Figure 11 (outlined in blue), for the more frequent storm events (99% - 10% AEP) the 1-year return period stage was used, 0.66 feet (0.20 m). For the less frequent events (4% - 0.2% AEP) the 10-year return period stage was used, 1.25 feet (0.38 m).

The downstream boundary condition adopted within the HEC-RAS model (refer to Sections 6.2.3 and 6.4) to assess sea level change impacts is adopted as 4.66 feet for 99-10% AEP events and 5.25 feet for 4%-0.2% AEP events to represent the 1-yr and 10-yr NOAA coastal Water Levels, respectively plus 4 feet of sea level rise. The boundary conditions and sources are summarized in Table 5.

Table 5: Summary of Boundary Conditions and Sources

NOAA Coastal Water Levels (refer to Figure 11), stage in feet converted from meters			
2-yr	0.66		
10-yr	1.25		
Project Sea Level Rise (SLR) **USACE Sea Level Change Calculator (Figure 17), feet**			
	Low	High	Adopted
2070	0.345	2.601	4.0
2120	0.567	6.641	
Future Condition with Sea Level Rise **Stage (ft) + SLR (ft)**			
50%-10% AEP Events	4.66		
4%-0.2% AEP Events	5.25		

Historically, the study area of the town of Guayanilla has never been flooded by hurricane or storm tides, although heavy wave action has occurred during the passage of some storms. Very high storm tides may cause disastrous flooding in the low-lying coastal areas, specifically in the Playa de Guayanilla and El Faro sectors.

This is demonstrated by the National Storm Surge Maps (https://www.nhc.noaa.gov/nationalsurge/) depicted below in Figure 12 and Figure 13. Recall that the outlet for the recommended plan is immediately downstream of PR-3336. In addition, based on local expert's (USACE SAJ, USGS, Guayanilla staff) knowledge of the area, the peak discharge due to riverine flooding and the high tides due to a storm surge do not occur at the same time. The high storm tides have always occurred prior to the peak of the riverine flooding, which is not reflected in the figures below. Additional discussion regarding future impacts to sea level rise based on climate change are discussed in Section 5.3.
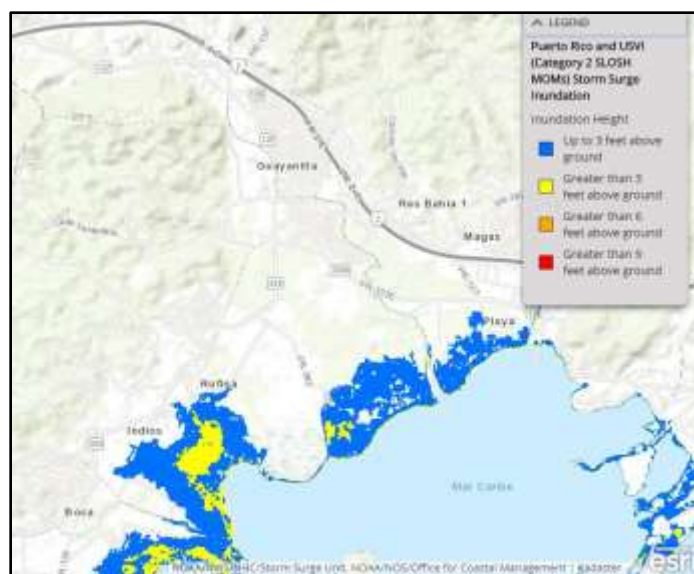
Figure 12: Potential Storm Surge Vulnerability for USVI Category 2 storm
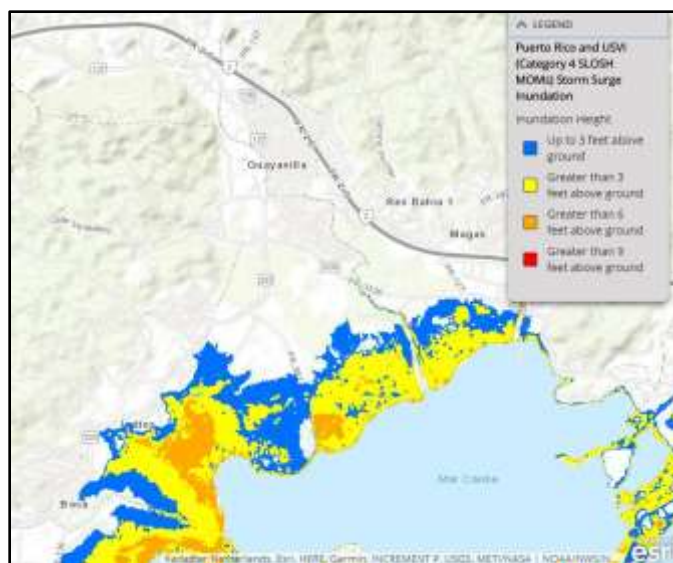
Figure 13: Potential Storm Surge Vulnerability for USVI Category 4 storm

5.0   Climate Change and Sea Level Rise

5.1   Literature Review

The USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available — and actionable — climate science. As part of this effort, the USACE has developed concise reports summarizing observed and projected climate and hydrological patterns, at a hydrologic unit code (HUC2) watershed scale. The information cited in these reports comes from reputable, peer-reviewed literature and authoritative national and regional reports. Trends are characterized in terms of climate threats to USACE business lines. The reports also provide context and linkage to other agency resources for climate resilience planning, such as downscaled climate data for sub-regions, and watershed vulnerability assessment tools.

The USACE literature review report focused on the Caribbean Region was finalized in June 2015 (USACE, 2015). Figure 14, portrays the 4th National Climate Assessment's (NCA) reported summary of the observed change in very heavy precipitation for the U.S., defined as the amount of precipitation falling during the heaviest 1% of all daily events. The 4th NCA results indicate that -12% more precipitation is falling in Puerto Rico now as compared with the first half of the 20th century, and that the precipitation is concentrated in larger events.
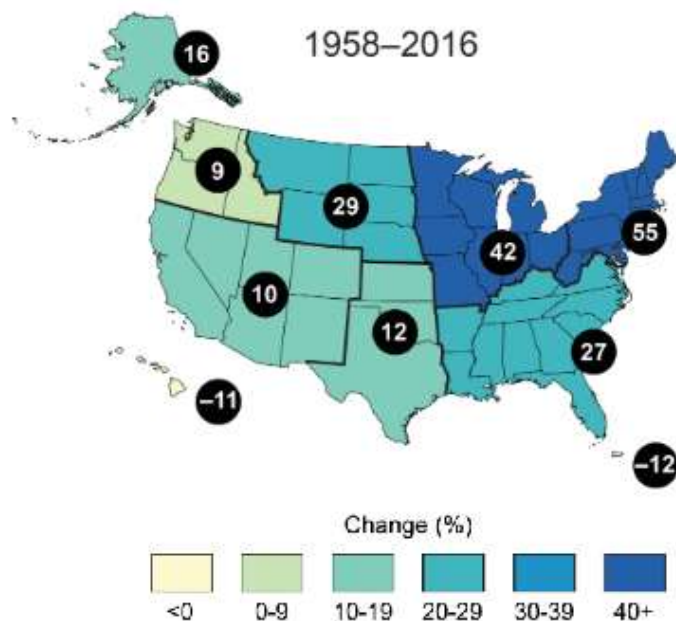
Figure 14: Percent changes in precipitation falling in the heaviest 1% of events from 1958 to 2016 for each region (Easterling et al., 2017).

The USACE literature review document summarizes several studies which have attempted to project future changes in hydrometeorology. There is strong consensus in the literature that air temperature will increase in the study area, and through the country, over the next century (USACE, 2015). However, there is no clear trend with regards to precipitation in the Caribbean Region. Regionally within the island of Puerto Rico, there are indications that the southern region of Puerto Rico has experiences positive trends in annual rainfall while the western and a portion of the northern region showed decreases (USACE, 2015). Figure 15, taken from the USACE Climate Change and Hydrology Literature Reviews, summarizes observed and projected trends for various variables reviewed.

For the Caribbean Region, increase in temperatures have been observed and additional increases in temperature are predicted for the future. For the region, "the general consensus points toward mild increases in annual and monthly average temperatures over the past century. There is further indication that some locations in Puerto Rico are warming faster than others due to urban heat island effect."

There is limited information with regards to the effects of climate change on streamflow trends and hydrologic conditions within the Caribbean Region. There is no clear consensus on projected streamflow trends in the Caribbean Region, "with some studies projecting a reduction in future, while others project a potential increase."
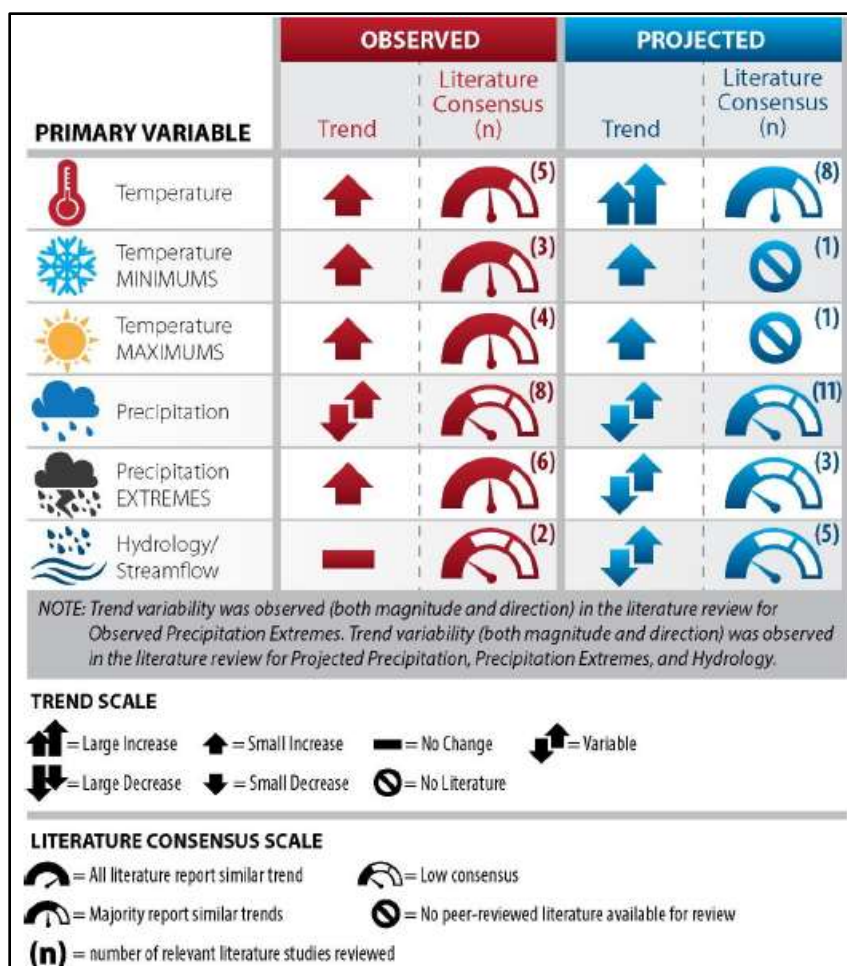
Figure 15: Caribbean Region - Summary matrix of observed and projected climate trends and literary consensus. (USACE, 2015)

Similar to the USACE report, the Puerto Rico Climate Change Council (PRCCC) prepared a report in 2013 titled Puerto Rico's State of the Climate 2010-2013: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. Similar conclusions were drawn from the PRCCC study, surface temperatures are increasing, observed trends in precipitation are unclear and sea levels are increasing for the island. The Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Extremes states that it is *very likely* that mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future. There is *high confidence* that locations currently experiencing adverse impacts, such as coastal erosion and inundation, will continue to do so in the future, due to increasing sea levels, all other contributing factors being equal.

5.2 Project Area Specific Meteorological Trends
5.2.1 Temperature Trends
As stated in the Literature Review section, several studies indicate that increases in temperatures have been observed and additional increases in temperature are predicted for the future. The 2013 Puerto Rico's State of the Climate 2010-2013: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate prepared by the PRCCC discusses these increasing trends as summarized in the subsequent paragraph.

In Puerto Rico, station analyses show significant increases in annual and monthly average temperatures and a rise of 0.012°C/yr to 0.014°C/yr (0.022 to 0.025°F/yr) was observed from 1900 to present. Therefore, Puerto Rico does follow the larger-scale trend in warming, although some locations on the island are warming faster than others. Urban heat islands exist in Puerto Rico where temperatures are higher in developed areas than in rural, vegetated areas. There is consensus on continued warming into the future amongst all modeling experiments. Over the coming century, projected temperature increases for the Caribbean are projected to be slightly below the global average of 2.5 - 4°C (4.5 – 7.2°F) by 2100, but slightly above the tropical average. Projected temperature increases are expected to be significant by late century at all locations. Projections for Puerto Rico show as little as 0.02°C/year warming through 2050, in other words at least 0.8 °C (1.44°F) by mid-century, and as much as 2-5°C (3.6-9°F) by the year 2100 (PRCCC, 2013).

5.2.2   *Precipitation Trends*
The 2013 PRCCC report also summarizes precipitation trends for the island. While no clear trend exists for the entire island, there is evidence for changes in the spatial distribution of rainfall. Although there are mixed trends in annual precipitation, there was an indication that the southern region of Puerto Rico, which is also the driest region, had positive trends in annual rainfall while the western and a portion of the northern region showed decreases, refer to Figure 16 (Mendez, 2010).

The 2013 PRCCC report states that for one analysis of weather station data in Puerto Rico for the period 1948 to 2007 found no clear trends in total annual rainfall for the island as a whole, while another analysis showed decreases in rainfall from -0.01 to -0.1 mm/day/yr. Regionally within the island, there are indications that the southern region of Puerto Rico has experienced positive trends in annual rainfall while the western and a portion of the northern region showed decreases. Additionally, seasonal trends with observed showing negative trends in summer and positive trends in winter. In order to simulate future climate change, global climate models need to accurately represent observed climate. There is a lot of uncertainty in the magnitude of precipitation changes in the Caribbean, though a majority of GCMs used in the IPCC fourth assessment report show future decreases in precipitation are likely. Model projections range from -78 to -10% (with a few GCMs showing +30%) and current evidence suggests drier conditions are more likely than wetter for Puerto Rico, a contrast to the global precipitation signal. Specifically the PRCCC analysis found that past and future trends are similar, a decrease of rainfall of -0.0012 to -0.0032 mm/day /yr, that are projected to continue through 2050 (PRCCC, 2013).
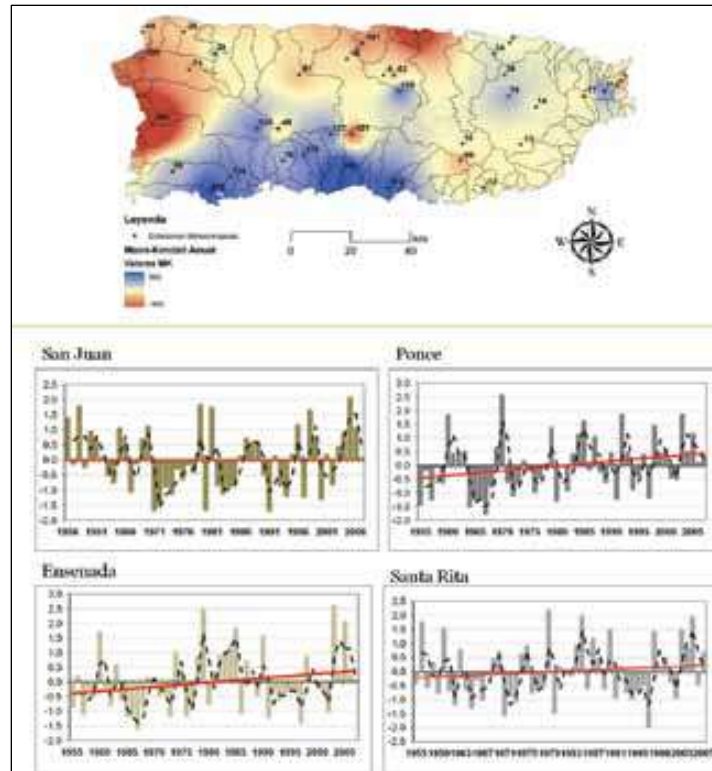
Figure 16: Precipitation Trends for Puerto Rico (Mendez, 2010)

5.3   Sea Level Rise

Relative Sea Level Change (RSLC) is an important variable in flood risk management projects because sea level change can potentially affect the project and system performance. Therefore, projects need to consider how sensitive and adaptable engineered systems are sea level change.

ER 1100-2-8162 requires that planning studies and engineering designs over the project life cycle, for both existing and proposed conditions, consider a range of possible future rates of SLC when formulating and evaluating alternatives. This includes both structural and non-structural solutions.

This study uses current USACE guidance to assess relative sea level change. Current USACE guidance (ER 1100-2-8162 and ETL 1100-2-1) specifies the procedures for incorporating RSLC into planning studies and engineering design projects. Projects must consider alternatives that formulated and evaluated for the entire range of possible rates of RSLC for both existing and proposed projects. USACE guidance specifies evaluating alternatives using "low, "intermediate", and "high" rates of future sea level change, refer to Figure 17.

- Low: Uses the historic rate of local mean sea-level change
- Intermediate: Estimate the "intermediate" rate of local mean sea-level change using the modified NRC Curve I. It is corrected for the local rate of vertical land movement.
- High: Estimate the "high" rate of local mean sea-level change using the modified NRC Curve III. It is corrected for the local rate of vertical land movement.
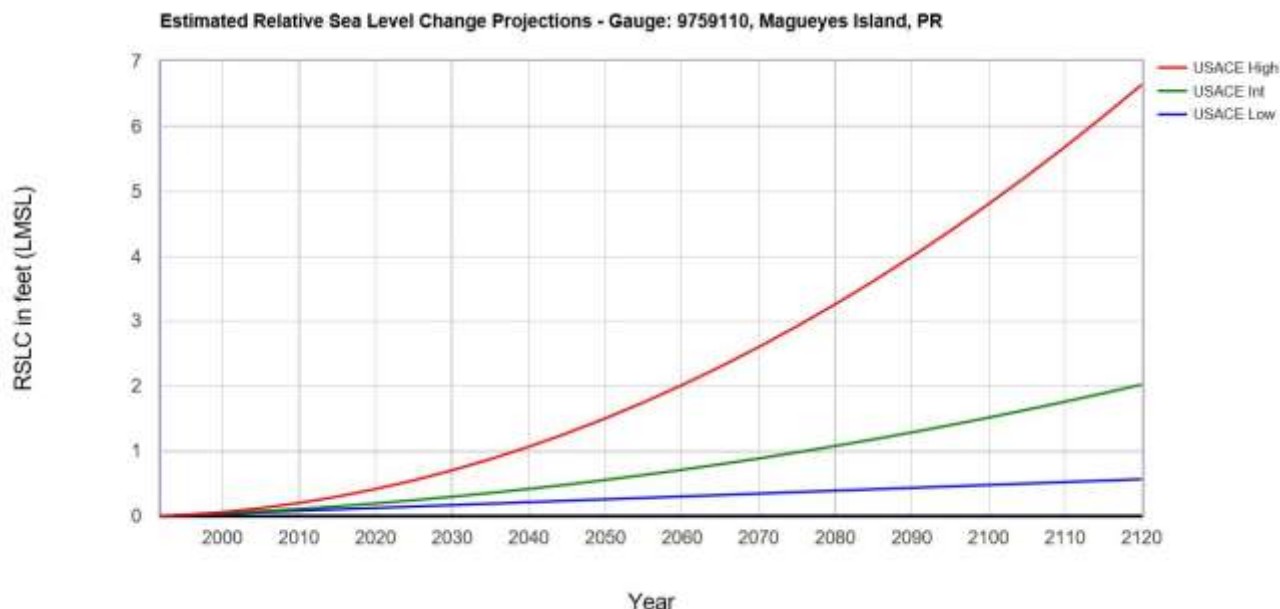
Figure 17: USACE Sea Level Change Curve Calculator, Magueyes Island, Puerto Rico

USACE (ETL 1100-2-1, 2014) recommends an expansive approach to considering and incorporating RSLC into civil works projects. It is important to understand the difference between the period of analysis (POA) and planning horizon. Initially, USACE projects are justified over a period of analysis, typically 50 years. However, USACE projects can remain in service much longer than the POA. The climate for which the project was designed can change over the full lifetime of a project to the extent that stability, maintenance, and operations may be impacted, possibly with serious consequences, but also potentially with beneficial consequences. Given these factors, the project planning horizon (not to be confused with the economic period of analysis) should be 100 years, consistent with ER 1110-2-8159. Current guidance considers both short- and long-term planning horizons and helps to better quantify RSLC.

Using the USACE Sea Level Change Calculator, Figure 17 shows that for a 50 year POA with sea level rise estimates ranging from 0.345 to 2.601 feet above relative mean sea level by the year 2070. For year 2120, the estimates range from 0.567 to 6.641 feet above relative mean sea level. To conservatively estimate the impacts of sea level rise on the study area for both the 100-year planning horizon and 50-year period of economic analysis sea level rise is assumed to be 4 feet by 2120. This value is what is used as a downstream boundary condition within HEC-RAS to assess sea level change impacts. Further discussion regarding how sea level change was accounted for in the design is provided in Section 6.4.

The Sea Level Tracker visualizes historical, observed changes in mean sea level (MSL) as measured and reported by National Oceanic Atmospheric Administration (NOAA) tide gauges, mapped against the USACE sea level change (SLC) projections. The tool enables the comparison of actual SLC with USACE SLC projections (as described in ER 1100-2-8162), along with observed monthly water levels and trends based on historical data. Figure 18, provides the output of the Sea Level Tracker tool for the Magueyes Island, PR gage.
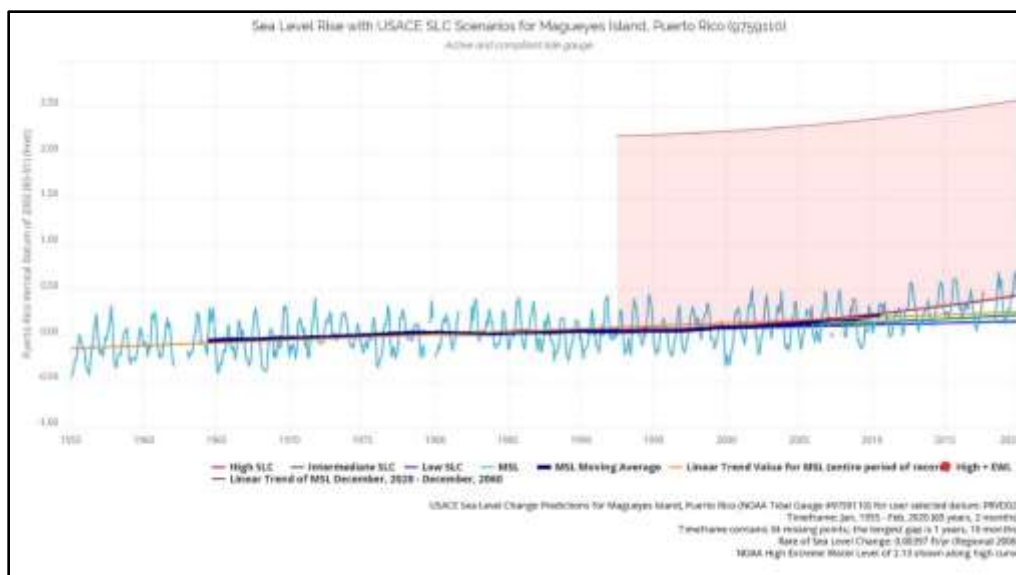
Figure 18: USACE Sea Level Tracker Tool, Magueyes Island, Puerto Rico

5.4   Inland Hydrology Climate Change

USACE Engineering and Construction Bulletin (ECB) 2018-14 (*Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects*), "provides guidance for incorporating climate change information in hydrologic analyses in accordance with the USACE overarching climate change adaptation policy. This policy requires consideration of climate change in all current and future studies to reduce vulnerabilities and enhance the resilience of our water resources infrastructure." The document "helps support a qualitative assessment of potential climate change threats and impacts" related to USACE analyses. The subsequent sections discuss the various tools that were developed by the USACE Climate Preparedness and Resiliency Community of Practice (CPR CoP), to meet the qualitative assessment requirements set forth in ECB 2018-14.

The objective of the proposed project is to reduce flood risk within the Rio Guayanilla floodplain in Guayanilla, Puerto Rico. Three flood risk reduction management alternatives were considered. The proposed plan consists of a diversion channel with single line protection (Alternative 3), support by non-structural measures (Alternative 1). Major project features include a diversion channel and surrounding levees. Nonstructural measures include a plan for clearing debris and a flood warning system. Because the objective of the project is flood risk management it is appropriate to carry out a first order statistical analysis using annual maximum peak flow to assess the potential impacts of climate change on the study area's hydrology.

There is one stream gaging station, 50124200, within the watershed that has been operated continually by the United States Geological Survey (USGS) on the Rio Guayanilla. The gage has a period of record from March 1981 to present day for stream discharge. The drainage area to the gage is approximately 18.9 square miles. Per the USGS, the gage datum converted to PRVD02 is +66.082. The gage is not impacted by regulation within the watershed. The gage is located where the Rio Guayanilla transitions from a mountainous river to a meandering ephemeral stream.

5.4.1   Nonstationary Detection Tool

Stationarity, or the assumption that the statistical characteristics of hydrologic time series data are constant through time, enables the use of well-accepted statistical methods in water resources planning and design in which the definition of future conditions relies primarily on the observed record, per

USACE guidance ETL 1100-2-3. However, recent scientific evidence shows that in some locations climate change and human modifications of watersheds are undermining this fundamental assumption, resulting in nonstationarity (Milly et al., 2008, Friedman, et. al, 2016). Using the web-based Nonstationary Detection Tool, USGS Gage 50124200 has a period of record of 30 years or more was investigated for nonstationarities. There are no nonstationarities or statistically significant monotonic trends detected in the peak streamflow record observed along Rio Guayanilla, refer to Figure 19 and Figure 20 below.
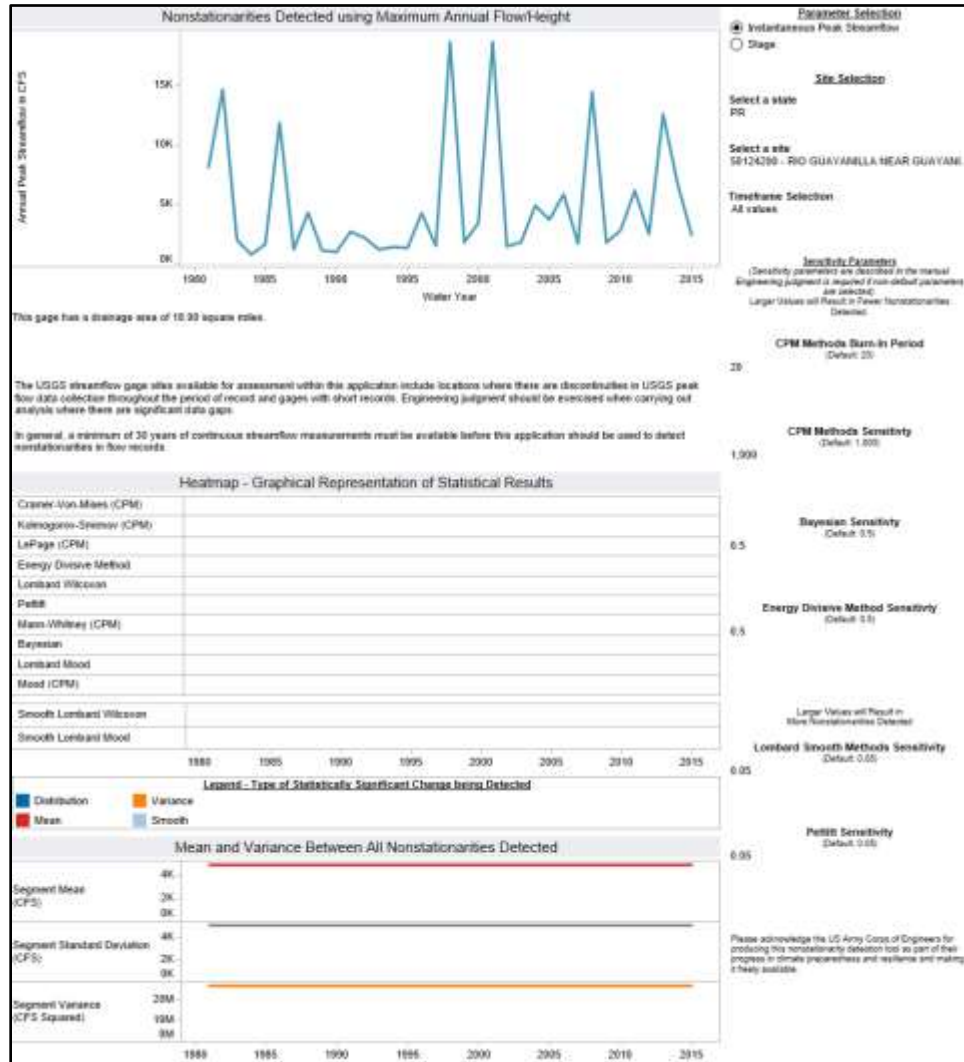
Figure 19: Nonstationarity Analysis, Rio Guayanilla at Guayanilla, Puerto Rico
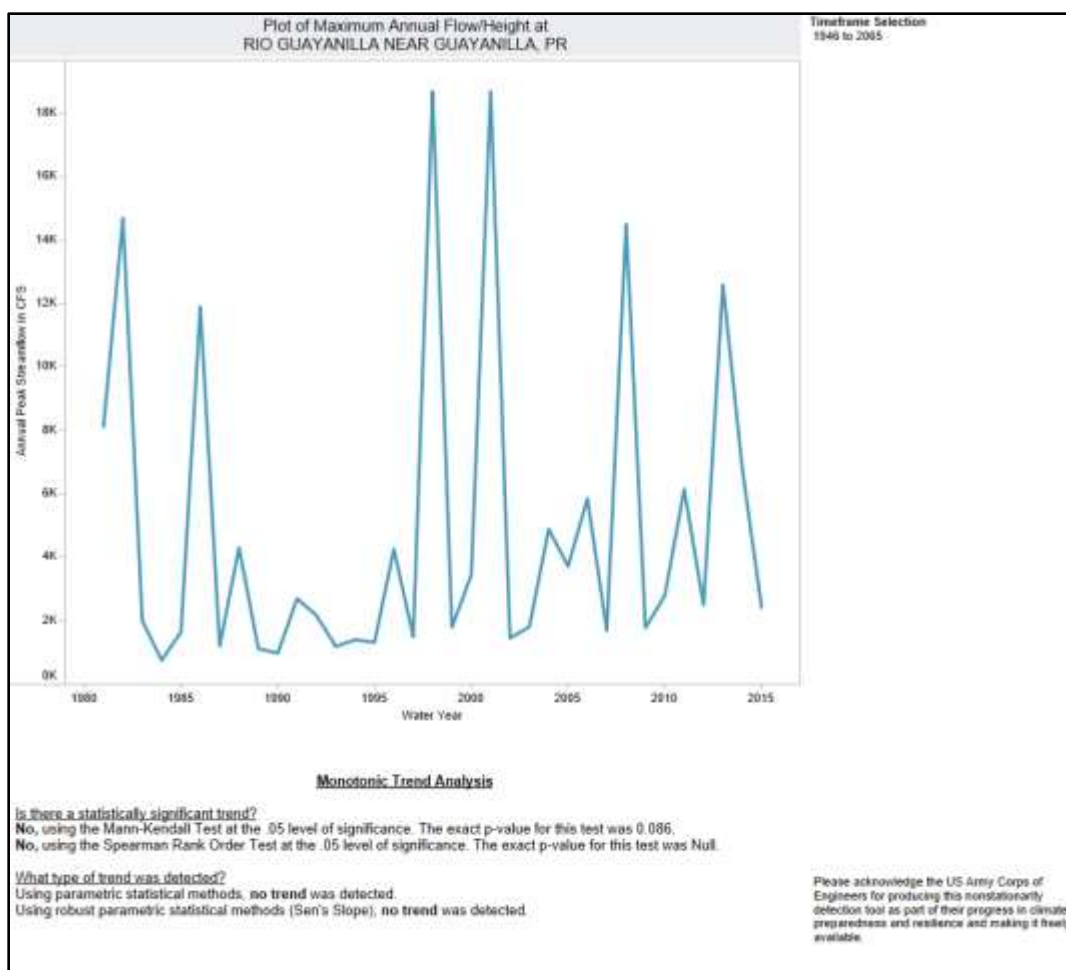
Figure 20: Trend Analysis for Rio Guayanilla at Guayanilla, Puerto Rico

5.4.2 Linear Trend Analysis

As required by ECB No. 2018-214, an investigation of the trends in the annual maximum flow gage data could not be performed using the USACE Climate Hydrology Assessment Tool, because the study is not located in one of the HUC-4 watersheds included in the tool. However, Figure 21 below shows the observed, annual instantaneous peak streamflow using the Time Series Toolbox with information obtained from the USGS website for the one gage (50124200). This gage is within the watershed and has a period of record greater than 30 years. Per the Time Series Toolbox, a statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test, nor was a statistically significant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.
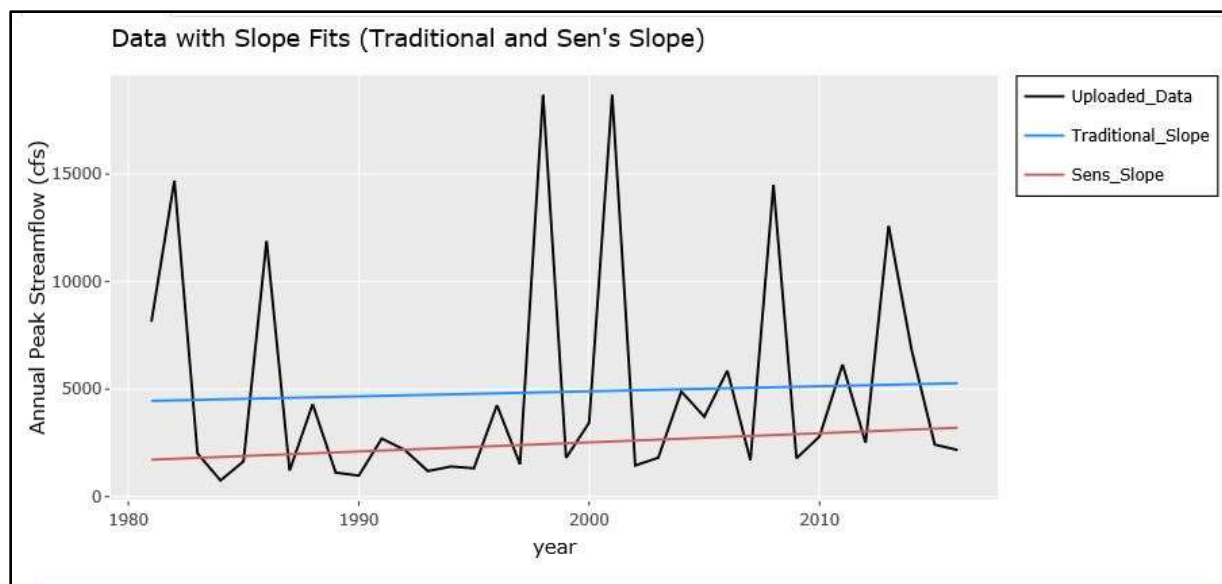
Figure 21: Annual Peak Streamflow, USGS 50124200 Rio Guayanilla near Guayanilla, PR

5.4.3   Vulnerability Assessment Tool

The USACE Vulnerability Assessment Tool was not applied, because the study is not located in the HUC-4 watersheds included in the tool.

5.5   Summary

Based on the literature review it is reasonable to conclude that temperatures are increasing in the study area, and will continue to increase within the foreseeable future. The literature review does not provide definitive evidence of increasing trends in either observed or projected, precipitation and streamflow records within the region. The first order statistical analysis conducted using observed, annual peak streamflow data collected within the study area does not indicate any statistically significant trends or nonstationarities in the dataset. This supports the findings presented in the literature review. Consequently, there is not a lot of concrete evidence that flood risk will increase due to climate change in the foreseeable future. For these reasons it is appropriate to assess the impacts of climate change on inland hydrology qualitatively throughout the plan formulation process.

Table 6 summarizes residual risk due to climate associated with the recommended plan. The quantitative assessment of the impact of climate change on the study area's inland hydrology implies a very low likelihood of either precipitation or streamflow impacting project performance over the 100-year planning horizon. Similarly, because project features are outside the area impacted by tidal influence even when sea level rise is accounted for it is unlikely that rising sea levels will impact project performance over the next 100-years. Based on this assessment, the recommendation is to treat the potential effects of climate change as occurring within the uncertainty range calculated for the current hydrologic and hydraulic analyses.

Table 6. Climate Risk Register

Feature or Measure	Trigger	Hazard	Consequence	Qualitative Likelihood
Levee Heights	Increased water levels in the floodplain from storm events due to sea level rise	Reduced assurance on levee/floodwalls; increased probability of overtopping	Flooding of protected area, economic damages and transportation delays	Unlikely – Peak elevations remain the same regardless of SLC
Levee Heights	Increased water surface elevations in levee/floodwall areas due to higher intensity rainfall	Reduced assurance on levee/floodwalls; increased probability of overtopping	Flooding of protected area, economic damages and transportation delays	Unlikely – observed trends in precipitation are unclear
Diversion Channel	Increased water surface elevations in the diversion channel due to sea level rise	Reduced assurance of channel containment; increase probability of overbank flooding	Flooding of protected area, economic damages and transportation delays reduction effectiveness.	Unlikely – Peak elevations remain the same regardless of SLC
Diversion Channel	Increased water surface elevations in the diversion channel due to higher intensity rainfall	Reduced assurance of channel containment; increase probability of overbank flooding	Flooding of protected area, economic damages and transportation delays reduction effectiveness.	Unlikely – observed trends in precipitation are unclear

6.0   Hydraulics

6.1   Model Development

The hydraulic analysis was completed using an unsteady 2D HEC-RAS model. The model extents include the lower Rio Guayanilla, from upstream of highway PR-2 though the confluence with the Caribbean Sea. The HEC-RAS model was developed in an iterative process.

Early on in the study planning process, the Project Development Team (PDT) made the risk-informed decision to move forward with development of the hydraulic model prior to obtaining any survey data. Therefore, the without- and with-project conditions were first developed in January 2019 using the light detection and ranging (LIDAR) data described in Section 3.1. Existing bridge data was also obtained from the Puerto Rico Department of Transportation and Public Works (PRDTPW) with assistance from SAJ staff. This was done so that screening of alternatives could be completed and so preliminary civil design, cost and economic analysis could also be completed. By accepting this documented risk the TSP milestone was completed three months ahead of schedule.

Once survey data was obtained in late April 2019, both the without- and with-project conditions were updated to incorporate surveyed cross sections, bridge data and other necessary model refinements that were needed, including slightly extending the upstream and downstream extents and modify 2D overflow areas. Initial review of the survey data compared to LIDAR data showed that very minimal model geometry changes to the existing channel would be required. Further discussion of the development of

the hydraulic model and associated parameters are included in following sections. Model schematics for the without- and with-project scenarios can be found on Plates A-1 through A-3.

6.2   Model Parameters

The hydraulic model requires three categories of input data: physical characteristics of the stream, discharge data, and boundary conditions. The physical characteristics include the geometry of cross sections and structures, reach lengths, and surface roughness. The discharge data used in this study were peak flows computed in HEC-HMS at various locations in the watershed for the eight synthetic storms discussed in Section 3.0. The physical characteristics and boundary conditions are described further in the following paragraphs.

6.2.1   Cross Section Geometry

As described above, cross section geometry data and reach lengths were obtained from field surveys and LIDAR data for the watershed. In general, detailed survey data, obtained in 2019, defined the channel geometry. The LIDAR was used in the 2D overbank areas and associated lateral structure connections to these areas. Interpolated cross sections were generated between surveyed cross sections in HEC-RAS using the XS Interpolation tool. Bridge data was first obtain from the PRDTPW and then updated based on the 2019 survey data.

6.2.2   Channel Roughness

Channel roughness, represented by Manning's n, was generally determined using data from previous reports, observations during site investigations, and aerial photography. The values, in general, are consistent with those referenced in Open-Channel Hydraulics (Chow, 1959). Table 7 summarizes the range of Manning's n values used in the hydraulic modeling.

Table 7: Range of Manning's n Values in Hydraulic Models

River Name	Channel "n"	Overbank "n"
Existing Channel	0.045-0.065	0.1
Alt 3- Existing Channel	0.03-0.065	0.1
Alt 3- Diversion Channel	0.013	0.05
Alt 6- Existing Channel	0.03-0.065	0.1
Alt 6- Diversion Channel	0.03-0.035	0.05

6.2.3   Boundary Conditions

The downstream boundary condition for Rio Guayanilla used a stage hydrograph, based on tidal conditions at the closet NOAA tide gage: Magueyes Island, PR Station ID 975911. Rather than use the Mean High Water (MHW) or mean sea level a return period stage was used, refer to Figure 11. In discussion with SAJ staff on what was typically seen in this area, for the more frequent storm events (99% - 10% AEP) the 1-year return period stage was used, 0.66 feet (0.20 m), due to the fact that the fluvial peak flows are correlated with tropical events which would have higher surges than normal maximum astronomical tides.   For the less frequent events (4% - 0.2% AEP) the 10-year return period stage was used, 1.25 feet (0.38 m). Additional discussion regarding tide datum is provided in Section 4.0. The upstream flow hydrographs and additional uniform lateral and lateral inflow hydrographs were taken from the HEC-HMS model at their respective locations. The minimum flow were defined flows, typically calculated as 5% of the peak flow.

6.3   With-Project Conditions

As stated previously, the hydraulic model was completed in an iterative process. After the hydraulic modeling was completed in early 2019, based on the LIDAR data, an economics analysis was completed.

Based on the initial results from the economic analysis, the recommended plan, Alternative 3, had slightly higher net benefits than Alternative 6. However, both were carried forward to TSP and are included in the documentation. Additional discussion regarding the alternatives can be found in the main report and summarized below in Section 7.0. Once the surveyed data was obtained, both alternatives in the hydraulic model were updated as well as the economic analysis.

6.4 Future Without- and With-Project Conditions
Consistent with Engineering Regulation (ER) 1100-2-8162, sea level rise was incorporated into the downstream boundary condition. For the more frequent events (50% - 10% AEP) a stage of 4.66 feet was used. For the less frequent events (4% - 0.2% AEP) a stage of 5.25 feet was used. Further discussion of these elevations are provided in Section 4.0. This represents a high rate estimate somewhere between the 50-yr period of analysis and 100-year period of analysis and is a fairly conservative estimate. This was used as the downstream boundary condition in all future without- and with-project conditions model runs.

Even with this conservative assumption, the increased water surface elevation has no impact on the recommended plan since it is outside of tidal influence. Plate B-5, included in this Appendix, depicts the profile plots of the lower portion of the Rio Guayanilla which outlets into the Caribbean Sea. The profiles shown are the 20% AEP and 2% AEP for the existing and future with-project conditions. The future with-project conditions profile indicates that sea level rise will not place the levee project endanger of overtopping even at the downstream most extents of the project. The El Faro levee project feature is directly adjacent to the Caribbean Sea. This project feature is not directly adjacent to the Rio Guayanilla River. This feature is located slightly southeast of the River's confluence with the Caribbean Sea (see Figure 22). Plate B-6 demonstrates that sea level rise will not place the El Faro Levee feature endanger of overtopping. The 0.02 AEP comes close to the top of levee at the most downstream end, however this is for the most extreme (high) sea level change estimate. In addition, the levee height and width can be adapted for future conditions. Therefore, additional analysis with regards to incorporating sea level rise was not completed. This can be reassessed during the Planning, Engineering and Design (PED) Phase, particularly since we are near the end of the present epoch.

6.5 Sediment Transport
In accordance with ER 1110-2-8153, the recommended plan reviewed and considered impacts due to sedimentation. Detailed information with regards to the type and amount of sediment within the river system currently does not exist. However, based on visual observation from site visits, and discussions with the local USACE and municipal staff, it is known that the existing system carries a high sediment load. The recommended plan is not anticipated to alter the amount of the sediment load. The PDT recognizes and anticipates that sediment will accumulate upstream of the diversion structure and at the outlet of the diversion channel.

The local municipality regularly removes accumulated sediment from the river as part of current maintenance measures and the plan anticipates that will continue once the project is constructed. It has been explained to the local municipality, documented in the main report, and accounted for in the recommend plan cost estimate, that periodic operation and maintenance activities throughout the project's life-cycle, including but not limited to removal of vegetation, removal of debris and sediment, will be required. The focus of the removal will be on the locations where it is anticipated that sediment will accumulate as well as periodic cleaning of the diversion channel as a whole to maintain conveyance.

6.6 Model Calibration
Similar to the hydrologic model, there was very limited data available for calibration of the hydraulic model, particularly taking into account post-Maria channel characteristics. The USGS provided a good High Water Mark of 89.50 feet for the October 26, 2012 event which had a peak discharge of

approximately 23,800 cfs. While this event was pre-Maria, the USGS had provided the elevation using the preliminary post-Maria rating curve. Comparing this to the HEC-RAS model, for that discharge, an elevation of 89.58 feet was calculated. Finally, the inundation extents and elevations of the 0.01 AEP closely matched that of the latest FEMA FIRM. During the Planning, Engineering and Design (PED) Phase and as the post-Maria gage rating curve is finalized, the HEC-RAS model will continued to be verified and refined as required.

6.7   Model Result

The without- and with-project water-surface profiles for Rio Guayanilla can be found on Plates A-4 through A-5. Finally, inundation maps depicting the 0.01 AEP for the with- and with-out recommend plan conditions are included as Exhibits 1 and 2 at the end of this appendix.

Table 8: Annual Exceedance Probability Discharges

Annual Exceedance Probability (AEP)	Discharge (cfs)
0.5	3,575
0.2	7,565
0.1	11,257
0.04	20,842
0.02	29,052
0.01	41,863
0.005	54,524
0.002	74,561

7.0   Plan Formulation

A detailed discussion of the plan formulation for this study is provided in the main report. To summarize the process, using the 1990 USACE Reconnaissance Report as a starting point, management measures were identified for the study area. Management measures are features or activities that can be implemented at a specific geographic location to address all or a portion of the problems. Measures can directly address the hazards, the way the hazards behave (performance), or indirectly address them through eliminating or reducing the consequences. Once the initial list of possible flood risk reduction measures was assembled, each measure was then considered in the context of the study area. From this, the initial alternatives array was developed. Two structural measures from the initial alternatives array were evaluated in the hydraulic model, Alternative 3 and Alternative 6. Detailed discussion regarding these alternatives with respect to the hydraulic model are provided in Section 7.1. Once the hydraulic modelling was complete, the resulting HEC-RAS water surface profiles were provided for further assessment in the economic analysis. In addition, profiles were reviewed to ensure that no adverse impacts to the regulatory floodplain occur, in accordance with Executive Order (EO) 11988.

7.1   Evaluation of Alternatives

Both Alternative 3 and Alternative 6 include construction of an approximate 9,000 foot long diversion channel starting at approximately 1,500 feet downstream of PR-127. Both alternatives include bridge and channel conveyance modifications starting 750 feet upstream of PR-2 to the location of the diversion channel. In addition, utility relocations, new bridge construction, construction of a diversion structure and levees/flood walls are included in both alternatives. The alignment for both alternatives directs flood water away from the center of town and to the west along the confining mountain valley wall, though agriculture fields, where it bends east though existing banana fields to join up with the constructed Phase I project near PR-3336, refer to Figure 22.
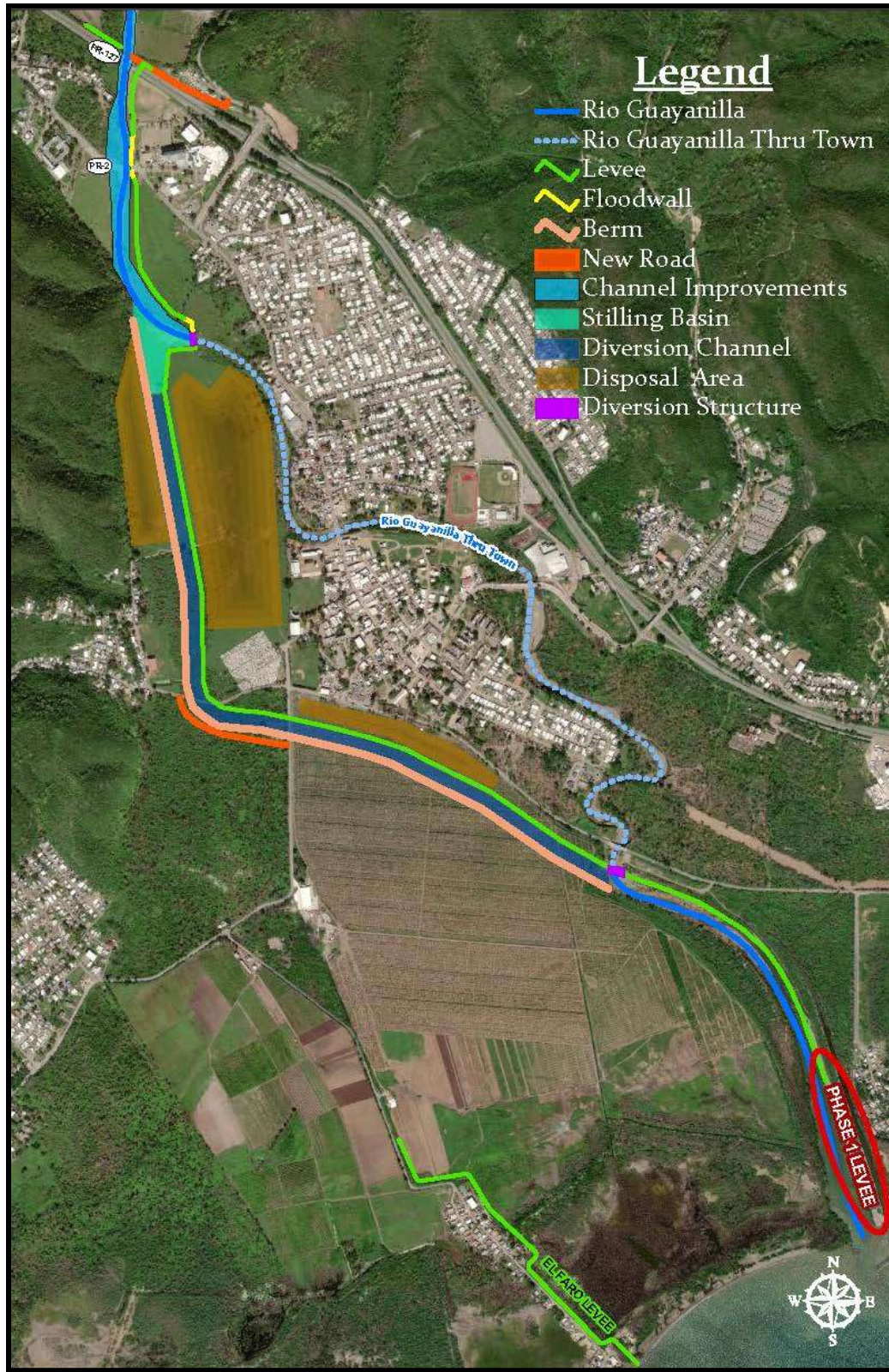
Figure 22: Diversion channel alignment and levee locations.

7.1.1   Alternative 3: Diversion Channel South with Single Line Protection

This alternative (recommended plan) would include construction of an engineered trapezoidal channel with a bottom width of 100-feet and 2:1 side slopes. A new diversion structure, constructed across the existing river channel, would split flows sending the majority of flood waters to the diversion channel while maintaining a bank-full flow in the existing channel. The diversion structure conceptual design includes riverine connectivity for sediment transport and fish passage. A levee would be built on the eastern side of the diversion channel. The riverside slope of the levee would be lined with riprap to prevent erosion. Upstream of the diversion channel, a combination of levees and floodwalls would be installed on the east side of the river channel at designated locations. A levee will also be constructed to protect the El Faro community from overbank riverine flooding.

This alternative is depicted in *Alternative 3, El Faro levee 7* HEC-RAS geometry file (.g22) and included in the Alternative 3 HEC-RAS with-project plans (.p21, .p22, .p10, .p23, .p24, .p63, .p25, .p26) and future with-project plans (.p42, .p43, .p44, .p45, .p46, .p47, .p48, .p19).

7.1.2   Alternative 6: Staged Greenway Terraces with Single Line of Protection

This alternative would include construction of a terraced greenway diversion channel. The channel would be a non-engineered, bowl and terrace shaped construction to allow channel morphology to be formed by flood pulses. This type of channel may be two to three times wider than Alternative 3 to ensure hydraulic forces do not degrade the integrity of the levee and terraces. The channel footprint for this alternative would be very wide in certain sections, about 780-feet based on current hydraulic modeling. In one location, where the diversion channel begins to bend east near the existing cemetery, due to the wide channel footprint the diversion channel would have to switch from a terraced greenway to an engineered trapezoidal channel and back to a terraced greenway.

Similar to Alternative 3, a new diversion structure, constructed across the existing river channel, would split flows sending the majority of flood waters to the diversion channel while maintaining a bank-full flow in the existing channel. In addition, a levee would be built on the eastern side of the diversion channel. The riverside slope of the levee would be lined with riprap to prevent erosion. Upstream of the diversion channel, a combination of levees and floodwalls would be installed at designated locations.

This alternative is depicted in *Alternative 3, updated* HEC-RAS geometry file (.g13) and included in the Alternative 6 HEC-RAS with-project plans (.p34, .p49, .p50, .p51, .p52, .p14, .p53, .p54) and future with-project plans (.p55, .p56, .p57, .p58, .p59, .p62, .p61, .p62).

7.2   Structure Damage Analysis

Structural Damages were estimated using the Hydrologic Engineering Center Flood Damage Assessment (HEC-FDA) model. Structures within the 0.2% annual exceedance probability (500-year) floodplain of the Guayanilla Watershed were included in the analysis. Geo-referenced structure data was gathered from Puerto Rican assessor (CRIM) data, and surveyed based on a randomized stratified assignment. All damage and benefit estimates are based off this structure inventory dataset. See the Economics Appendix for a more detailed description of the structure inventory and survey methodology.

7.3   Risk and Uncertainty

In accordance with EM 1110-2-1619 "Risk-Based Analysis for Flood Damage Reduction Studies", a risk analysis was performed for this study using HEC-FDA. This program uses Monte Carlo simulation to sample the interaction among the various hydrologic, hydraulic, and economic uncertainties. Uncertainties in the hydrology and hydraulics include the uncertainties associated with the discharge-frequency curve and the stage-discharge curve. Both of these relationships have statistical confidence bands that define the uncertainty of the relationships at various target frequencies. The Monte Carlo

simulations randomly sample within these confidence bands over a range of frequencies until target performance criteria are met. Reliability statistics are based on the results of the Monte Carlo simulations. Based on Table 4-5 in EM 1110-2-1619, equivalent record length was represented graphically using an equivalent record length of 30 years. A detailed discussion of the risk and reliability analyses can be found in the Economics Appendix.

In accordance with Planning Bulletin 2019-04, Incorporating Life Safety in to Planning Studies, the PDT evaluated potential life safety risks during the development of the Recommended Plan. The evaluation identified future work during the Planning, Engineering and Design (PED) Phase to reduce design uncertainties that could affect potential life risk such as but not limited to the following: collecting additional site characteristics, refining the 2-D hydraulic model to inform design, and refining design features to incorporate new information and analyses. The evaluation also identified OMRR&R activities that would be required by the NFS and could have an impact on potential life risk. Those OMRR&R activities include, but are not limited to: maintaining the existing channel clear of vegetation and debris, maintaining the levee free of woody vegetation and encroachments, and monitoring for maintenance needs before and after a storm or seismic event to ensure proper functioning of the system.

8.0   Summary

Alternative 3 has a higher net benefit and therefore is considered the recommended plan. Results from the hydraulic model for both alternatives were reviewed for compliance with federal regulations. There will be no adverse flooding impacts upstream or downstream of the project features.

9.0   References

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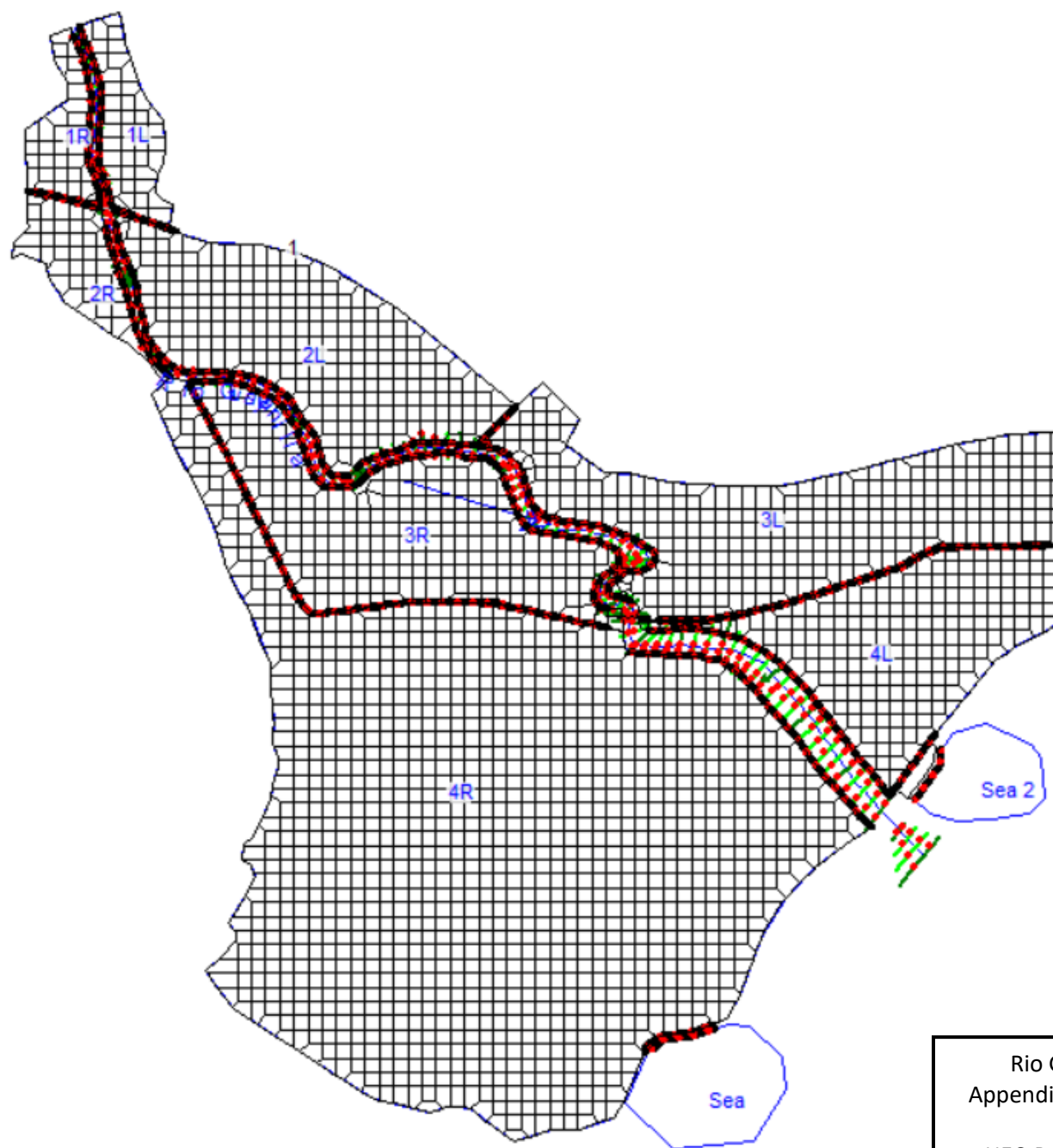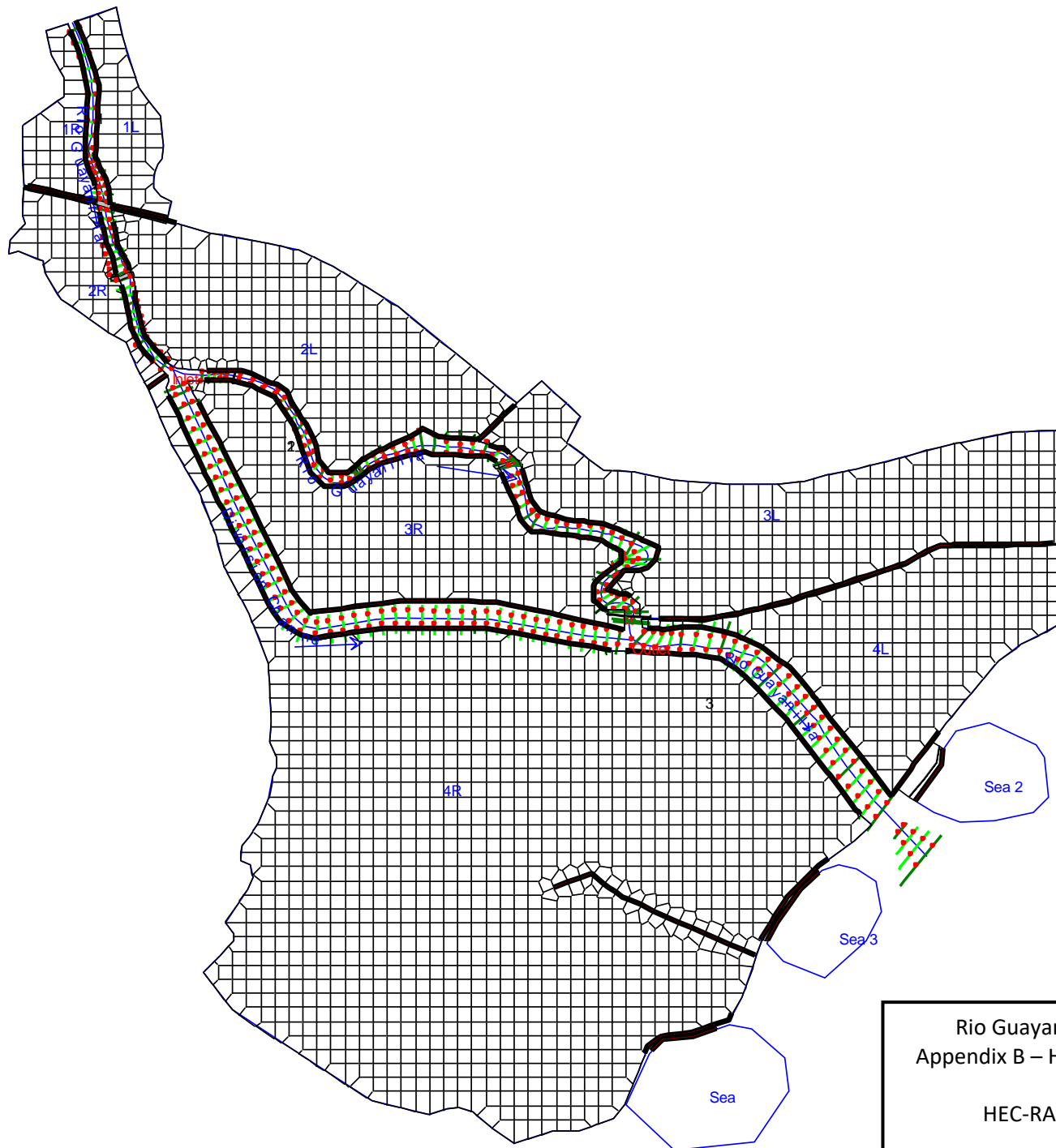
Rio Guayanilla Feasibility Study
Appendix B – Hydraulics and Hydrology

HEC-RAS Without Project Schematic
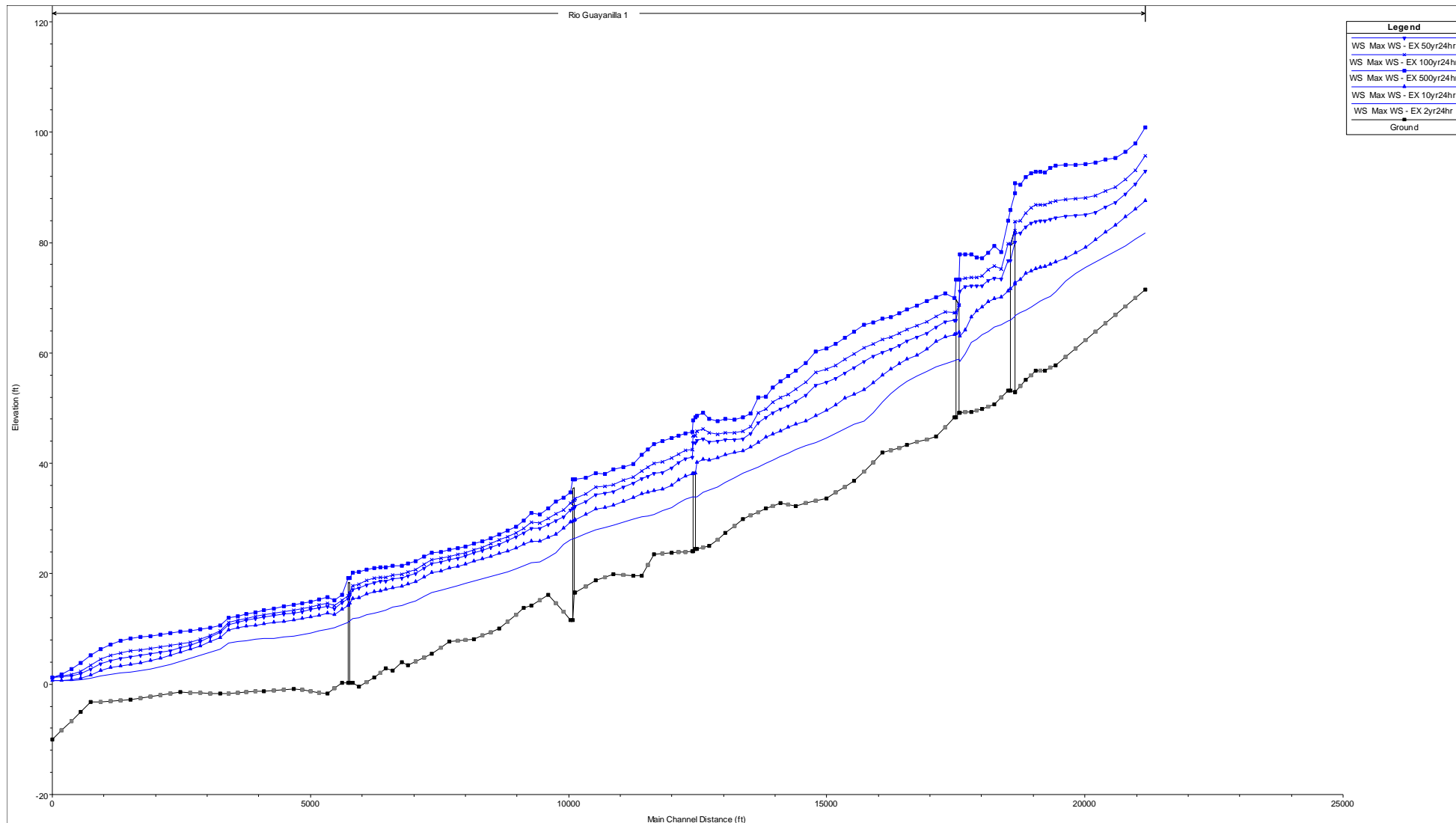
FEBRUARY 2020   Plate B-1

Rio Guayanilla Feasibility Study
Appendix B – Hydraulics and Hydrology

HEC-RAS Alt 3. Schematic

FEBRUARY 2020   Plate B-2

Rio Guayanilla 1

Elevation (ft)

Main Channel Distance (ft)
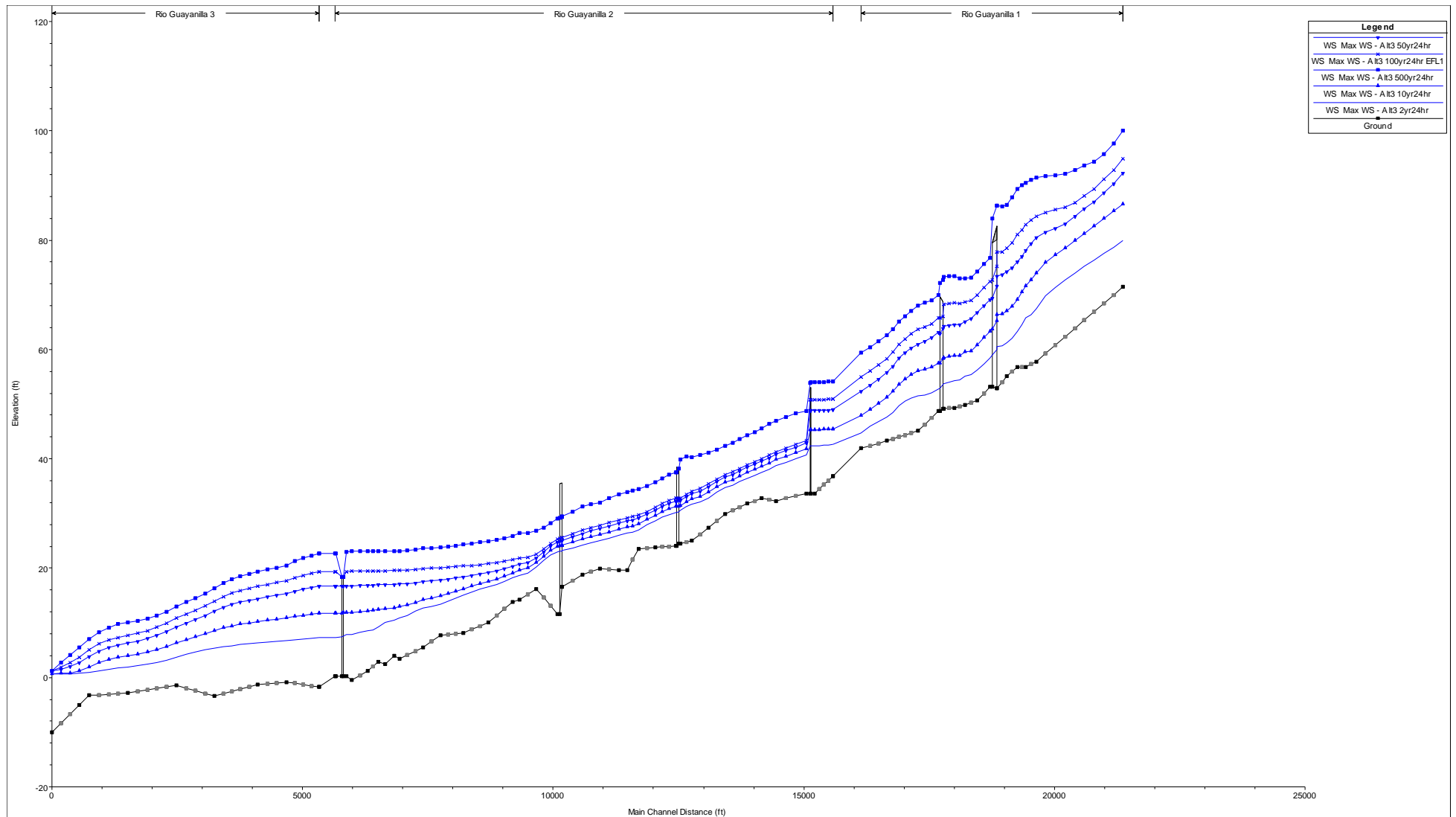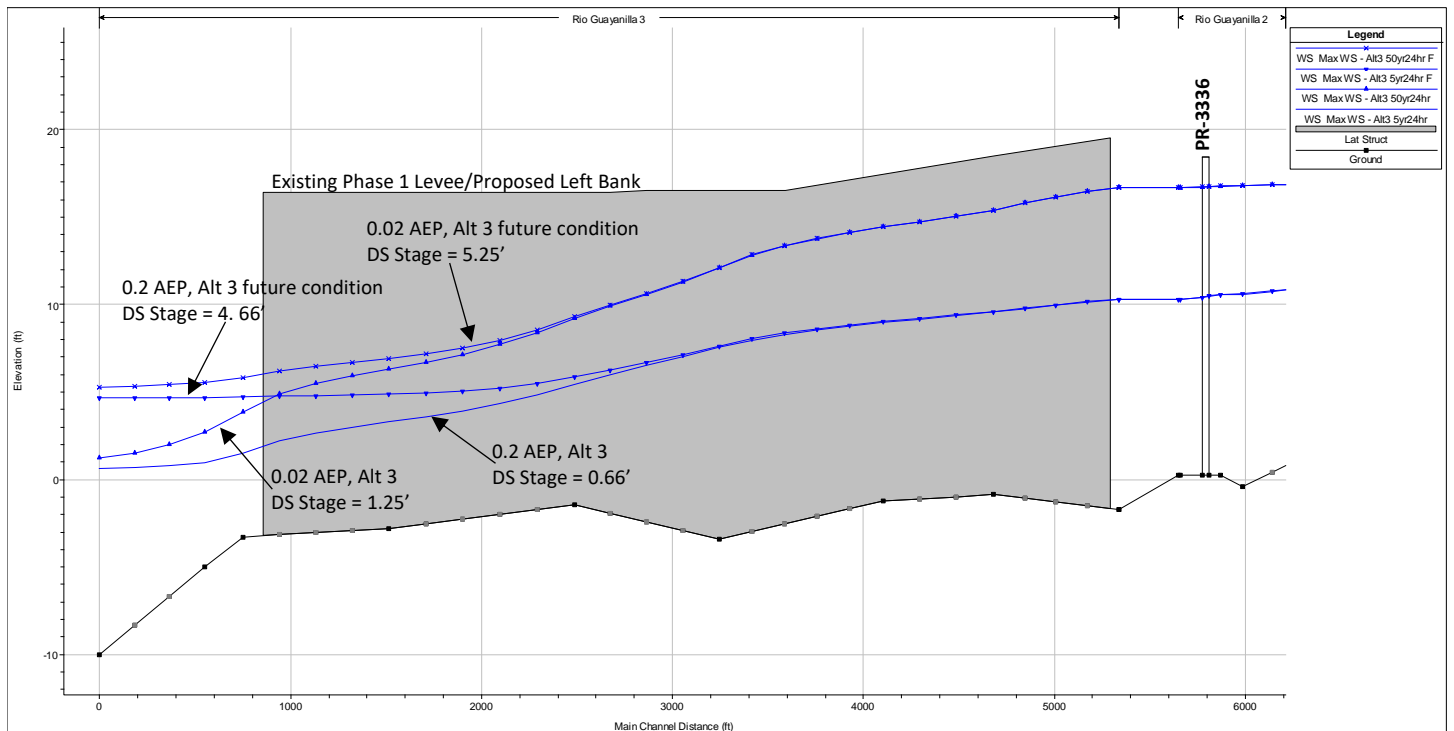
Rio Guayanilla Feasibility Study
Appendix B – Hydraulics and Hydrology

HEC-RAS Without Project Profiles

FEBRUARY 2020   Plate B-3

Rio Guayanilla Feasibility Study
Appendix B – Hydraulics and Hydrology

HEC-RAS Alt 3. Project Profiles

FEBRUARY 2020   Plate B-4

PR-3336 Bridge

Existing Phase 1 Levee/
Proposed Left Bank

NOT TO SCALE

Rio Guayanilla 3

Rio Guayanilla 2

PR-3336

Existing Phase 1 Levee/Proposed Left Bank

0.02 AEP, Alt 3 future condition
DS Stage = 5.25'

0.2 AEP, Alt 3 future condition
DS Stage = 4. 66'

0.02 AEP, Alt 3
DS Stage = 1.25'

0.2 AEP, Alt 3
DS Stage = 0.66'

Elevation (ft)

Main Channel Distance (ft)

Rio Guayanilla Feasibility Study
Appendix B – Hydraulics and Hydrology

HEC-RAS Alt. 3 Future Condition Profiles

APRIL 2020   Plate B-5

Proposed El Faro Levee
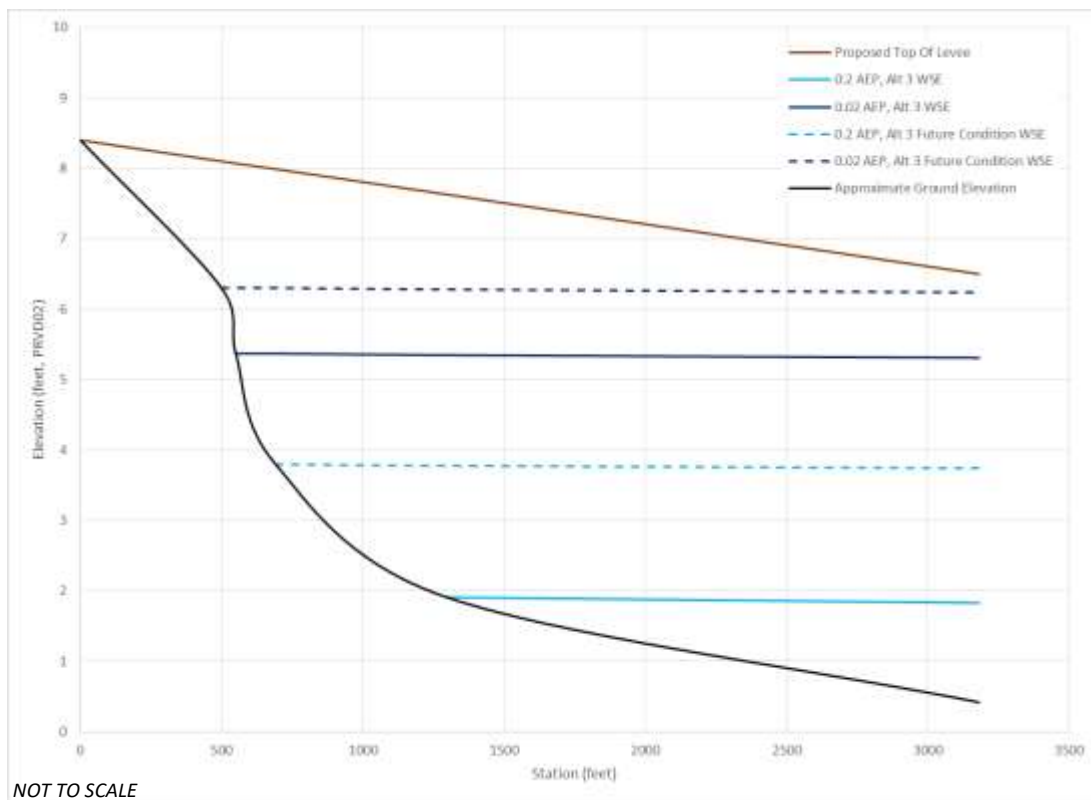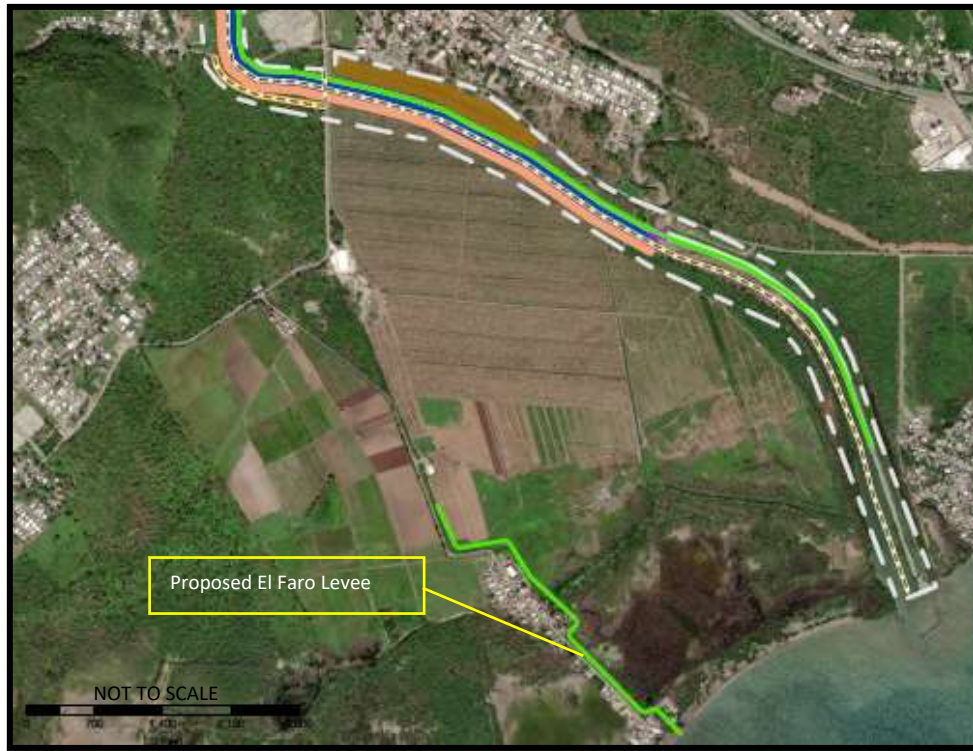
NOT TO SCALE

NOT TO SCALE

Rio Guayanilla Feasibility Study
Appendix B – Hydraulics and Hydrology

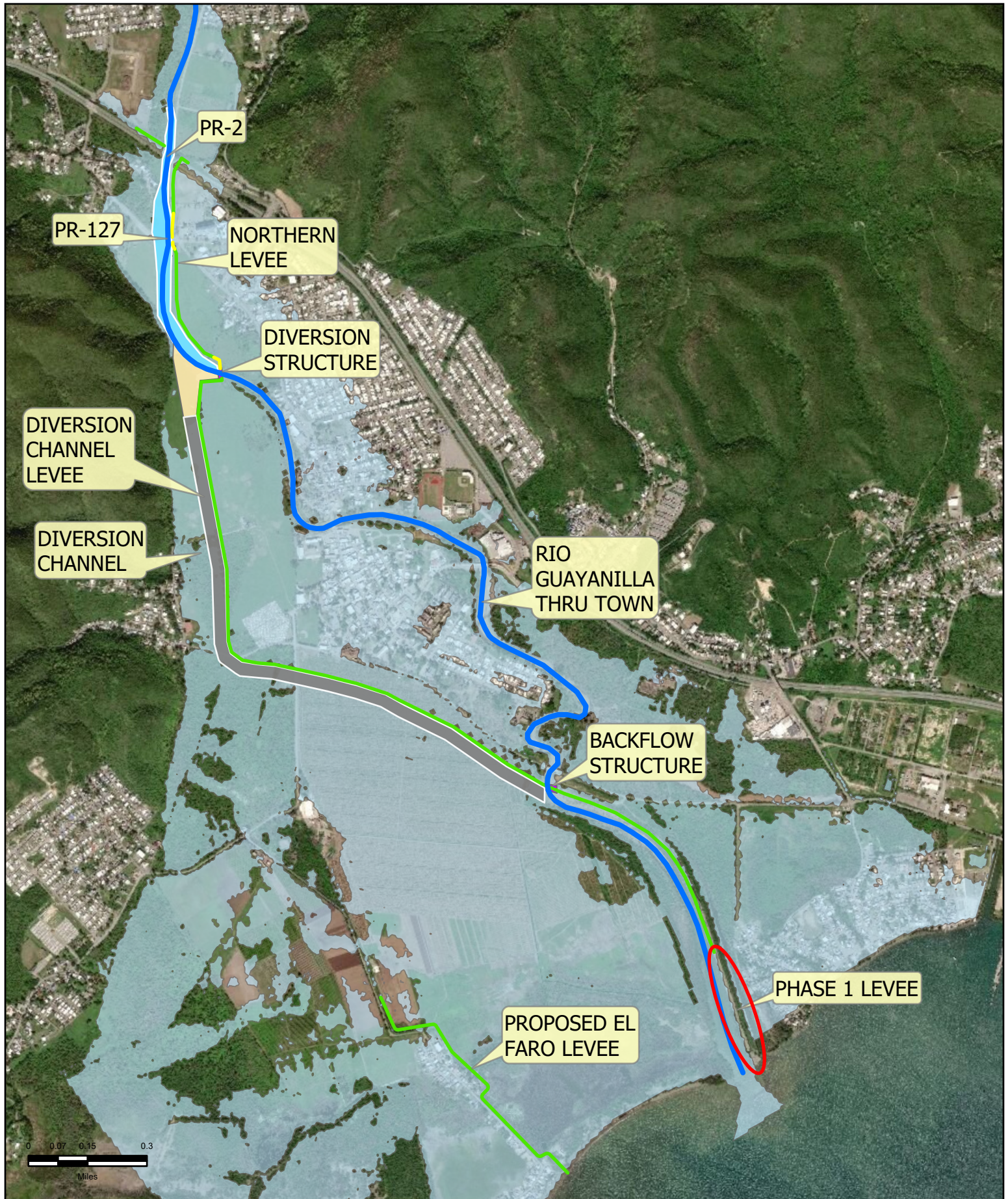HEC-RAS Alt. 3 Future Condition Profiles

APRIL 2020   Plate B-6

PR-2

PR-127

NORTHERN
LEVEE

DIVERSION
STRUCTURE

DIVERSION
CHANNEL
LEVEE

DIVERSION
CHANNEL

RIO
GUAYANILLA
THRU TOWN

BACKFLOW
STRUCTURE

PHASE 1 LEVEE

PROPOSED EL
FARO LEVEE

0   0.07 0.15   0.3
Miles

U.S. Army Corps of Engineers
Chicago District

Path: D:\Rio\ArcGIS_Proj\MyProject1\MyProject1.aprx

〰 Guayanilla River   Channel Improvements   DiversionStructure
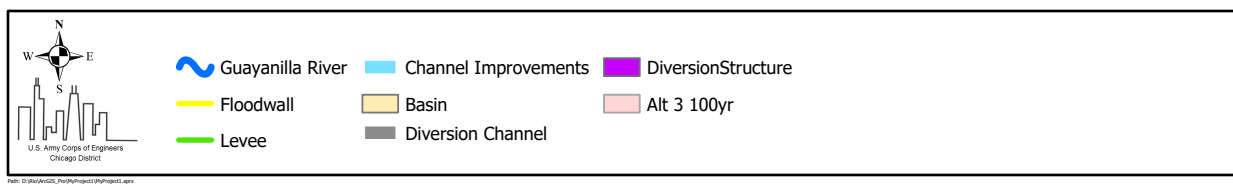Floodwall   Basin   Existing 100yr
Levee   Diversion Channel

Rio Guayanilla

Project Features

Existing 100yr

Date Modified: 4/21/2020

NAD 1983 StatePlane Puerto Rico Virgin Islands FIPS 5200 Feet

PR-2

PR-127

NORTHERN
LEVEE

DIVERSION
STRUCTURE

DIVERSION
CHANNEL
LEVEE

DIVERSION
CHANNEL

RIO
GUAYANILLA
THRU TOWN

BACKFLOW
STRUCTURE

PHASE 1 LEVEE

PROPOSED EL
FARO LEVEE

0   0.07 0.15   0.3
Miles

W N E S
U.S. Army Corps of Engineers
Chicago District

~~~ Guayanilla River   Channel Improvements   DiversionStructure
— Floodwall   Basin   Alt 3 100yr
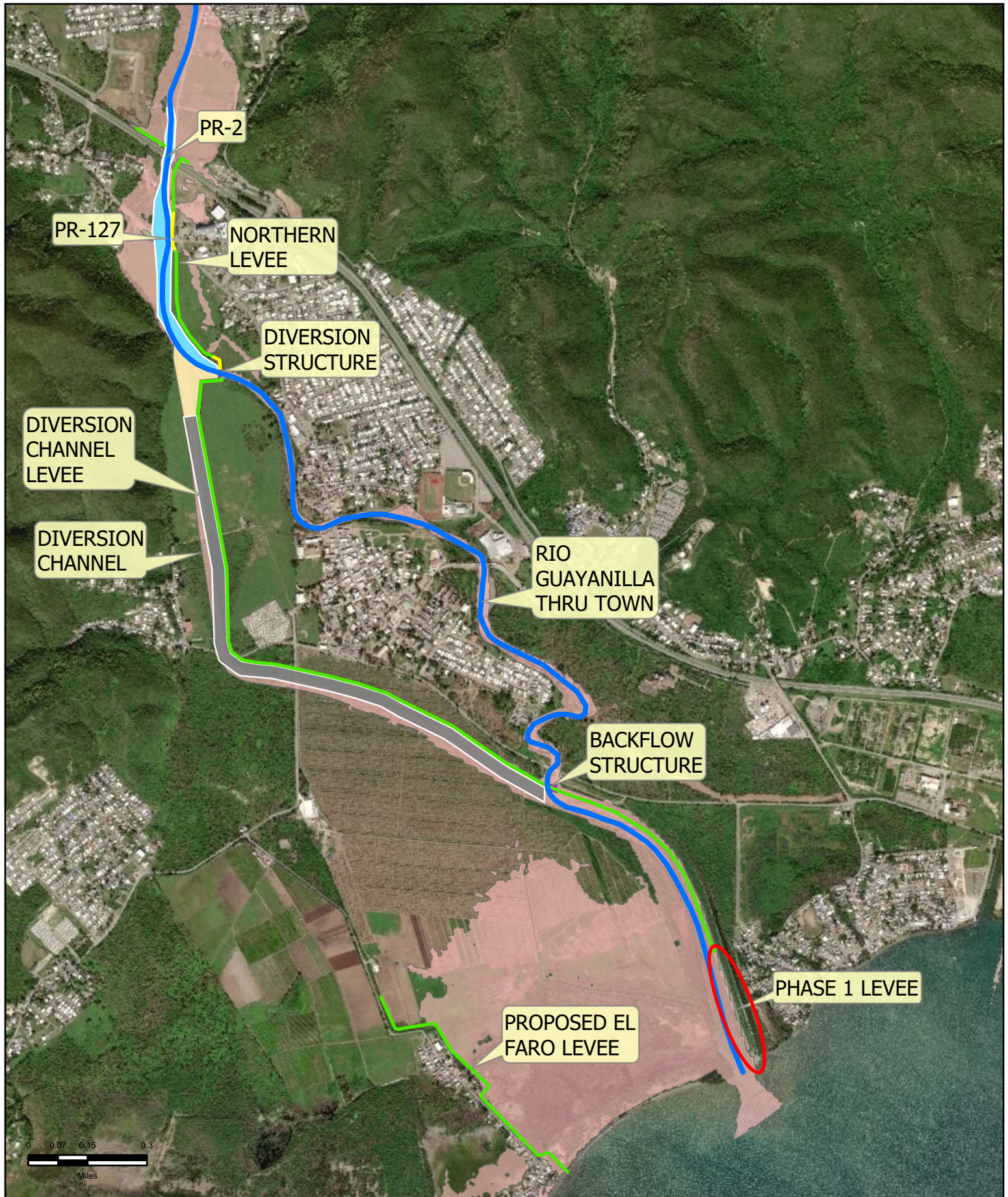— Levee   Diversion Channel

Rio Guayanilla
Project Features
Alt 3 100yr

Date Modified: 4/21/2020
NAD 1983 StatePlane Puerto Rico Virgin Islands FIPS 5200 Feet