Patillas Dam Failure Analysis Modeling Using HEC-HMS, HEC-RAS Simulation Programs and Geographic Information System

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Abstract – *Carlos Negron Alfonso, Master's in Civil Engineering Candidate, in cooperation with the Final Project conducted a Dam Breach Analysis for the Patillas Dam. This hydrologic and hydraulic study will assess the potential hazar to human life and property downstream from the Patillas Dam, associated with the hypothetical failures of the dam for the probable maximum floods resulting from a 6 and 24-hour duration probable maximum precipitation and for the 100-year floods resulting from a 6 and 24-hour duration 100-year rainfall. The study consists of the determination of outflow hydrographs from Patillas Dam under non-failure and failure conditions corresponding to the probable maximum flood, 100-year flood, and non-flood condition (sunny day), and their subsequent routing through the lower reach of the Rio Grande de Patillas. To perform the hydraulic analysis, the U.S. Army Corps of Engineers HEC-RAS program was utilized to simulate and analyze the various flood conditions produced by breaching the Patillas Dam. The dam break analysis was performed using the unsteady flow module available in HEC-RAS.*

Key Terms *— Geographical Information System, HEC-HMS, HEC-RAS and HEC-GeoRAS.*

JUSTIFICATION

The digital hydraulic information as well as the available technology like HEC-HMS and HEC-RAS justifies the necessity to improve different H-H analysis and to introduce a practice that is being used in the water resources industry by different State and Federal Agencies and by private engineering firms, induced the motivation to present the methodology used on this hydrologic-hydraulic study.

The GIS tool combined with the hydrologic models is becoming a common practice in some of the states of the United States of America, and Puerto Rico can be part of this group if the GIS analysis is recommended to be used in the water resources practice by the federal and the local agencies.

INTRODUCTION

The Puerto Rico Electric Power Authority (PREPA) administrates and operates the Patillas Dam and reservoir, which is owned by the Government of the Common Wealth of Puerto Rico. Figure 1 provides a picture of the Patillas Dam, Spillway and Reservoir. Water in the reservoir is used for public irrigation, domestic water supply and industrial purposes [1].

Figure 1
Patillas Dam, Reservoir and Spillway [2]

Under this project there is an interest in developing inundation mapping from a hypothetical breach of Patillas Dam under several loading scenarios including "sunny-day", 100-year storm event and the probable maximum precipitation (PMP). Hydrologic analyses to determine runoff hydrographs from the various precipitation events under consideration were developed. These hydrographs were applied to the hydraulic analyses of dam failure at Patillas Dam in order to estimate potential resultant flooding associated with the dam failure. Results from the hydraulic analyses enabled detailed downstream inundation mapping, which supports PREPA's Dam Safety Program.

Description of Patillas Dam Study Area

Patillas Dam is located in the southeast area of Puerto Rico, about 1 mile northeast of the town of Patillas and within the municipal boundary of Patillas. Figure 2 provides a graphic of the general location of the Patillas Reservoir in southeast Puerto Rico.

Figure 2
Proximity of Patillas Dam to the Patillas Municipality

Built in about 1914, this embankment dam built by the hydraulic fill method is about 147 feet high with a length of about 1,067 feet. A concrete spillway with three 30 feet x 33.8 feet radial gates controls the reservoir level and has a design capacity of about 79,000 cubic feet per second (Figure 3). The 368-acre reservoir impounded by the Patillas Dam at normal pool has a contributing drainage area of 25.2 square miles and had a planned storage capacity of about 14,300 acre-feet. In 2007, a bathymetric survey of the reservoir indicated a storage capacity of about 10,990 acre-feet, a reduction of approximately 23.1 percent [1].

Additional characteristics of the dam are provided in Table 1, below [1].

Table 1
General Characteristics of Patillas Dam

Original Capacity, acre-feet (up to spillway)	**14,300**
Actual Capacity, based in Last Bathymetry Study by USGS, acre-feet	10,990 (USGS,2007)
Surface Area of Reservoir (Full), acres	368
Type of Material of Dam	Earth Hydraulic Fill Method
Drainage Area, square miles	25.2
Length of Dam, feet	1,067
Height of Dam, feet	147
Elevation of Top of Dam, feet above MSL	238
Spillway Type, feet	Concrete Spillway with Radial Gates(3) 30'x33.8'
Spillway Length, feet	90
Elevation of Concrete Ogee Spillway Crest, feet above MSL	191
Design Flood for Spillway, cfs	79,000

Figure 3
An Aerial View of the Spillway for Lago Patillas

GIS Data

The geographic information system (GIS) shown on Table 2 sources were referenced during the development of this study:

Table 2
Referenced GIS Data Sources

NATURAL RESOURCES CONSERVATION SERVICE • **Soil Survey PR_686** • **Soil Survey PR_689**
Land Use Coverage – PR Office of Management and Budget, 2006, WMS Webserver, http://gis.otg.pr.gov/
Digital Elevation – CRIM PR OMB, 1998, WMS Webserver, http://gis.otg.pr.gov/ **DEM 30m x 30m resolution**

METHODOLOGY

The following information explains the methodology used in this research.

Hydrologic Study

The U.S. Army Corps of Engineers (USACE), Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) program (2010) was used to determine runoff hydrographs from the Lago Patillas watershed for the 6 and 24-hour PMPs and for the 6- and 24-hour 100-year rainfall events. The HEC-HMS program consists of three model components: the Basin Model, the Meteorological Model, and the Control Specifications. The Basin Model represents the physical basin; the Meteorological Model calculates the precipitation input required by a sub-basin element; and the Control Specifications set the time span of a simulation run [3].

The HEC-HMS Basin Model component is made up of a series of models that represent each component of the runoff process: runoff volumes, direct runoff (overland flow and interflow), base flow, and channel flow. The selected methods used in each of these models are further discussed in the following sections.

General Approach

Runoff hydrographs and peak discharges were determined for the Lago Patillas watershed for selected, frequency-based, hypothetical storms. The simulated storms are the 6 and 24-hour PMP and the 6 and 24-hour 100-year rainfall events. The procedure to estimate the rainfall depths for these selected storms are discussed in the Rainfall section of this Report.

The U.S. Soil Conservation Service (SCS), currently known as the Natural Resources Conservation Service (NRCS), Loss Model available in the HEC-HMS program was used to compute the runoff volume for each of the simulated storm rainfall events [4]. This model, also known as the SCS Curve Number (CN) Loss Model, estimates basin runoff using the following equation [3]:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \quad (1)$$

Where:

Q is runoff, in inches.
P is rainfall, in inches.
I_a is the initial abstraction (initial loss), in inches.
S is the potential maximum retention after runoff begins, in inches.

The initial abstraction consists mainly of intersection, infiltration, and surface storage, all of which occur before runoff begins. This initial loss includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. Initial abstraction is related to the potential maximum retention after runoff begins by the following empirical equation [4]:

$$I_a = 0.2S \quad (2)$$

Therefore, substituting the previous equation into the runoff equation gives [4]:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (3)$$

S is related to the soil and cover conditions of the basin through the CN. This relation is expressed as follows [43]:

$$S = \frac{(1000 - 10CN)}{CN} \quad \text{(English units)} \quad (4)$$

The CN is a dimensionless parameter indicating the runoff response characteristic of a drainage basin. In the SCS method, this parameter is related to land use, soil type, and antecedent moisture conditions (AMC) in the drainage basin. Land use represents the surface conditions in the drainage basin and is related to degree of cover. Soil properties greatly influence the amount of runoff. Infiltration rates of soils vary widely and are affected by subsurface permeability as well as surface intake rates. The NRCS classifies the soils into four hydrologic soil groups (A, B, C, and D) according to their minimum infiltration rate, which is obtained for bare soil after prolonged wetting.

Another important factor influencing the CN value is the soil moisture condition in the drainage basin before runoff occurs. The soil moisture condition is classified by the NRCS in three AMC classes: AMC I (dry conditions), AMC II (average conditions), and AMC III (saturated conditions). This classification is based on the 5-day antecedent rainfall. To determine the appropriate CN value, the NRCS developed several tables that relate the value of CN to the factors discussed above. The CN values, shown in these tables, range from 30 (permeable soils with high infiltration rates) to 98 (impervious areas). Publications from the NRCS provide further background and details on use of the CN Loss Model [4].

The SCS Unit Hydrograph method included in the HEC-HMS Basin Model was utilized to estimate the direct runoff from each of the simulated storm rainfall events. This method is based upon averages of unit hydrographs derived from gauged rainfall and runoff for a large number of small agricultural basins, which varied greatly in characteristics such as size and geographic location. The required input parameters are limited to basin area and are an estimate of time of concentration (T_c) or basin lag time (T_l). The T_c is defined as the travel time of flow from the most hydraulically distant point in the basin to the outlet of the basin.

The Kirpich equation was used to estimate the T_c for the Lago Patillas drainage basin. This equation is expressed as follows [5]:

$$T_c = 0.0078 L^{0.77} S^{-0.385} \qquad (5)$$

Where:

T_c is the time of concentration, in minutes.

L is the length of main channel, in feet.

S is the slope, equal to H/L. Where H, in feet, is the difference in elevation between the most hydraulically remote point in the basin and the outlet.

Once the time of concentration is determined, the lag time (T_l) is computed as follows [5]:

$$T_l = 0.6 T_c \qquad (6)$$

The lag time is the time-of-travel parameter used by the HEC-HMS Basin Model. This method is well documented by the NRCS [5].

Storage-Stage

The stage-storage curve shown on Figure 4 for the reservoir was determined from the Sedimentation Surveys of Lago Patillas [6]. This study provided stage-storage information from bottom of lake to spillway level, accounting for loss of storage due to sedimentation.

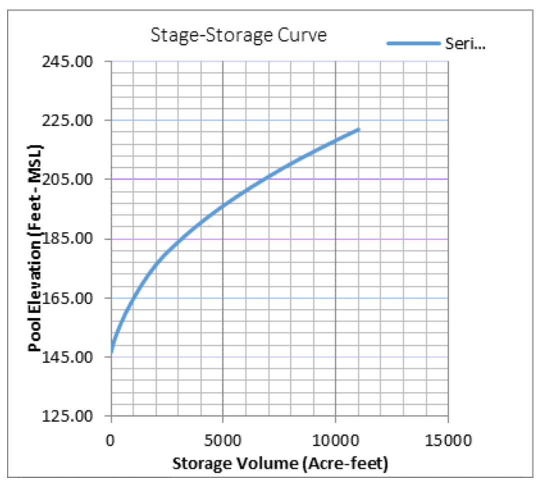

Figure 4

Relation between Water-Storage Capacity and Pool Elevation Lago Patillas [6]

Basin Characteristics

The Lago Patillas receives runoff from a watershed with a drainage area of approximately 25.2 square miles. The watershed is nearly rectangular in shape and generally encompasses wooded rural areas. A watershed delineation map is provided in Figure 5.

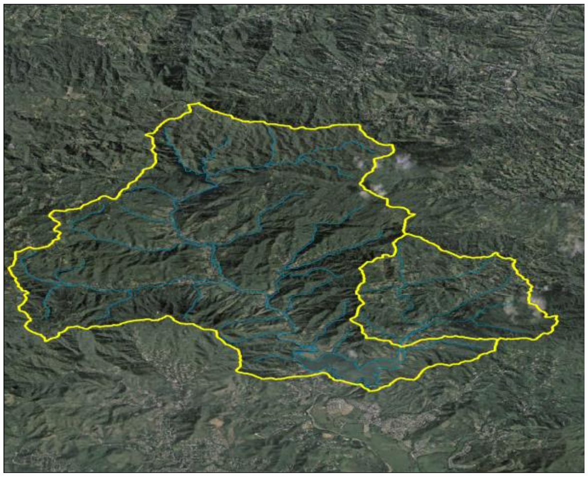

Figure 5
Rio Patillas and Rio Marin Watershed

Land Use

The latest land use cover of the Lago Patillas watershed was provided from the government of Puerto Rico and represents 2006 development conditions.

Soil Types

Los Guineos clays and silty clay loam, Caguabo clay loam, Pandura Loam and Pandura very stony land are the predominant soils within the watershed, covering approximately 90 percent of the entire Lago Patillas basin, while surface waters (stream and lakes) cover 5.4 percent of the basin. These soils have slow infiltration potential and are prone to higher runoff. Based on the SCS soil classification system, these soils are classified under Hydrologic Soil Group (HSG) C. HSG C soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water.

Land use within the Lago Patillas basin was classified into the following main categories: Evergreen Shrub Land, Forests and Woodland (Bosques y Arboledas), Moist Grassland and Pasture (Pastos y Arbustos), Low and Medium Density Urban Development (Dessarrollados o Baldi) and Freshwater (Humedales).

BASIN PARAMETERS

A weighted CN for the watershed was developed based on land use, HSG and AMC. As described in the previous section, HSG type C was used for the soil types found in the watershed. In the 1998 study (PREPA), an AMC II, which is an average moisture condition, was used for estimating rainfall runoff. AMC type II was also used as the average moisture condition for the watershed in the current study [4]. Table 3 presents the identified CN for each land use classification and the weighted CN estimated for the watershed as a whole.

Table 3
Calculated Weighted CN for the Lago Patillas Watershed

LU CLASSIFICATION	% OF WS	CN (AMC II; HSG C)
Forest, Evergreen Shrub Land and Woodland (Bosques y Arboledas (ByA))	75%	73
Moist Grasslands and Pasture (Pastos y Arbustos (PyA))	12.2%	74
Low Density Urban Development (Desarrollados o Baldi (DoB))	0.7%	77
Landuse not Indicated Assumed by A	6.9%	70
Freshwater (Humedales (H))	5.4%	100
WEIGHT CURVE NUMBER		74.5

Rainfall

Four precipitation events were considered for this study; they included the 6 and 24-hour PMP and the 6 and 24-hour 100-year rainfall events.

Data Sources

A PMP is considered to be an event that represents the upper limit of precipitation possible for a given location. To date, the reference for estimation of PMPs for Puerto Rico is the National Weather Bureau Technical Paper No. 42 (TP-42) [7]. According to this report, PMPs for durations of 6 hours and longer would most likely be associated with hurricanes. The distribution of the PMP over the event duration is also specified within the TP-42 document. TP-42 also presents depth-area reduction factors based on watershed size, which are applicable to watersheds larger than 10 square miles.

Estimation of precipitation for frequency based events, such as the 100-year rainfall event, are prepared by the National Oceanic Atmospheric Association's (NOAA) National Weather Service (NWS) [8]. NOAA Atlas 14, Volume 3, Version 4 (2006) is the most recent update to precipitation frequency estimates for Puerto Rico. NOAA Atlas 14 is intended as the official documentation of precipitation frequency estimates for the United States, Puerto Rico and U. S. territories and it supersedes precipitation frequency estimates contained in TP-42 (excluding PMPs). NOAA Atlas 14 is based on more recent and extended data sets, currently accepted statistical approaches, and improved spatial interpolation and mapping techniques. Rainfall event distribution is based on SCS Type II, which is typical and appropriate for Puerto Rico.

Precipitation Estimates

The rainfall estimates for the precipitation events modeled under this study are presented in Table 4.

Table 4
Rainfall Estimates for Precipitation Events

Precipitation Event	Total Rainfall (inches)
6-Hour, 100-Year	9.0
24-Hour, 100-Year	13.75
6-Hour PMP	32.5
24-Hour PMP	45

FLOOD HYDROGRAPHS AND PEAK DISCHARGES

The peak inflows into Lago Patillas, peak WSEs and peak discharges from the spillway as modeled by the HEC-HMS model without a dam break scenario are presented in Table 5. Peak discharges under a dam break scenario were modeled in the hydraulic HEC-RAS model and are further discussed in the Hydraulic Study section of this report. Figure 6 illustrates the inflow hydrographs for each of the four events modeled.

Table 5
Calculated Peak Inflows, WSEs and Outflows for Lago Patillas

Precipitation Event	Peak Inflow	Peak WSE	Peak Outflow
6-hour, 100-yr	34,100	224.35	19,167
24-hour, 100-yr	40,862	225.1	27,815
6-hour, PMP	129,260	236.6	100,904
24-hour, PMP	136,018	238.1	105,146

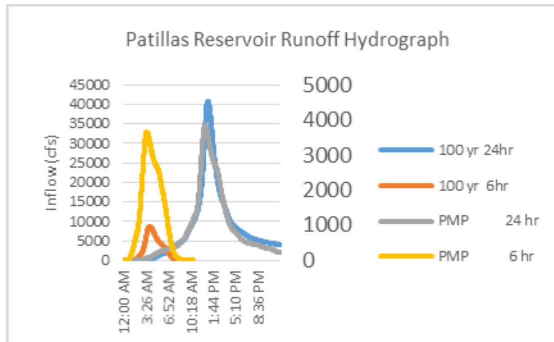

Figure 6
Patillas Reservoir Runoff Hydrograph

HYDRAULIC STUDY

The purpose of the hydraulic analysis is to assess the potential hazard to human life and property downstream from the Patillas Dam associated with hypothetical failures of the dam under PMF, 100-year, and non-flood conditions (Sunny Day failure). The U.S. Army Corps of Engineers, Hydrologic Engineer Center's River Analysis System (HEC-RAS) computer program (2010) was utilized to determine flood level, flood peak, and time to peak after dam failure at selected locations downstream from the dam for each simulated breach condition [9]. The dam break analysis was performed using the unsteady flow module available in HEC-RAS. Using the unsteady flow module enables the model to estimate the impacts of flow routing and system storage which result in flow attenuation.

GENERAL APPROACH

The inflow design hydrographs to the Patillas Dam were generated using the HEC-HMS computer program. Information about basin hydrographs and peak discharges for the PMFs resulting from a 6 and 24-hour PMP and for the 100-year floods resulting from a 6 and 24-hour rainfall event was discussed in the Flood Hydrographs and Peak Discharges section of this Report.

The runoff hydrographs were input into the HEC-RAS computer program and the unsteady component of the program was used to determine the water-surface profiles downstream of the dam. The Dam Breach simulation option was used in HEC-RAS for the Sunny Day breach, 100-year 6- and 24-hour flood breach and the PMF 6- and 24-hour flood breach. Stage-Storage information obtained from various sources, as discussed in the Stage-Storage section of this Report, was used with a HEC-RAS storage node to model the attenuation of inflow.

STUDY REACH CHARACTERISTICS

The first mile of the 3.6 mile modeled river reach of the Rio Grande de Patillas, downstream of Patillas Dam, flows through low, medium and high urban settings of predominantly houses with some pastures and grasslands. Downstream of Highway 3, the land cover becomes much more urbanized, but still with large tracts of pasture and grasslands.

BOUNDARY AND INITIAL CONDITIONS

The WSE in Lago Patillas was set at the spillway level before commencement of the hydraulic simulation. The inflow hydrographs, as presented in Flood Hydrographs and Peak Discharges section of this Report, were input upstream of the dam and the inflows were routed through the reservoir, to the dam and through the spillway until dam breach occurred. Flows at the downstream end of the hydraulic reach (at Highway 3) were set to normal depth based on the average slope of the river bed in the area.

For all dam break scenarios, except the Sunny Day event, a constant lateral inflow hydrograph was inserted on the Patillas River as an Initial Flow Condition in the hydraulic. This approach enables the model to more conservatively predict hydraulic conditions downstream of the dam prior to dam breach.

PATILLAS DAM CHARACTERISTICS

Both the stage-storage curve and the spillway discharge rating curve presented in the Hydrologic Modeling Section of this Report were used in the hydraulic model for this evaluation.

BREACH PARAMETERS AND FAILURE CRITERIA

Key parameters to be considered in any dam breach evaluation are the maximum size of the breach opening and the time to full breach development. Breaches of embankment dams are typically assumed to be trapezoidal in shape. The following breach parameters must be provided in the hydraulic model to simulate a dam breach scenario:

W = Breach width
B_h = Breach height
T = Time to full failure (hours)
Z = Side slope

These parameters describe the breach geometry; subsequent discharge is estimated assuming the discharge characteristics of a broad-crested weir.

Table 6 presents suggested breach parameters for earthen dams, as presented in the FEMA Federal Guidelines for Inundation Mapping of Flood. Selected breach parameters for Patillas Dam are within the ranges of the values suggested [10].

Table 6
Suggested Breach Parameters from Various Sources [10]

Source	Average Breach Width (ft)*	Breach Side Slope (1V:ZH)	Breach Failure Time (hours)
NWS (1988)	1H to 5H	Z = 0 to 1	0.1 to 2.0
COE (1980)	0.5H to 4H	Z = 0 to 1	0.5 to 4.0
FERC (1991)	1H to 5H	Z = 0 to 1	0.1 to 1.0
USBR (1982)	3H	N/A	0.00333b
Boss Dambrk (1988)	0.5H to 4H	Z = 0 to 1	0.5 to 4.0
Harrington (1999)	1H to 8H	Z = 0 to 1	H/120 to H/180
H = Height of water against dam above breach bottom elevation in feet			

The Patillas Dam breach analysis was performed under a piping failure condition since the peak WSEs for the runoff hydrographs were below the top of the dam. A piping failure occurs when the initial breach formation takes place below the top of the dam, simulating a point of seepage through the dam and subsequent failure. The location of the seepage/piping failure was assumed to be at 3 feet below the spillway level for all dam breach scenarios considered in this study. Table 7 presents the breach parameters that were selected for the Patillas Dam Failure Study.

Table 7
Patillas Dam Breach Parameters

Breach Parameter	Value
Final bottom width (feet)	240
Final bottom elevation (feet)	144.34
Side slopes xV:1H	x = 0.25
Time to full formation (hours)	0.85-0.95
Failure Mode	Piping
Trigger Elevation (feet)	219 for all Simulation Events

***Peak WSE under Sunny Day conditions is based on a base flow of 1000 cfs into Lago Patillas. Thirty-five cfs is the long-term daily average flow, based on available gauge data. Actual breach trigger was set at 45 minutes into simulation.**

A breach height of 94.66 feet was used based on a top of dam at elevation 239 feet. The bottom of the breach was assumed as 144.34 feet, which corresponds with the bottom of the lake storage volume, as indicated in the 2007 Sedimentation Study [5].

Dam Break Simulations and Results

Simulations of the hypothetical overtopping failure of the Patillas Dam were performed for the PMF, 100-year flood, and non-flood (Sunny Day) conditions. Five dam failure events were simulated: 6 and 24-hour PMF, 6- and 24-hour 100-year flood and Sunny Day. Dam break analysis results along the modeled river reach for these simulated flood conditions are provided in this section. Maximum water surface profiles were computed for each flood condition. A discussion of the maximum WSE and time to maximum river stage level at selected locations for each of the flood conditions is included.

Failure under PMF Conditions

The dam failure for the 6 and 24-hour PMF was set to initiate at the time of the hydrograph peak, which was 4:00 and 12:00, respectively. Just downstream of the dam (0.1 miles), the peak discharges calculated for each of the PMF dam breach scenarios were 431,000 cfs and 438,019 cfs, respectively. The maximum water surface profiles resulting from the first event is presented in Figure 7, while dam break results for various cross-sections for the PMF 24 hr along the modeled river reach are provided in Table 8. Results include: peak flow, peak WSE, and time elapsed since the onset of dam failure (time to peak).

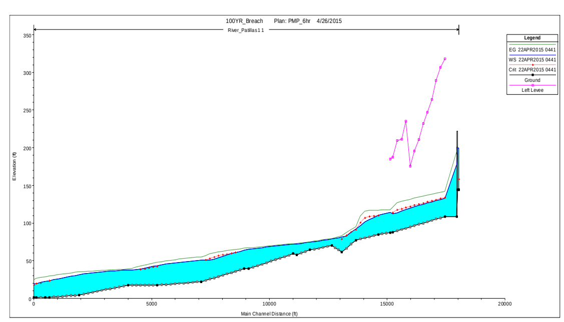

Figure 7
Maximum Water Surface Profile for 6hr-PMF

Table 8
Patillas Dam Failure Results at XS for the 24 hr PMF

Cross-Section	Distance from Dam (miles)	Peak Discharge (cfs)	Peak Elev (feet)	Time to Peak (min)
XS-1 (RS-5422.93)	0.1	438,308	137.96	13.45
XS-2 (RS-4716.61)	0.55	434,792	118.20	13.46
XS-3 (RS-4330.60)	0.79	431,814	98.34	13.48
XS-4 (RS-3961.02)	1.02	424,390	80.38	13.50
XS-5 (RS-2885.74)	1.69	388,515	65.17	13.60
XS-6 (RS-1594.56)	2.49	365,454	42.14	13.71
XS-7 (RS-139.52)	3.39	338,618	22.59	13.86

FAILURE UNDER 100 YR CONDITIONS

The dam failure for the 6 and 24-hour 100-year flood was set to initiate at the time of the hydrograph peak, which was 4:00 and 12:00, respectively. Just downstream of the dam (0.1 miles), the peak discharges calculated for each of the 100-year flood event dam breach scenarios were 309,756 cfs and 311,162, respectively. The dam break results for various cross-sections for the 100 yr -24 hr along the modeled river reach are provided in Table 9. Results include: peak flow, peak WSE, and time elapsed since the onset of dam failure (time to peak).

Table 9
Patillas Dam Failure Results at XS for the 24 hr 100-year Flood

Cross-Section	Distance from Dam (miles)	Peak Discharge (cfs)	Peak Elev (feet)	Time to Peak (min)
XS-1 (RS-5422.93)	0.1	311,422	133.80	51
XS-2 (RS-4716.61)	0.55	308,162	114.52	52
XS-3 (RS-4330.60)	0.79	305,335	96.71	53
XS-4 (RS-3961.02)	1.02	300,220	78.02	54
XS-5 (RS-2885.74)	1.69	268,377	62.70	62
XS-7 (RS-1594.56)	2.49	251,536	38.80	71
XS-8 (RS-139.52)	3.39	229,930	18.52	79

FAILURE UNDER SUNNY DAY CONDITIONS

Failure of the Patillas Dam under Sunny Day conditions was initiated with the WSE 219 feet. The peak discharge just downstream from the dam was 239,673 cfs. And with a WSE of 131.10 feet. Dam break results for various cross-sections along the modeled river reach are provided in Table 10. Results include: peak flow, peak WSE, and time elapsed since the onset of dam failure (time to peak).

Table 10
Patillas Dam Failure Results at Selected Cross-Sections for the Sunny Day Scenario

Cross-Section	Distance from Dam (miles)	Peak Discharge (cfs)	Peak Elev (feet)	Time to Peak (min)
XS-1 (RS -5422.93)	0.1	239,673	131.10	51
XS-2 (RS-4716.61)	0.55	236,961	112.02	52
XS-3 (RS-4330.60)	0.79	235,602	95.50	52.2
XS-4 (RS-3961.02)	1.02	230,808	76.17	54
XS-5 (RS-2885.74)	1.69	203.,375	61.01	1.2
XS-6 (RS-1594.56)	2.49	189,929	36.96	70
XS-7 (RS-139.52)	3.39	174,949	16.36	80

INUNDATION MAPS

Dam breach results were compiled for each of the 6 and 24-hour PMF and 100-year storm events to determine the event that produced the larger inundation limits for mapping and safety purposes. For both the PMF and the 100-year events, the 24-hour condition produced larger flows and flood depths than the 6 hour condition. The flood boundaries are based on the maximum WSEs resulting from the simulated dam breaches. The flood boundaries are approximate and may not include areas where shallow flooding would occur. An example of the inundation limits caused by the 100 yr-6hr Dam Breach simulation is presented on Figure 8.

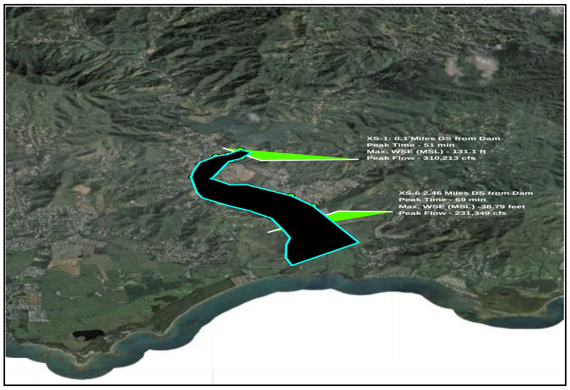

Figure 8
Inundation Map for 100 Yr-6hr Simulation

In addition to showing the flood boundaries, the inundation maps present information at selected locations including the distance from the dam, flood peak or maximum WSE, and time since the failure of the dam to maximum water level. This important information can be used to help develop an Emergency Action Plan (EAP) for the Patillas Dam. While this study is not an EAP, it presents expected inundation areas for the particular events to help determine possible evacuation areas. It also presents time to maximum WSE to give an estimate of the lead time that may be available before the peak of the breach flood wave moves through a specific location.

Model results indicate that dam failure of the Patillas Dam under 100-year flood or PMF conditions would result in severe flooding to both urbanized and rural areas in the vicinity of the municipality of Patillas.

Summary and Conclusions

Both hydrologic and hydraulic analyses were conducted to assess the potential hazard to human life and property associated with hypothetical dam failures of the Patillas Dam, under PMF, 100-year flood and Sunny Day conditions. These analyses were conducted to prepare inundation maps that delineate those areas that are most likely to experience flooding in the event of a dam failure. This analysis was conducted in cooperation with PREPA to enable the agency to prepare an EAP for the Patillas Dam. The EAP is required by the National Dam Safety Program and the Puerto Rico Inspection and Regulation of Dams and Reservoir Program.

The hydrologic analyses consisted of the following:

- Delineating the Patillas Dam watershed.
- Estimating the runoff potential from the watershed based on land use and soil classifications.
- Determining 6-hour and 24-hour, 100-year precipitation events and the 6-hour and 24-hour PMPs.
- Estimating time of concentration for runoff in the watershed.
- Calculating an inflow hydrograph into Patillas Dam using the HEC-HMS software and applying the SCS Curve Number Loss Model for each of the precipitation events.

The 6-hour and 24-hour PMP events yielded peak inflows into Lago Patillas of 129,260 cfs and 136,018 cfs, respectively. 34,100 cfs and 40,862 cfs, respectively.

Inflow hydrographs to Lago Patillas and subsequent breach flows were routed through Patillas Dam and downstream, approximately 3.6 miles, to a location just downstream of Highway 3. The peak outflow approximately 0.1 miles downstream of the dam resulting from a dam breach was estimated as:

- 6-hour, PMF = 431,348 cfs
- 24-hour, PMF = 438,308 cfs
- 6-hour, 100-year flood = 310,213 cfs
- 24-hour, 100-year flood = 311,422 cfs
- Sunny Day = 239,673 cfs

Results of the hydrologic and hydraulic analyses indicate that the Patillas Dam would not overtop under 6 hour or 24-hour PMP conditions.

Substantial flooding is predicted downstream of the dam under 100-year flood and PMF conditions, even without dam failure.

REFERENCES

[1] *Compendio de Represas y Embalses*, Programa de Inspección y Reglamentación de Represas y Embalses, 2012, pp. 21, 51.

[2] *Autoridad de Energía Eléctrica*, *División de Riego*, *Represas y Embalses*, Plan de Acción Para Emergencias, 2012, pp. 3-5.

[3] United States Army Corps of Engineers (USACE), Hydrologic Engineering Center (HEC), Hydrologic Modeling System (HEC-HMS), Version 3.5. August 2010, pp. 2-6.

[4] *United States Department of Agriculture (USDA)*, NRCS, Technical Release 55 (TR-55) – Urban Hydrology for Small Watersheds, 1986, Ch. 2, pp. 1-16

[5] *United States Department of Agriculture (USDA)*, NRCS, Technical Release 55 (TR-55) – Urban Hydrology for Small Watersheds, 1986, Ch. 3 pp. 1-6

[6] L. R. Soler-López, "Sedimentation Survey of Lago Patillas Puerto Rico," March 2007, United States Geological Survey, 2010, Scientific Investigation Map - 3128.

[7] *United States Department of Commerce*, Weather Bureau. Technical Paper 42 (TP-42) – "Generalized Estimates of Probable Maximum Precipitation and Rainfall-Frequency Data for Puerto Rico and Virgin Islands", 1961, pp. 6.

[8] *National Oceanic and Atmospheric Association (NOAA)*, Atlas 14, Precipitation Frequency Data Server, 2006, Volume 3, Version 4.

[9] *United States Army Corps of Engineers (USACE)*, Hydrologic Engineering Center (HEC), River Analysis System (HEC-RAS), Version 4.0, Ch. 1, pp. 1-4

[10] *FEMA Federal Guidelines for Inundation Mapping of Flood Risks Associated with Dam Incidents and Failures*, 1st ed., July 2013, pp. 9.9-9.11.