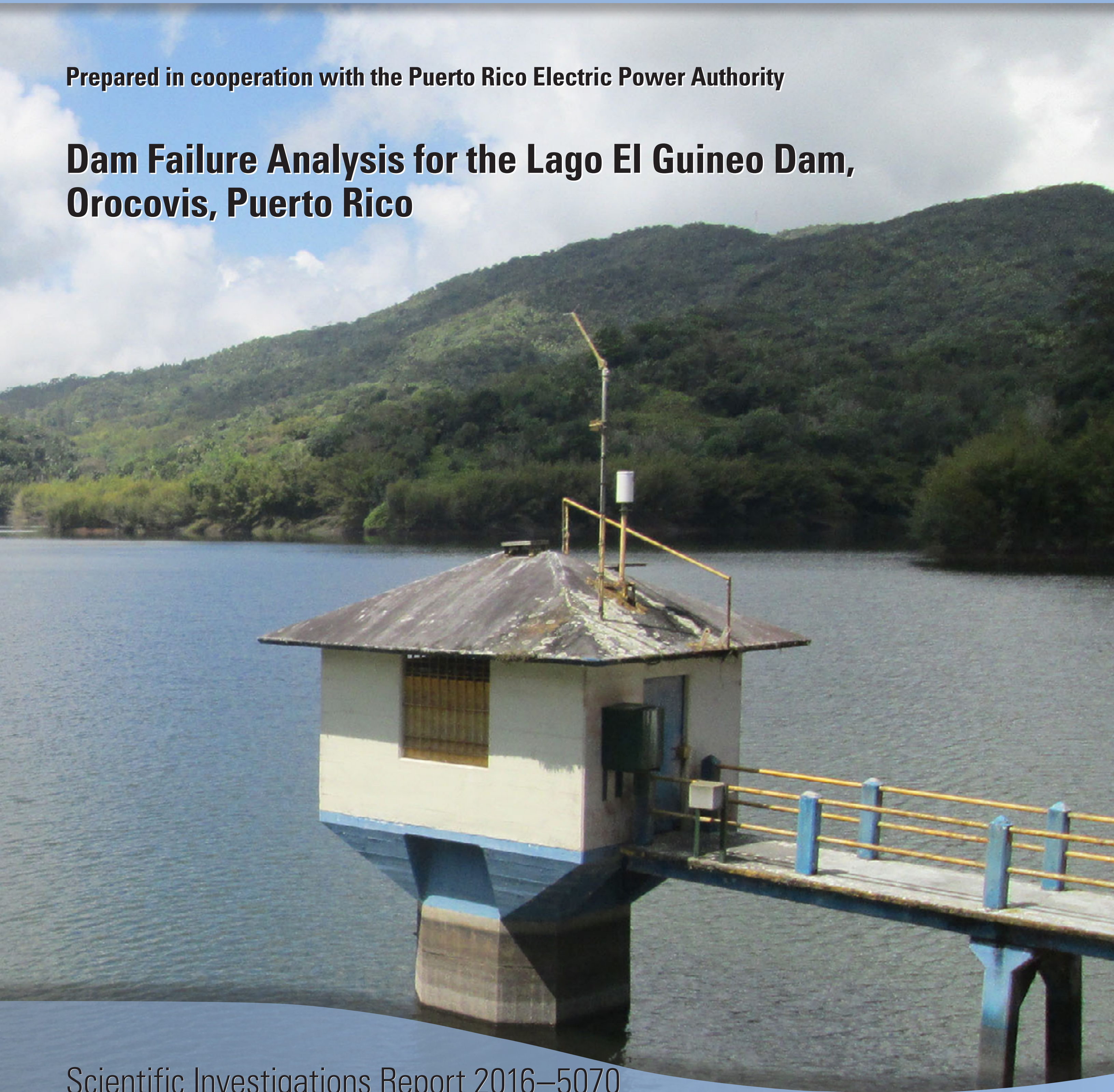
Prepared in cooperation with the Puerto Rico Electric Power Authority

Dam Failure Analysis for the Lago El Guineo Dam, Orocovis, Puerto Rico



Scientific Investigations Report 2016–5070

U.S. Department of the Interior
U.S. Geological Survey

Cover. Aerial photograph of the Lago El Guineo Reservoir facing upstream.
Photograph by Julieta Gómez-Fragoso.

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By Julieta Gómez-Fragoso and Heriberto Torres-Sierra

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

U.S. Geological Survey, Reston, Virginia: 2016

Suggested citation:
Gómez-Fragoso, Julieta, and Torres-Sierra, Heriberto, 2016, Dam failure analysis for the Lago El Guineo Dam, Orocovis, Puerto Rico: U.S. Geological Survey Scientific Investigations Report 2016–5070, 49 p., 4 pls., http://dx.doi.org/10.3133/sir20165070.

ISSN 2328-0328 (online)

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
million cubic meters (Mm^3)	264.172	million gallons (Mgal)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
meter per second (m/s)	3.281	foot per second (ft/s)

Datums

Elevation, as used in this report, refers to distance above the vertical datum.

Vertical coordinate information is referenced to local mean sea level.

Horizontal coordinate information is referenced to the Puerto Rico Datum, 1940 Adjustment.

Supplemental Information

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Abbreviations

CN	curve number
EAP	Emergency Action Plan
HEC–HMS	Hydrologic Engineering Center's Hydrologic Modeling System
HEC–RAS	Hydrologic Engineering Center's River Analysis System
NRCS	Natural Resources Conservation Service
PMP	probable maximum precipitation
PREPA	Puerto Rico Electric Power Authority
SCS	Soil Conservation Service
SSURGO	Soil Survey Geographic (database)
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

Translations

Spanish	English
cordillera	mountain range or chain
lago	lake
río	river

Dam Failure Analysis for the Lago El Guineo Dam, Orocovis, Puerto Rico

By Julieta Gómez-Fragoso and Heriberto Torres-Sierra

Abstract

The U.S. Geological Survey, in cooperation with the Puerto Rico Electric Power Authority, completed hydrologic and hydraulic analyses to assess the potential hazard to human life and property associated with the hypothetical failure of the Lago El Guineo Dam. The Lago El Guineo Dam is within the headwaters of the Río Grande de Manatí and impounds a drainage area of about 4.25 square kilometers.

The hydrologic assessment was designed to determine the outflow hydrographs and peak discharges for Lago El Guineo and other subbasins in the Río Grande de Manatí hydrographic basin for three extreme rainfall events: (1) a 6-hour probable maximum precipitation event, (2) a 24-hour probable maximum precipitation event, and (3) a 24-hour, 100-year recurrence rainfall event. The hydraulic study simulated a dam failure of Lago El Guineo Dam using flood hydrographs generated from the hydrologic study. The simulated dam failure generated a hydrograph that was routed downstream from Lago El Guineo Dam through the lower reaches of the Río Toro Negro and the Río Grande de Manatí to determine water-surface profiles developed from the event-based hydrologic scenarios and "sunny day" conditions. The Hydrologic Engineering Center's Hydrologic Modeling System (HEC–HMS) and Hydrologic Engineering Center's River Analysis System (HEC–RAS) computer programs, developed by the U.S. Army Corps of Engineers, were used for the hydrologic and hydraulic modeling, respectively. The flow routing in the hydraulic analyses was completed using the unsteady flow module available in the HEC–RAS model.

Above the Lago El Guineo Dam, the simulated inflow peak discharges from HEC–HMS resulted in about 550 and 414 cubic meters per second for the 6- and 24-hour probable maximum precipitation events, respectively. The 24-hour, 100-year recurrence storm simulation resulted in a peak discharge of about 216 cubic meters per second. For the hydrologic analysis, no dam failure conditions are considered within the model. The results of the hydrologic simulations indicated that for all hydrologic conditions scenarios, the Lago El Guineo Dam would not experience overtopping. For the dam breach hydraulic analysis, failure by piping was the selected hypothetical failure mode for the Lago El Guineo Dam.

Results from the simulated dam failure of the Lago El Guineo Dam using the HEC–RAS model for the 6- and 24-hour probable maximum precipitation events indicated peak discharges below the dam of 1,342.43 and 1,434.69 cubic meters per second, respectively. Dam failure during the 24-hour, 100-year recurrence rainfall event resulted in a peak discharge directly downstream from Lago El Guineo Dam of 1,183.12 cubic meters per second. Dam failure during sunny-day conditions (no precipitation) produced a peak discharge at Lago El Guineo Dam of 1,015.31 cubic meters per second assuming the initial water-surface elevation was at the morning-glory spillway invert elevation.

The results of the hydraulic analysis indicate that the flood would extend to many inhabited areas along the stream banks from the Lago El Guineo Dam to the mouth of the Río Grande as a result of the simulated failure of the Lago El Guineo Dam. Low-lying regions in the vicinity of Ciales, Manatí, and Barceloneta, Puerto Rico, are among the regions that would be most affected by failure of the Lago El Guineo Dam. Effects of the flood control (levee) structure constructed in 2000 to provide protection to the low-lying populated areas of Barceloneta, Puerto Rico, were considered in the hydraulic analysis of dam failure. The results indicate that overtopping can be expected in the aforementioned levee during 6- and 24-hour probable maximum precipitation events. The levee was not overtopped during dam failure scenarios under the 24-hour, 100-year recurrence rainfall event or sunny-day conditions.

Introduction

The National Dam Safety Program and the Puerto Rico Inspection and Regulation of Dams and Reservoirs Program require each dam owner to prepare an Emergency Action Plan (EAP). The EAP must be prepared, maintained, and executed when needed to minimize property damage, injury, or loss of life in the event of an emergency-flooding situation caused by dam failure. The EAP requires hydrologic and hydraulic analyses of the dam to assess the potential downstream hazard to human life and property. To fulfill this need, the U.S. Geological Survey (USGS) completed hydrologic and hydraulic analyses of the Lago El Guineo Dam in Orocovis, Puerto Rico (fig. 1), in cooperation with the Puerto Rico

Figure 1. Location of Lago El Guineo in the Rio Grande de Manatí hydrographic basin, Puerto Rico.

Electric Power Authority (PREPA). The hydrologic analysis included the development of flood hydrographs resulting from 6- and 24-hour probable maximum precipitation (PMP) events, and a 24-hour, 100-year recurrence rainfall event. Flood hydrographs resulting from the hydrologic analysis were used as the inflow hydrographs in the hydraulic analysis; thus, no failure conditions were considered during hydrologic modeling.

The hydraulic analysis focused on the downstream routing of the breach hydrograph of Lago El Guineo generated during the dam failure, as well as the flood hydrographs representing runoff from downstream basins of the Lago El Guineo Dam. Four hypothetical dam failure scenarios were included in the analysis: (1) a 6-hour PMP event, (2) a 24-hour PMP event, (3) a 24-hour, 100-year recurrence rainfall event, and (4) a nonprecipitation scenario (commonly known as "sunny-day conditions"). The breach hydrograph resulting from failure of the Lago El Guineo Dam, as well as other lateral inflows, were routed downstream through the lower reaches of the Río Toro Negro and the Río Grande de Manatí (fig. 1).

The results of the hydraulic analysis included flood levels for various locations along the study reach. Maps showing the maximum inundation limits during the passage of the flood wave resulting from each of the four hypothetical dam failure scenarios were constructed for the flooded areas downstream from the Lago El Guineo Dam (specifically the lower reach of the Río Grande de Manatí). Information about maximum water-surface elevations and peak flood-wave arrival times are also included on the inundation maps.

Purpose and Scope

The purpose of this report is to present the results of the hydrologic and hydraulic analyses completed to assess the potential hazards resulting from hypothetical dam failures of the Lago El Guineo Dam under 6- and 24-hour PMP events, a 24-hour 100-year recurrence rainfall event, and sunny-day conditions. The potential hazard at a specific location was defined in terms of (1) maximum river elevation reached at the selected location during the passage of the flood wave, and (2) arrival time after dam failure at the selected location.

Description of the Study Area

The Lago El Guineo Dam is within the Municipality of Orocovis, Puerto Rico (fig. 1). The Lago El Guineo Dam impounds the waters of the Río Toro Negro upper basin, and has a surface area of about 4.25 square kilometers (km^2). This reservoir is part of the Toro Negro Hydroelectric Project, which consists of two lakes, Lago El Guineo and Lago de Matrullas; and two hydroelectric plants, Toro Negro I and Toro Negro II. The main purpose of the Toro Negro Hydroelectric Project is to provide a water supply for hydroelectric energy generation and irrigation. The Lago El Guineo drainage basin (upstream from the Río Toro Negro Dam) is on the northern slopes of the Cordillera Central in the central region of Puerto Rico and is part of the Río Grande de Manatí hydrographic basin (subbasin 1, fig. 2). The Lago El Guineo Dam is about 20.4 kilometers (km) north of Ciales and about 15.9 km west of Orocovis (fig. 1).

The Lago El Guineo Dam is about 19.6 km upstream from the Río Toro Negro-Río Matrullas confluence (fig. 1). The contributing drainage area of the Río Toro Negro (subbasins 1 and 2, fig. 2) at its confluence with the Rio Matrullas (subbasins 3 and 4, fig. 2) is about 46.81 km^2. The Rio Bauta (subbasin 5, fig. 2), with a drainage area of about 73.3 km^2, enters Rio Toro Negro upstream from its confluence with the Río Grande de Manatí (subbasin 7, fig. 2). About 7 km downstream from the Río Toro Negro-Río Grande de Manatí confluence, the Río Cialitos enters the Río Grande de Manatí (subbasin 8, fig. 2). Downstream from this confluence, the Río Grande de Manatí meanders through about 28 km of a deeply entrenched alluvial valley, flanked on both sides by limestone hills, before reaching the coastal plain.

The Lago El Guineo Dam construction was completed in 1931. The Lago El Guineo Dam is owned and operated by the PREPA (Puerto Rico Electric Power Authority, 1980a). The Lago El Guineo Dam is a rock-fill embankment with a crest length of 172.2 meters (m), a structural height of 38.10 m, and a top width of 6.09 m (table 1). The elevation of the Lago El Guineo Dam at the top of the dam crest width is 905.51 m (Soler-López, 2003b) and has a corewall with an elevation of 906.78 m. An uncontrolled morning-glory type spillway with a crest elevation of 902.21 m and a crest diameter of 12.50 m is within the left abutment of the Lago El Guineo Dam. The morning-glory type spillway discharge passes over the crest of the morning glory into a tapered shaft ending in a 3.65-m-diameter circular elbow and sloping circular tunnel of the same diameter located 30.48 m below the spillway crest. The spillway discharge capacity at a pool elevation of 904.13 m is 198.24 cubic meters per second (m^3/s). Data related to the construction specifications of Lago El Guineo Dam were obtained from the USGS (Soler-López, 2003b) and dam inspection reports provided by the PREPA (Puerto Rico Electric Power Authority, 1980a).

The original storage capacity (1931) of Lago El Guineo Dam [2.29 million cubic meters (Mm^3); table 1] was reduced by sedimentation to 2.03 Mm^3 in 1986 and 1.89 Mm^3 in 2001 (Soler-López, 2003b). This decrease represents a storage-capacity loss of about 0.21 percent per year. The primary water use of the Lago El Guineo Dam is for hydroelectric power generation and to increase water supply for irrigation of croplands in the southern coastal plains of Puerto Rico.

The principal tributary to the reservoir is the Río Toro Negro (fig. 1), which originates in the northern slopes of the Cordillera Central mountain range where the overall stream channel slope is about 9 percent. The tributary streams of the Río Toro Negro are formed by a series of unnamed creeks with steep slopes. Some tributaries originate at elevations in excess of 1,000 m and have stream slopes of about 25 percent.

The land use within the Río Grande de Manatí hydrographic basin includes evergreen forest, shrub/scrub, hay/pasture/herbaceous, barren land, developed land (open space

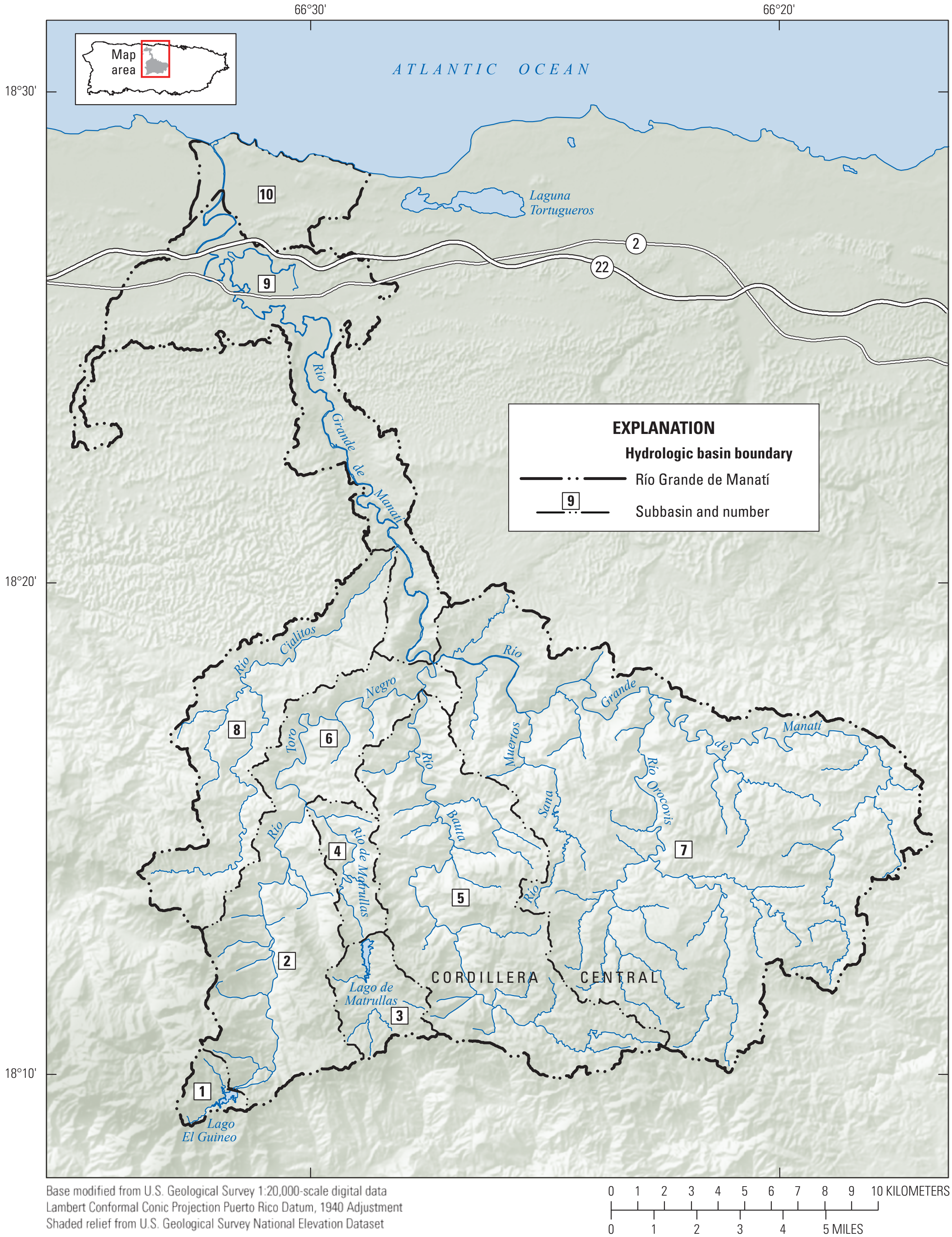


Figure 2. Study subbasins within the Río Grande de Manatí hydrographic basin used for the dam failure analysis for the Lago El Guineo Dam, Orocovis, Puerto Rico.

Table 1. Dam characteristics of the Lago El Guineo Dam, Orocovis, Puerto Rico.

Dam characteristic	Description of value
Dam type	Earthfill embankment with rock toes
Spillway type	Uncontrolled morning glory with vertical shaft and sloping tunnel
Crest length of El Guineo Dam, in meters	172.2
Height of El Guineo dam (to top of concrete corewall), in meters	38.10
Dam crest elevation, in meters above mean sea level:	
Top of El Guineo Dam	905.51
Top of corewall	906.78
Morning-glory type spillway crest elevation, in meters above mean sea level	902.21
Dam crest width, in meters	6.09
Storage capacity (2001), in million cubic meters	1.89

to high density), and cultivated crops (fig. 3) (U.S. Geological Survey, 2003). Evergreen forests and hay/pasture/herbaceous cover large amounts (54 and 36 percent, respectively) of the total area of the Río Grande de Manatí hydrographic basin. Each of the remaining aforementioned land-use categories cover less than 5 percent of the Río Grande de Manatí hydrographic basin area. In the highlands of the Río Grande de Manatí hydrographic basin, land cover mostly consists of evergreen forest, shrub/scrub, cultivated crops and developed lands, which are mostly within coastal areas.

The Río Grande de Manatí hydrographic basin has a variety of soil series (Natural Resources Conservation Service, 2013). The Mucara series (MuE, MuF, MuF2, MxE, and MxF) is in about 20 percent of the Río Grande de Manatí hydrographic basin, whereas the Maricao soil series (MoF, McF, and MxF2) is in about 15 percent of the Río Grande de Manatí hydrographic basin; both series belong to the hydrologic group type D. The Los Guineos soil series (LgD, LgE, LgF, LsE, LsF, LuE, and LuF) is in about 11 percent of the Río Grande de Manatí hydrographic basin and is classified within the hydrologic group type C. The Mucara and Maricao soil series consist of well-drained soils with moderate permeability and slopes ranging from 5 to 60 percent, and 20 to 90 percent, respectively.

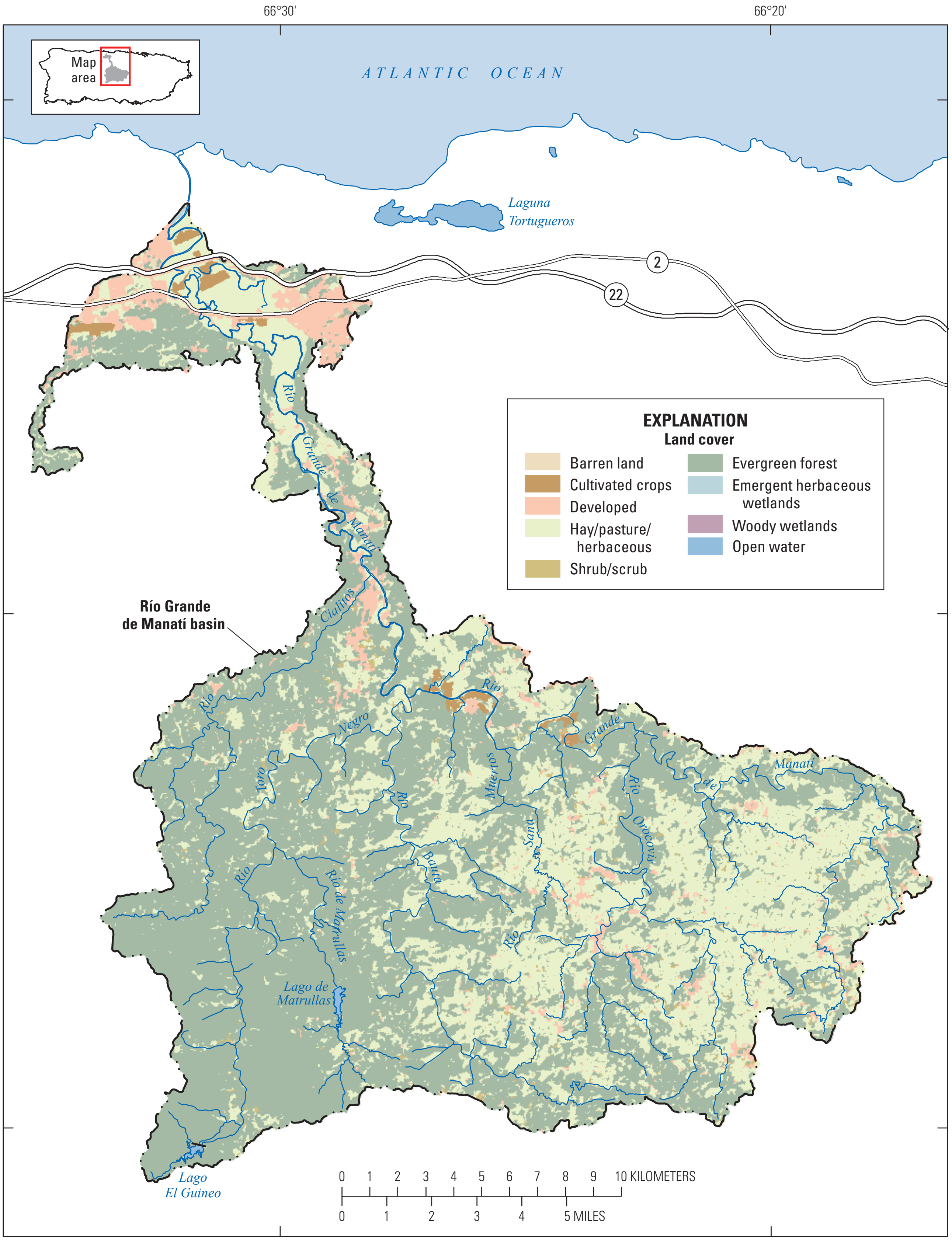
The drainage basin impounded by Lago El Guineo Dam is composed of the following soil series: Los Guineos clay (LgF and LsF), Mayagüez silty clay loam (MaF2) and Maricao (MoF). LgF and LsF clay have hill slopes ranging from 40 to 60 percent, and are in about 88 percent of the Lago de Guineo drainage basin. These soil series consist of moderately well-drained, moderate to very steep slopes, and moderately slow permeable soils. The erosion hazard for LgF and LsF clay is moderate and high, respectively. Typically, the surface layer of LsF clay consists of a dark, yellowish-brown, friable clay about 10 centimeters (cm) thick. For LgF clay, a dark brown surface having a friable clay about 15 cm thick is typical. The Mayagüez soil series (MaF2) has slopes from 40 to 60 percent and low potential of shrink swell. Maricao clay (MoF) has moderate potential of shrink swell. The hydrologic soil group classifications found within the drainage basin impounded by Lago El Guineo Dam are B and C (fig. 4) (Natural Resources Conservation Service, 2013).

The mean annual rainfall in the coastal area within the Río Grande de Manatí hydrographic basin (fig. 1) is about 1,566 millimeters (mm) at the Manatí 2E weather station (National Oceanic and Atmospheric Administration, 2011), and the average temperature is 85.5 degrees Fahrenheit (°F). In the mountainous zones, at an elevation near 555 m, the mean annual rainfall is about 2,155 mm at the Cacaos-Orocovis weather station (National Oceanic and Atmospheric Administration, 2011). Monthly discharge at the Río Grande de Manatí (measured at USGS streamgage No. 50038100 Río Grande de Manatí at Highway 2, near Manatí, PR) varies between 152 and 707 m^3/s (Figueroa-Alamo and others, 2004). Estimates of peak discharges during extreme events have been greater than 140,000 m^3/s (Torres-Sierra, 1997).

General Study Approach

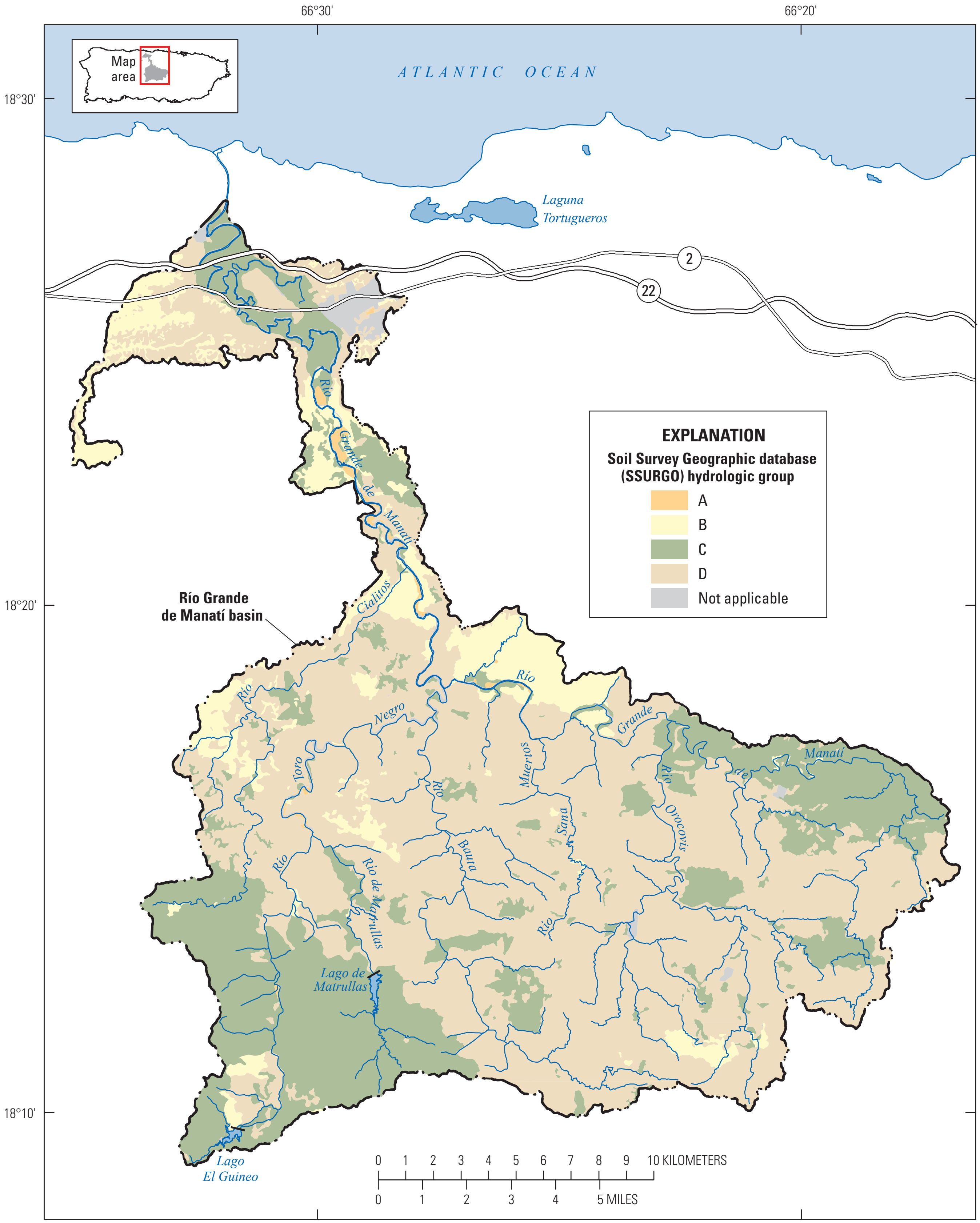
The analysis of the Lago El Guineo Dam was designed to simulate the flood-wave elevation and extent of the flood caused by dam failure under four hypothetical dam failure scenarios. The simulated scenarios include dam failure caused by precipitation and sunny-day conditions, which has no flood hydrograph. For the three hypothetical dam failure scenarios caused by precipitation, flood hydrographs were generated using the U.S. Army Corps of Engineers (USACE), Hydrologic Engineering Center’s Hydrologic Modeling System (HEC–HMS) computer program (Scharffenberg and Fleming, 2010). The HEC–HMS allows for simulation of rainfall-runoff processes for a drainage basin based on its hydrologic properties and a specified storm design. The hydrologic events considered in the analysis were 6- and 24-hour PMP events, and a 24-hour 100-year recurrence rainfall event.

Dam-breach hydraulic analysis was completed using flood hydrographs generated from HEC–HMS for the Lago El Guineo drainage basin including downstream lateral inflows into the study reach (for example, Río Bauta, Río Cialitos, and Río Grande de Manatí). Inflow flood hydrographs for each of the three hypothetical dam failure events were input to the USACE Hydrologic Engineering Center’s River Analysis System (HEC–RAS) program, and the unsteady component of the program was used to determine the water-surface profiles downstream from the Lago El Guineo Dam, which could happen as a result of dam failure. The sunny-day conditions scenario was also incorporated in the hydraulic analysis by using base-flow estimates as input flow data. Dynamic wave routing was also completed through the Lago El Guineo reservoir using the most recent bathymetric survey (2000) available for the reservoirs to develop cross-section profiles within the reservoir.



Base modified from U.S. Geological Survey 1:20,000-scale digital data
Lambert Conformal Conic Projection Puerto Rico Datum, 1940 Adjustment

Figure 3. Land cover within the Río Grande de Manatí hydrographic basin, Puerto Rico.



Base modified from U.S. Geological Survey 1:20,000-scale digital data
Lambert Conformal Conic Projection Puerto Rico Datum, 1940 Adjustment

Figure 4. Hydrologic soil groups within the Río Grande de Manatí hydrographic basin, Puerto Rico.

Hydrologic Study

The HEC–HMS computer program (Scharffenberg and Fleming, 2010) was used to determine the Lago El Guineo Basin hydrographs. Only those peak discharges resulting from the 6- and 24-hour PMP events, and 24-hour, 100-year recurrence rainfall event are evaluated in this report.

Modeling Approach

The HEC–HMS program consists of three model components: the basin model, the meteorological model, and the control specifications. The basin model is used to represent the physical properties of the basin that characterize the runoff. The meteorological model uses either historical or hypothetical values of precipitation and evapotranspiration to determine the precipitation input and distribution into each subbasin. The control specifications are used to set the time span of a simulation run.

The HEC–HMS basin model component is 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 (Scharffenberg and Fleming, 2010). The HEC–HMS model allows for the calculation of the runoff volume by estimating the precipitation losses and subtracting them from the total precipitation over the basin. These precipitation losses may include interception, infiltration, depression storage, evaporation, transpiration, or all the above. The HEC–HMS basin model includes several alternatives to account for the precipitation losses: the initial and constant-rate loss model (also known as the initial and uniform loss rate model), the deficit and constant-rate loss model, the Soil Conservation Service (SCS) curve number (CN) loss model, and the Green-Ampt loss model. Each model computes the precipitation loss for each computation time interval and subtracts it from the mean-areal precipitation depth for that interval. The remaining precipitation depth (precipitation excess) is considered to be uniformly distributed over the basin area; therefore, it represents a runoff volume.

The direct runoff models, in turn, allow for the transformation of the excess precipitation into overland flow by using transforming methods such as unit hydrograph models and kinematic-wave models. The HEC–HMS allow users to (1) complete channel routing to consider the effects of storage within the channels, and (2) model water control facilities such as reservoirs or ponds (Feldman, 2000).

Hydrographic Basin Delineation

The boundaries of the Río Grande de Manatí hydrographic basin were obtained from the Watershed Boundary Database (U.S. Geological Survey, 2002). For the dam failure analysis of Lago El Guineo Dam, the surface area of the Río Grande de Manatí hydrographic basin encompasses about 453 km^2 (fig. 2). The average slope of the Río Grande de Manatí hydrographic basin is about 35 percent and land-surface elevations within the Río Grande de Manatí hydrographic basin exceed 1,000 m in some areas. For the analysis, the Río Grande de Manatí hydrographic basin was subdivided into 10 subbasins to account for inflows from the Río Toro Negro, Río Bauta, Río Cialitos, and other desired outlet points (fig. 2). A brief description of each subbasin is presented in the "Basin Parameters" section herein.

Runoff Losses

For the hydrologic modeling approach used in this study, the primary source of precipitation losses was infiltration. The SCS CN method, developed by the Natural Resources Conservation Service (NRCS, formerly SCS) and widely used to transform rainfall into runoff, was selected to account for precipitation losses (Mays, 2005). The runoff parameter used to determine the potential of runoff development is estimated as a function of land use, soil type, and soil antecedent moisture.

The CN is a dimensionless parameter used to describe runoff response and was calculated for the Río Grande de Manatí hydrographic basin by categorizing the soils within the basin into hydrologic soil groups (fig. 4). This hydrologic soil group classification used digital maps from the Soil Survey Geographic (SSURGO) database published by the Natural Resources Conservation Service (2013). A unique combination of the hydrologic soil groups and land-cover conditions from the Puerto Rico land-cover layer obtained from the Natural Resources Conservation Service (2003) (fig. 2) was applied to assign CN values from reference tables provided by the NRCS (Mays, 2005). The land cover and hydrologic soil groups categorized for the Río Grande de Manatí hydrographic basin and the CN assigned to each combination is shown in table 2. A requirement of the SCS CN method is to include the effects of antecedent moisture conditions in the hydrographic basin. The SCS CN method provides three antecedent moisture condition classes: AMC I (dry conditions), AMC II (average conditions), and AMC III (saturated conditions). For the study, AMC II was selected as the antecedent moisture condition for runoff loss estimates. The composite values of CN for each subbasin included in the hydrologic model are summarized in the "Basin Parameters" section.

Unit Hydrograph

The traditional unit hydrograph technique was selected to transform the precipitation excess into direct runoff for each subbasin. The technique is a well-known, commonly used empirical method for relating the direct runoff to excess precipitation (Soil Conservation Service, 1986). As noted earlier, empirical (unit hydrograph) and conceptual methods are included in HEC–HMS for modeling direct runoff. The empirical models provide the user with a choice of methods that incorporate one of the following: a user-specified unit hydrograph, a Clark's unit hydrograph, a Snyder's

Table 2. Curve number used in the hydrologic analysis based on hydrologic groups and land cover data used for the dam failure analysis of the Lago El Guineo Dam, Orocovis, Puerto Rico.

[Curve number are dimensionless values]

Land cover	Hydrologic group			
	A	B	C	D
Evergreen forest	44	65	76	82
Herbaceous	49	70	80	87
Barren land	77	86	91	94
Developed, low intensity	54	70	80	85
Developed, medium intensity	61	75	83	87
Developed, high intensity	89	92	94	95
Developed, open space	49	69	79	84
Shrub/scrub	48	67	77	83
Cultivated crops	67	78	85	89

unit hydrograph, or a SCS unit hydrograph. The SCS unit hydrograph method was selected to determine the hydrographs used as inflow in the hydraulic model. The basic principles of the SCS unit hydrograph method establish that the peak discharge, q_p, is inversely related to the time to peak, T_p, and directly related to the drainage area. Ratios of the dimensionless unit hydrograph ordinates, t/T_p and q/q_p, where t is the time since the beginning of rainfall and q is discharge at a given time, are provided by the NRCS (Mays, 2005) and were used to generate the hydrograph based on the calculated peak discharge and time to peak flow. The input parameters required by the HEC–HMS model include the lag time and hydrographic basin area for each subbasin.

As stated by the NRCS, the lag time is the time interval between the centroid of the mass of rainfall excess and the time to achieve the peak discharge (Mays, 2005), and is related to time of concentration using the following equation:

$$T_{lag} = 0.6T_c \,, \qquad (1)$$

where

T_c is the time of concentration, in minutes; and
T_{lag} is the lag time, in minutes.

The Kirpich method (Gupta, 2001) was used to estimate T_c for each of the ten subbasins within the Río Grande de Manatí hydrographic basin, and is expressed as follows:

$$T_c = 0.02L^{0.77}S^{-0.385} \,, \qquad (2)$$

where

L is the length of main channel, in meters; and
S is the slope, equal to H/L where H, in meters, is the difference in elevation between the most remote point in the basin and the outlet.

The results of the lag time and time concentration calculations for each subbasin are presented in the "Hydrographic Basin Delineation" section herein.

Channel Routing

In large streams where channel storage may have an effect on the peak flow magnitude and time to peak flow, the HEC–HMS provides flow-routing techniques to account for the effects of channel storage on the runoff hydrograph (Feldman, 2000). As the flood's runoff moves through the channel, storage and energy may be lost within the streams, and it is important to account for these losses when generating runoff hydrographs for subbasins that receive runoff from an upstream subbasin (McCuen, 2005). In this study, channel routing was applied only between subbasin 3 and subbasin 4 to generate the inflow hydrograph from the Lago El Guineo Dam into Río Toro Negro (subbasin, 2, fig. 2). Flow-routing techniques were not applied to the remaining subbasins included in the breach analysis because channel routing was completed in the hydraulic analysis.

The Muskingum routing model was used to simulate channel routing and storage. The model uses the flow continuity equation to account for the storage within the channel. Model parameters required by HEC–HMS to complete channel routing include the travel time, K, of the discharge wave through the routing reach and the inflow/outflow dimensionless weighting factor, x. These parameters are commonly estimated using observed streamflow data; however, in absence of recorded streamflow data, extensive literature describes the use of the Muskingum routing method with estimated parameters. Carter and Godfrey (1960) suggest that for natural channels 0.25 may be an appropriate value for x, and travel time through the routing reach may be estimated by dividing the reach length by the mean channel velocity and a coefficient (1.44) based on the shape. Using the geometric characteristics of the reach, the mean velocity of the channel was estimated by applying Manning's equation (Gupta, 2001). The estimated K through the routing channel was about 1.5 hours assuming a mean velocity for the channel of 2 meters per second (m/s).

Basin Parameters

The SCS unit hydrograph method, used to estimate the direct runoff at each subbasin outlet resulting from each simulated rainfall event, requires estimation of the following three basin parameters: CN, T_c, and drainage area; thus, for each subbasin included in the hydrologic analysis of the Río Grande de Manatí hydrographic basin, these basin parameters were determined (table 3). In the HEC–HMS model, general characteristics for the Lago El Guineo Dam and Lago de Matrullas Dam were also included in the basin model. Stage-storage and outflow rating curves for both dams were obtained using the information provided by the Puerto Rico Electric Power Authority (1980a, 1980b) and the USGS (Soler-López, 2003a, 2003b).

Rainfall

The HEC–HMS meteorological model is the module in which the basin precipitation depth data are entered. The precipitation data may be observed rainfall from a historical event, a frequency-based hypothetical rainfall event, or an event that represents the upper limit of precipitation possible at a given location. Rainfall data for the 6- and 24-hour PMP events included in the meteorological model for the Lago El Guineo, and the other subbasins within the Río Grande de Manatí hydrographic basin, were obtained from the U.S. Department of Commerce (1961). The report provides PMP amounts for durations of 1, 3, 6, 12, 18, and 24 hours. The point PMP, derived for each subbasin, was converted to a basin-average amount using the respective depth-area relations provided in the report. The computed rainfall depths were distributed in time and space to generate the direct runoff hydrographs for the selected frequency-based hypothetical storms. Precipitation depths for various durations within the storm event with a 24-hour, 100-year recurrence interval were obtained from Bonnin and others (2006). The rainfall amounts for each subbasin and simulated storm are shown in table 4.

The user-specified hyetograph method was selected to enter the rainfall data into the meteorological model for the 6- and 24-hour PMP events. This method allows for defining the depth and temporal distribution of a hypothetical rainfall event (storm). The time distribution was derived following the chronological distribution suggested in U.S Department of Commerce (1961, p. 23–24) The Frequency-Based Hypothetical Storm method was used for the 24-hour, 100-year recurrence rainfall event simulation. All hydrologic simulations assumed the rainfall distribution, and the time at the beginning and completion of the storm, were equitable for all subbasins.

Flood Hydrographs and Peak Discharges

The flood hydrographs and peak discharges resulting from 6- and 24-hour PMP events, and for the 24-hour, 100-year recurrence rainfall event for the subbasins within the Río Grande de Manatí hydrographic basin were obtained from the HEC–HMS computer program (table 5). Results of the HEC–HMS simulations showing the flood hydrographs and peak discharges resulting from the selected frequency-based hypothetical storms are shown in appendix 1. The 6-hour PMP event generated a peak discharge of about 550 m^3/s at Lago El Guineo Dam, and a peak inflow of about 1,104 m^3/s

Table 3. Basin parameters for the study of subbasins within the Río Grande de Manatí hydrographic basin used for the dam failure analysis of the Lago El Guineo Dam, Orocovis, Puerto Rico.

[HEC-HMS, Hydrologic Engineering's Center, Hydrologic Modeling System; DA, drainage area; L, length of reach; H, elevation difference between higher and lower point in subbasin; T_c, time of concentration; T_l, travel lag time; CN, curve number]

HEC-HMS subbasin identifier	Subbasin description	DA (square kilometers)	L (kilometers)	H (meters)	T_c (hours)	T_l (hours)	CN (unitless)
1	Lago El Guineo Dam	4.25	2.74	250	0.37	0.22	73.80
2	Río Toro Negro between Lago El Guineo Dam and Río Toro Negro-Río de Matrullas confluence	42.60	16.90	895	1.86	1.12	77.70
3	Lago de Matrullas Dam	11.60	4.99	255	0.70	0.44	75.90
4	Río Matrullas between Lago de Matrullas Dam and Río Toro Negro	9.61	8.37	510	1.03	0.62	80.70
5	Río Bauta	73.30	28.60	770	3.62	2.17	83.20
6	Río Toro Negro between Río Toro and Río Grande de Manatí	22.70	14.60	455	2.04	1.22	81.90
7	Río Grande de Manatí at confluence with Río Toro Negro	189.70	38.30	710	5.23	3.14	81.20
8	Río Cialitos	43.60	26.90	830	3.28	1.97	78.40
9	Río Grande de Manatí between Río Toro Negro and Barceloneta, Puerto Rico	65.70	12.20	45	4.04	2.42	78.10
10	Río Grande de Manatí between Barceloneta, Puerto Rico and river mouth	6.99	5.70	47	1.65	0.99	82.20

Table 4. Computed rainfall at each subbasin for the selected frequency-based hypothetical dam failure scenarios used for the dam failure analysis of the Lago de Guineo Dam, Orocovis, Puerto Rico.

[Data from U.S. Department of Commerce (1961); Bonnin and others (2006); HEC-HMS, Hydrologic Engineering Center, Hydrologic Modeling System PMP; probable maximum precipitation; N/A, not applicable]

HEC-HMS subbasin identifier	Subbasin description	Computed rainfall (millimeters)		
		24-hour PMP	6-hour PMP	24-hour, 100-year rainfall
1	Lago El Guineo Dam	1,397	851	630
2	Río Toro Negro between Lago El Guineo Dam and Río Toro Negro-Río de Matrullas confluence	1,170	788	528
3	Lago de Matrullas Dam	1,390	828	599
4	Río Matrullas between Lago de Matrullas Dam and Río Toro Negro	1,157	792	452
5	Río Bauta	1,317	792	467
6	Río Toro Negro between Río Matrullas and Río Grande de Manatí	1,010	747	422
7	Río Grande de Manatí at confluence with Río Toro Negro	1,015	648	376
8	Río Cialitos	998	709	490
9	Río Grande de Manatí between Río Toro Negro and Barceloneta, Puerto Rico	965	686	310
10	Río Grande de Manatí between Barceloneta, Puerto Rico and river mouth	N/A	N/A	340

Table 5. Peak discharges at each subbasin resulting from the 6- and 24-hour probably maximum precipitation events, and the 24-hour, 100-year recurrence interval used for the dam failure analysis of the Lago El Guineo Dam, Orocovis, Puerto Rico.

[HEC-HMS, Hydrologic Engineering Center, Hydrologic Modeling System; PMP, probable maximum precipitation; m^3/s, cubic meter per second; ft^3/s cubic foot per second]

HEC-HMS subbasin identifier	Subbasin description	Peak discharge		
		6-hour PMP, m^3/s (ft^3/s)	24-hour PMP, m^3/s (ft^3/s)	24-hour, 100-year flood m^3/s (ft^3/s)
1	Lago El Guineo Dam	550 (19,426)	414 (14,626)	216 (7,636)
2	Río Toro Negro between Lago El Guineo Dam and Río Toro Negro-Rio de Matrullas confluence	2,464 (87,030)	2,665 (94,122)	960 (33,890)
3	Lago de Matrullas Dam	1,104 (38,995)	1,032 (36,442)	418 (14,750)
4	Río Matrullas between Lago de Matrullas Dam and Río Toro Negro	771 (27,221)	696 (24,589)	248 (8,762)
5	Río Bauta	3,141 (110,945)	4,150 (146,560)	1,077 (38,025)
6	Río Toro Negro between Río Matrullas and Río Grande de Manatí	1,218 (43,005)	1,200 (42,393)	408 (14,409)
7	Río Grande de Manatí at confluence with Río Toro Negro	5,350 (188,967)	5,469 (193,150)	1,860 (65,702)
8	Río Cialitos	1,691 (59,730)	1,842 (65,075)	654 (23,096)
9	Río Grande de Manatí between Río Toro Negro and Barceloneta, Puerto Rico	2,200 (77,689)	2,397 (84,670)	576 (20,359)
10	Río Grande de Manatí between Barceloneta, Puerto Rico and river mouth	N/A	N/A	(278) 9,816

at Lago de Matrullas Dam. The 24-hour PMP event produced peak inflows of 414 m^3/s and 1,032 m^3/s at Lago El Guineo Dam and Lago de Matrullas Dam, respectively. The 24-hour, 100-year recurrence event simulations resulted in a peak inflow of about 216 m^3/s at Lago El Guineo Dam and about 418 m^3/s at Lago de Matrullas Dam.

The simulation results indicate that Lago El Guineo Dam would not experience overtopping for any of the hydrologic simulations. In addition, the morning-glory type spillway would discharge water at its maximum capacity of 212 m^3/s. The results showed that the 6-hour PMP event produced a higher peak discharge than the 24-hour PMP event. The maximum precipitation flood, which is the flood resulting from the more severe combination of hydrologic and meteorological conditions, resulted in 550 m^3/s.

Hydraulic Study

The purpose of the hydraulic study was to assess the potential hazard to human life and property downstream from the Lago El Guineo Dam associated with the hypothetical dam failure during floods from 6- and 24-hour PMP events, a 24-hour, 100-year recurrence rainfall event, and sunny-day conditions (nonflood). The HEC–RAS computer program (Brunner, 2010) was used to determine flood level, flood peak, and time to peak after dam failure at selected locations downstream from the Lago El Guineo Dam for each simulated breach condition.

Modeling Approach

The HEC–RAS unsteady flow analysis uses a breach model to simulate dam failure. The hydraulic model requires the following input data: the stream cross section, hydraulic structure, dam and reservoir geometry, inflow hydrographs, dam breach parameters, and Manning's roughness coefficient (n). Unsteady flow simulations require the user to define conditions at all external boundaries of the system and at internal locations where inflows enter (or exit) the system. Additionally, the manner by which reaches are joined or connected together in the system must also be specified; hence, dam breach flows are routed downstream through the river system. The hydraulic model is archived and accessible to the public in the USGS Water Resources NSDI Node [http://dx.doi.org/10.5066/F72J690R].

The breach model uses an inline weir to simulate the dam embankment and the breach shape. A simple temporal and geometrical description of the breach is used to simulate how the breach progresses during the failure. The outflow hydrograph, routed through the reservoir, which results from the breach, is computed using a broad-crested weir flow estimation that includes the effects of submergence from downstream tail-water depths. Dynamic wave routing is used to attenuate the inflow hydrograph within the reservoir. The computer model solves the one-dimensional unsteady flow equations using the four-point, implicit, finite-difference scheme also known as the box scheme. The four-point, implicit, finite-difference scheme results in a system of nonlinear algebraic equations. To avoid the nonlinear solution, the HEC–RAS application incorporates into its computer routine a technique developed by Preissmann (as reported by Liggett and Cunge, 1975) and Chen (1973) for linearizing the equations. Downstream routing through the channel includes the hydrograph resulting from the failure of the dam and the lateral inflows (from tributaries) entering the study reach.

In the HEC–RAS model, the hydraulic system was subdivided into three hydraulic reaches: the Río Toro Negro upper reach, the Río Toro Negro lower reach, and the Río Grande de Manatí lower reach (fig. 5). Each study reach was analyzed in separate models so the outflow hydrograph resulting from the hydraulic model of the Río Toro Negro upper reach is used as the inflow hydrograph to the Río Toro Negro lower reach. Similarly, the outflow hydrograph of the Río Toro Negro lower reach corresponded to the inflow hydrograph for the Río Grande de Manatí lower reach. For the Río Grande de Manatí, the geometric module included an additional reach segment from Barceloneta, Puerto Rico, through the river mouth (subbasin 10, fig. 2) to determine the water-surface elevations for the 24-hour, 100-year recurrence rainfall event and sunny-day conditions. Contributions from other streams discharging into each hydraulic reach are also included as lateral inflows.

Geometric Data

The hydraulic analysis used 69 cross sections to define the natural channel geometry of the stream reaches. A total of 28 cross sections defined the geometry of the upper reach of the Río Toro Negro, 12 cross sections defined the geometry of the lower reach of the Río Toro Negro, and 29 cross sections defined the geometry of the lower reach of the Río Grande de Manatí. The cross-section data were generated from the 1:20,000 USGS topographic quadrangles of Barceloneta, Barranquitas, Ciales, Corozal, Florida, Jayuya, Manatí, Orocovis, and Vega Alta, Puerto Rico. The lower reach of the Río Grande de Manatí also included cross-section data obtained from the Flood Insurance Study [FIS, (Carmen Delgado, Federal Emergency Management Agency, oral commun., 2014)] The upper reach of the Río Toro Negro is about 14.5 km long and includes the Lago El Guineo Reservoir and the river segment downstream between the Lago EL Guineo Dam and the confluence of Rio Toro Negro and Rio de Matrullas. The Lago El Guineo Reservoir bottom was defined using 11 cross-section lines. These cross sections were obtained from a bathymetric survey of Lago El Guineo completed by the USGS in December 2001 (Soler-López, 2003b). A cross section defining the Lago El Guineo Dam structure was obtained from engineering construction drawings provided by the PREPA (Puerto Rico Electric Power Authority, 1980a). The Manning's roughness coefficient (n) selected for the reservoir segment was set to 0.040. Along the lower reach length below the dam, the streambed elevation drops about 500 m, and n values range from 0.055 to 0.15.

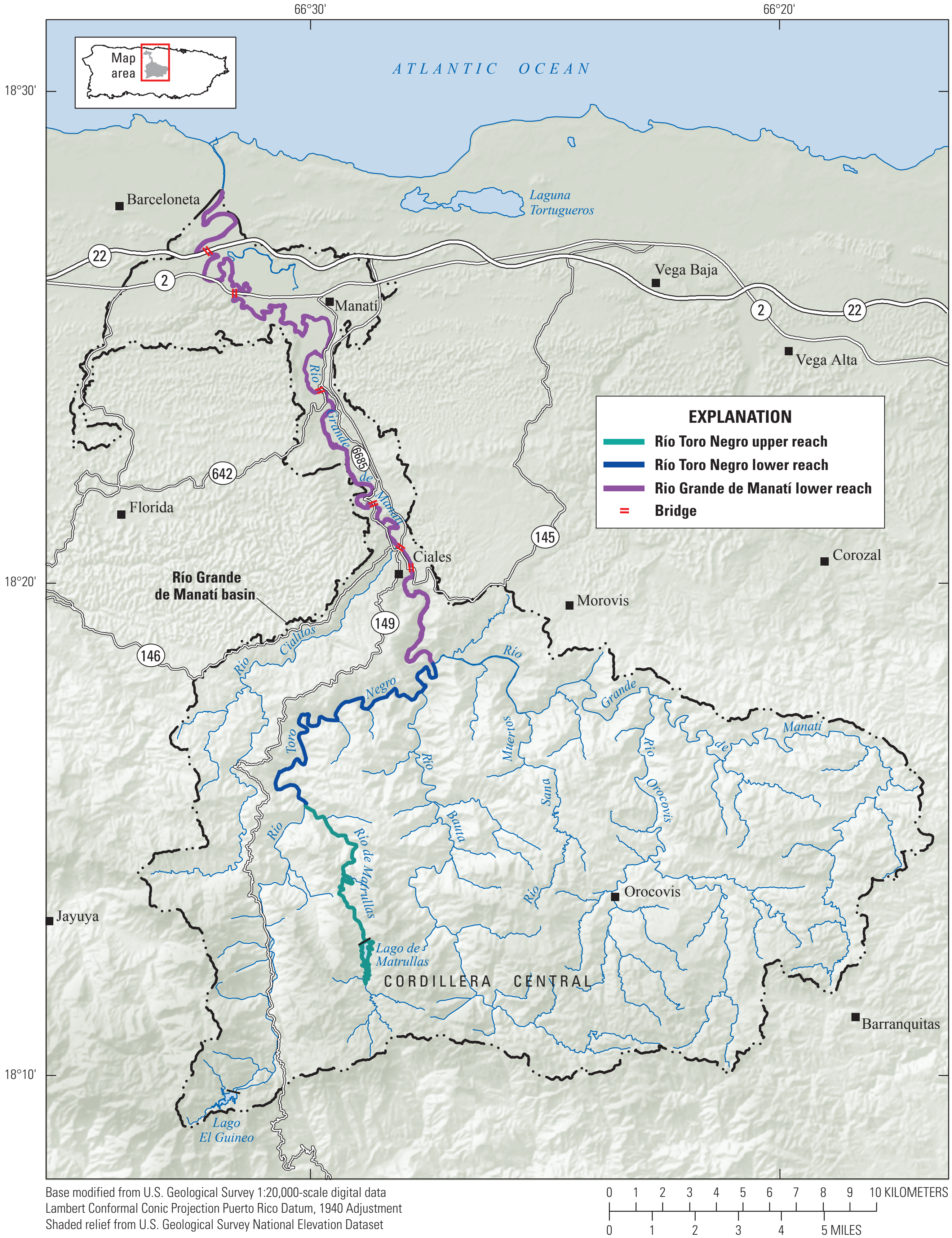


Figure 5. Hydraulic system simulated as part of the dam failure analysis for the Lago El Guineo Dam, Orocovis, Puerto Rico.

The hydraulic system including the lower reach of the Río Toro Negro is about 14.5 km long and extends from the Río Toro Negro-Rio de Matrullas confluence to the Rio Toro Negro-Río Grande de Manatí confluence. An *n* value of 0.045 was assigned for the main channel, and *n* values from 0.065 to 0.075 were used for the channel banks.

The lower reach of the Río Grande de Manatí is about 22 km long and extends from the junction with the Río Toro Negro north to Barceloneta,. A further reach extension from Barceloneta to the river mouth (subbasin 10, fig. 2) was included in the analysis for the simulated scenarios of a 24-hour, 100-year recurrence rainfall event and sunny-day conditions. For the 6- and 24-hour PMP events, the aforementioned extension was not considered because preliminary results showed that overtopping happened near to Barceloneta and appropriate geometric data were not available to determine the flood extent beyond levee structure. The *n* values for the lower reach of the Río Grande de Manatí vary widely. An *n* value from 0.038 to 0.045 was assigned for the main channel, and from 0.07 to 0.10 for the flood plain. All the *n* values were assigned based on field reconnaissance during March 2014 and interpretation of aerial photographs (U.S. Corps of Engineers, 2010).

Hydraulic structures such as main bridges were included in the lower reach of Río Grande de Manatí. A total of six bridges were incorporated in the analysis, and their geometric data were obtained from the Puerto Rico Highway and Transportation Authority (Dr. Luis Col, Bridge Engineering Office, oral commun., 2014). Additional geometric data for the area were obtained from the hydrologic-hydraulic study used for the Flood Insurance Study [FIS, (Carmen Delgado, Federal Emergency Management Agency, oral commun., 2014)] published for the study area. A levee located near Barceloneta was included in the model by using the levee option available in the HEC–RAS model.

Boundary, Reach Connections, and Initial Conditions

The upstream boundary conditions of the Río Toro Negro upper reach correspond to the inflow hydrograph determined by the HEC–HMS model for each of the three simulated rainfall events. For the Río Toro Negro lower reach, the upstream boundary conditions correspond to the outflow hydrograph resulting from the Río Toro Negro upper reach simulation. Similarly, the upstream boundary conditions of the Río Grande de Manatí lower reach are obtained from the outflow hydrographs that resulted from the simulation of the Río Toro Negro lower reach. The downstream boundary conditions for the three study reaches were assumed to represent normal depth (defined as a condition in which the slope of the surface water and the bottom of the channel are equal).

Internal boundary conditions, also known as lateral inflows, were used to represent inflows from the lower reach of the Río Matrullas, the Río Bauta, the Río Cialitos, and the upper reach of the Río Grande de Manatí (fig. 5). The lateral inflows were determined by the HEC–HMS model for each of the simulated rainfall events.

To avoid model instability, the HEC–RAS model provides an alternative simulation that uses "hot start" initial conditions from a previous simulation with all inflow hydrographs set to a constant flow and the downstream boundary conditions set as a stage hydrograph from a high tail water elevation to normal depth. The hot start simulation prevents unsteady flow simulation issues resulting from channels becoming dry during simulation. Typical values for upstream boundary conditions in the hot start simulation are based on observed base-flow data or a constant flow estimated using 1 to 10 percent of the peak discharge of the simulated storm (Chris Goodell, West Consultant Inc., oral commun., 2014). For the Lago El Guineo reach, the upstream boundary condition used in the hot start simulation specified a constant flow equal to 5 percent of the peak flow calculated in the hydrologic study for the 6-hour PMP event. For the internal boundary conditions (lateral inflows) included along the three hydraulic reaches, a constant flow equal to 1 percent of the peak flow estimated from the 24-hour, 100-year recurrence rainfall event for each subbasin was used.

Breach Parameters and Failure Criteria

The parameters considered most critical in any analysis of dam breaching are the maximum size of the breach opening and the breach formation time (Federal Emergency Management Agency, 2013). Embankment dam breaches are typically assumed to be generally trapezoidal in shape. The breach geometry can be described in terms of breach height, average breach width, and breach side slope. The slope of the breach invert is assumed to be horizontal in the direction of flow. The breach formation time is the elapsed time between the first breaching of the upstream face of the dam and the complete formation of the breach. These parameters describe the breach geometry to the extent needed to compute flow rates through the breach, assuming the discharge characteristics of a broad-crested weir.

Several methods can be used to estimate dam breach parameters and are classified in three main groups: physically-based erosion methods, parametric regression equations, and predictor regression equations. The first group of methods predicts the breach development and outflow hydrograph based on physical properties such as stage-storage relationships, soil properties in the dam, and dam dimensions. The second group of methods is based on the analysis of dam breach case studies and uses empirical equations developed for estimating the breach width and time to failure. The third group involves regression equations obtained using case-study information to estimate breach peak discharges (Federal Emergency Management Agency, 2013). The Bureau of Reclamation, as well as others who study dam breach, has developed several empirical relations to estimate breach parameters. For dam failure analysis of the Lago de Guineo Dam, relations proposed by Wahl (1998) were selected to estimate the breach width and time of failure. The following equations were used to estimate the dam breach parameters:

$$B = 3 * h_w, \quad (3)$$

and

$$t_f = 0.011 * B, \quad (4)$$

where

- B is the average dam-breach width, in meters;
- h_w is the height of water above the dam breach invert at time of failure, in meters; and
- t_f is the time of failure since the beginning of the upstream face breach, in hours.

A unique set of dam breach parameters (breach width and time to failure) was selected for all breach scenarios; however, a sensitivity analysis was completed to evaluate breach peak discharge variability when changing breach parameters. The height of water above the dam breach used for dam breach parameter calculations was based on the highest water-surface elevation resulting from the HEC–HMS model. The results of the hydrologic analysis indicated that the maximum water-surface elevation within the Lago El Guineo Reservoir (906.43 m) was achieved during the 24-hour PMP rainfall event. Assuming the final elevation of the breach is at approximately 882.05 m, the height of water (h_w) above the breach crest is approximately 24.38 m. Using relations developed by Reclamation, the average dam-breach width is about 73.2 m, and the time to failure is 0.80 hour. The HEC–RAS model uses a trapezoidal section to simulate the final form of the dam breach. The breach side slopes were assumed to have a side slope of 0.5, and the final bottom width was approximately 60.96 m.

Dam breach caused by piping was selected for all breach scenarios based on the hydrologic analysis results, which showed that for any of the hydrologic conditions, no overtopping would happen at the dam. For the piping failure condition, the breach started when the peak discharge for each simulated storm reached the dam (worst-case scenario). The breach for the sunny-day simulation was initiated when the water-surface elevation in Lago El Guineo Dam was approximately 902.16 m (morning-glory spillway invert). All scenarios assumed that the reservoir emptied during the simulation. Dam breach parameters used to simulate the dam failure are listed in table 6.

Dam Failure Simulations and Results

Results are presented only for selected locations along the lower reach of the Río Grande de Manatí even though the flood wave was routed downstream through the Rio Toro Negro upper reach, the Rio Toro Negro lower reach, and the Rio Grande de Manatí lower reach (fig. 5). The results of the dam failure analysis during the 6- and 24-hour PMP events, 24-hour, 100-year recurrence rainfall event, and sunny-day conditions are presented in figures 6–7.

Dam Failure Under Probable Maximum Precipitation Conditions

The peak discharges produced by dam failure at the toe of Lago El Guineo Dam were computed as 1,342.43 m^3/s for the 6-hour PMP event and 1,434.69 m^3/s for the 24-hour PMP event. Along the Río Grande de Manatí lower reach and about 0.6 km upstream from the PR–145 bridge (fig. 5), the peak discharge was 11,524.35 m^3/s for the 6-hour PMP event and 13,281.63 m^3/s for the 24-hour PMP event. Near Barceloneta at PR–22 bridge (fig. 5), the peak discharge was 12,618.97 m^3/s for the 6-hour PMP event and 14,441.60 m^3/s for the 24-hour PMP event. The results showed that the flow contribution owing to failure of Lago El Guineo Dam would be about 12 percent and 11 percent of the total flow arriving in the downstream zone for the 6-hour PMP and 24-hour PMP, respectively. The maximum water-surface profiles resulting from these flood events along the lower reach of the Río Grande de Manatí are shown in figures 6 and 7. Both breach scenarios result in overtopping of the PR–6685, PR–642, PR–149, and PR–145 bridges. The results also showed that the levee overtopped near Barceloneta; however, additional information was not available to determine the flood extension. Dam failure analysis results are summarized in tables 7 and 8.

Table 6. Breach parameters used for the dam failure analysis of the Lago El Guineo Dam, Orocovis, Puerto Rico.

[PMP, probable maximum precipitation]

Breach parameter	Value
Center station, in meters (feet)	146.29 (480)
Final bottom width, in meters (feet)	60.96 (200)
Final bottom elevation, in meters (feet) above mean sea level	882.05 (2,894)
Left side slope	0.5
Right side slope	0.5
Full formation time, in hours	0.80
Failure mode	Piping
Piping coefficient	0.8
Initial piping elevation, in meters (feet)	896.07 (2,940)
Trigger elevation for sunny day, in meters (feet) above mean sea level	902.16 (2,960)
Trigger time for 6-and-24 hour PMP, and 100-year flood	Time to peak of inflow hydrograph

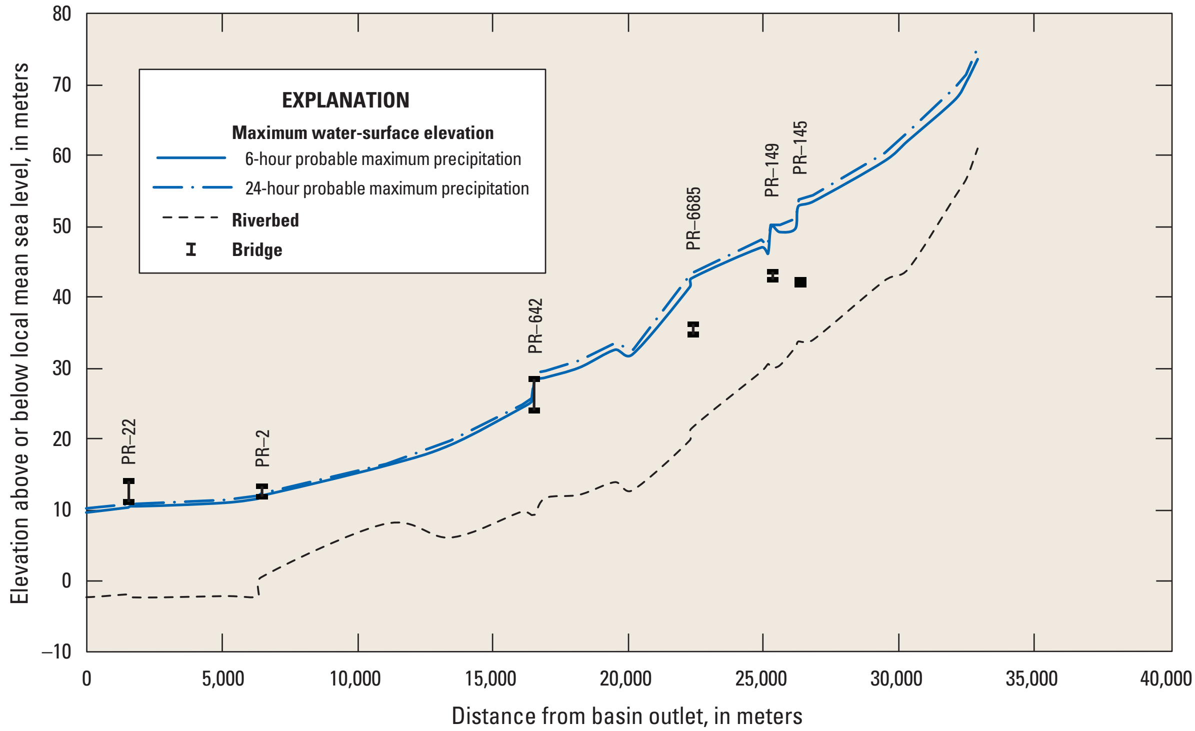


Figure 6. Maximum water-surface profile along the lower reach of the Rio Grande de Manatí for the 6-and 24-hour probable maximum precipitation storm events of the dam failure analysis for the Lago El Guineo Dam, Orocovis, Puerto Rico.

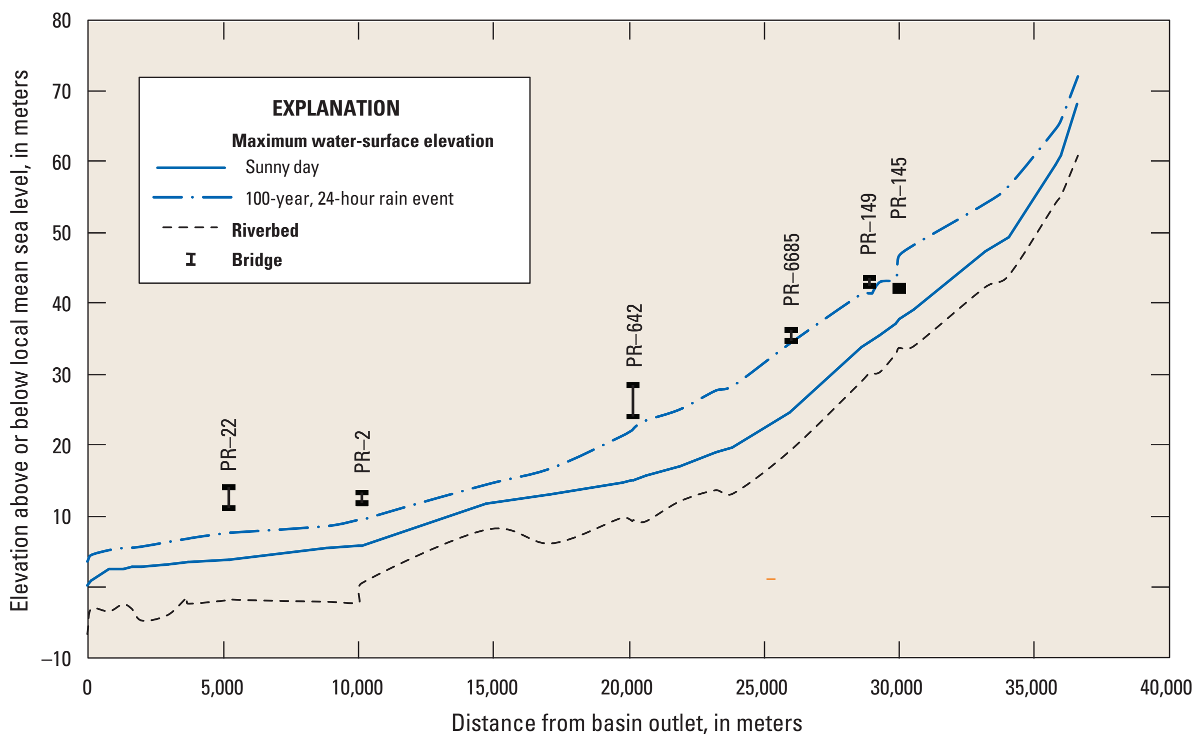


Figure 7. Maximum water-surface profile along the lower reach of the Rio Grande de Manatí for the 24-hour, 100-year recurrence rainfall event and sunny-day conditions of the dam failure analysis for the Lago El Guineo Dam, Orocovis, Puerto Rico.

Table 7. Results for the 6-hour probable maximum precipitation event at selected cross sections along the lower reach of the Río Grande de Manatí for the dam failure analysis of the Lago El Guineo Dam, Orocovis, Puerto Rico.

[Refer to plate 1 for location of cross sections. km; kilometer]

Cross-section number	Nearby landmark	Distance from Lago El Guineo Dam (kilometers)	Peak discharge, cubic meters per second (cubic feet per second)	Peak elevation, meters (feet)	Time to peak (hours)
13	2.7 km downstream from the confluence between Río Toro Negro and Río Grande de Manatí	31.6	11,535.56 (407,434)	62.85 (206.22)	2.00
11	0.6 km upstream from PR–145 Bridge	35.1	11,524.35 (407,038)	54.12 (177.56)	2.25
9	At PR–6685 Bridge	39.6	13,043.94 (460,710)	41.49 (136.12)	2.50
7	1.7 km upstream from PR–642 Bridge	43.7	13,015.52 (459,706)	30.12 (98.80)	2.75
5	1.8 km south of Manatí, Puerto Rico	48.5	12,981.6 (458,508)	19.21 (63.03)	3.00
3	At PR–2 Bridge	55.6	12,794.28 (451,892)	11.82 (38.79)	3.25
1.4	Near Barceloneta, Puerto Rico, at PR–22 Bridge	61.9	12,618.97 (445,700)	10.37 (34.03)	3.75

Table 8. Results for the 24-hour probable maximum precipitation event at selected cross sections along the lower reach of the Río Grande de Manatí for the dam failure analysis of Lago El Guineo Dam, Orocovis, Puerto Rico.

[Refer to plate 2 for location of cross sections. km, kilometer]

Cross-section number	Nearby landmark	Distance from Lago El Guineo Dam (kilometers)	Peak discharge, cubic meters per second (cubic feet per second)	Peak elevation, meters (feet)	Time to peak (hours)
13	2.7 km downstream from the confluence between Río Toro Negro and Río Grande de Manatí	31.6	13,307.79 (470,029)	64.19 (210.61)	1.75
11	0.6 km upstream from PR–145 Bridge	35.1	13,281.63 (469,105)	55.39 (181.74)	2.00
9	At PR–6685 Bridge	39.6	14,994.04 (529,587)	42.89 (140.71)	2.25
7	1.7 km upstream from PR–642 Bridge	43.7	14,953.18 (528,144)	31.05 (101.89)	2.50
5	1.8 km south of Manatí, Puerto Rico	48.5	14,913.32 (526,736)	19.67 (64.53)	2.75
3	At PR–2 Bridge	55.6	14,664.9 (517,962)	12.26 (40.24)	3.00
1.4	Near Barceloneta, Puerto Rico, at PR–22 Bridge	61.9	14,441.6 (510,075)	10.84 (35.58)	3.50

Dam Failure Under 100-Year Flood Conditions

The dam failure for the 24-hour, 100-year recurrence rainfall event (100-year flood) started when the peak inflow discharge reached the Lago El Guineo Dam, the pool elevation at the dam was approximately 903.12 m. At the toe of the Lago El Guineo Dam, the computed peak discharge produced by the dam failure was 1,183.12 m^3/s. Along the Río Grande de Manatí lower reach, a peak discharge of 4,850.19 m^3/s was estimated about 0.6 km upstream from the near the PR–145 bridge. Near Barceloneta at PR–22 bridge, the peak discharge was 4,641.95 m^3/s. Flow contribution of the Lago El Guineo Dam resulted in about 25 percent of total flow affecting the downstream zone. The maximum water-surface profile resulting from this flood event along the lower reach of the Río Grande de Manatí is shown in figure 7. The water-surface profile indicates overtopping of the PR–6685 and PR–145 bridges. Dam failure analysis results for selected cross sections are summarized in table 9.

Dam Failure Under Sunny Day Conditions

Failure of the Lago El Guineo Dam under sunny-day conditions was initiated at a reservoir pool elevation of approximately 902.16 m. The estimated peak discharge just downstream from the Lago de Guineo Dam was 1,015.31 m^3/s. Sunny-day conditions, which by definition consider only flooding from the dam breach, assumed lateral inflows equal to base-flow values defined on initial conditions section. Along the Río Grande de Manatí lower reach, the peak discharge about 0.6 km upstream from the PR–145 bridge was 568.66 m^3/s. Estimated discharge was 229.28 m^3/s near Barceloneta at PR–22 bridge. Substantial attenuation is observed by comparing the breach peak flow and flood wave arriving at downstream zone with a decrease of about 77 percent. The maximum water-surface profile along the lower reach of the Río Grande de Manatí indicates no bridge overtopping (table 9). Dam failure analysis results at selected cross sections are summarized in table 10.

Sensitivity Analysis

A sensitivity analysis was designed to determine the effect in the breach peak discharge estimates by varying the breach parameters. The base-case scenario considered a piping dam failure mode, and involved a final breach width and breach formation time of 60.96 m and 0.8 hour, respectively. These breach parameters were modified for the simulated hydrologic condition of 6-hour PMP, which resulted with the higher peak discharge in the hydrologic analysis. Piping dam failure was evaluated by varying the breach final bottom width and breach formation time (table 11).

The breach simulation results indicated that the breach-formation time has a greater effect on the breach peak discharge at the Lago El Guineo Dam than the final bottom width of breach (table 11). A difference of 26 percent was observed when the breach-formation time was reduced compared to the base-case scenario, which uses a breach-formation time of 0.80 hour; nevertheless, the results indicated a difference of less than 5 percent when the final bottom width is reduced compared to the base-case scenario. Sensitivity

Table 9. Results for the 24-hour 100-year recurrence rainfall event at selected cross sections along the lower reach of the Río Grande de Manatí for the dam failure analysis of the Lago El Guineo Dam, Orocovis, Puerto Rico.

[Refer to plate 3 for location of cross sections. km, kilometer]

Cross-section number	Nearby landmark	Distance from Lago El Guineo Dam (kilometers)	Peak discharge, cubic meters per second (cubic feet per second)	Peak elevation, meters (feet)	Time to peak (hours)
13	2.7 km downstream from the confluence between Río Toro Negro and Río Grande de Manatí	31.6	5,010.19 (176,959)	56.68 (185.98)	1.00
11	0.6 km upstream from PR–145 Bridge	35.1	4,850.19 (171,308)	48.25 (158.63)	1.25
9	At PR–6685 Bridge	39.6	5,380.49 (190,038)	34.46 (113.06)	1.50
7	1.7 km upstream from PR– 642 Bridge	43.7	5,233.97 (184,863)	25.11 (82.37)	2.00
5	1.8 km south of Manatí, Puerto Rico	48.5	5,086.77 (179,664)	16.78 (55.05)	2.5
3	At PR–2 Bridge	55.6	4,907.04 (173,316)	9.50 (31.16)	3.00
1.4	Near Barceloneta, Puerto Rico, at PR–22 Bridge	61.9	4,641.95 (163,953)	7.64 (25.07)	3.75

Table 10. Results for sunny-day conditions at selected cross sections along the lower reach of the Río Grande de Manatí for the dam failure analysis of the Lago El Guineo Dam, Orocovis, Puerto Rico

[Refer to plate 4 for location of cross sections. km, kilometer]

Cross section number	Nearby landmark	Distance from Lago El Guineo Dam (kilometers)	Peak discharge, cubic meters per second (cubic feet per second)	Peak elevation, meters (feet)	Time to peak (hours)
13	2.7 km downstream from the confluence between Río Toro Negro and Río Grande de Manatí	31.6	700.48 (24,741)	49.57 (162.65)	1.50
11	0.6 km upstream from PR–145 Bridge	35.1	568.66 (20,085)	39.07 (128.19)	2.00
9	At PR–6685 Bridge	39.6	520.59 (18,387)	24.63 (80.81)	2.25
7	1.7 km upstream from PR–642 Bridge	43.7	450.06 (15,896)	17.06 (55.97)	2.75
5	1.8 km south of Manatí, Puerto Rico	48.5	339.87 (12,004)	13.16 (43.17)	3.50
3	At PR–2 Bridge	55.6	271.2 (9,579)	5.84 (19.16)	5.00
1.4	Near Barceloneta, Puerto Rico, at PR–22 Bridge	61.9	229.28 (8,098)	3.88 (12.72)	6.00

Table 11. Breach parameters used in the sensitivity analysis considering adjustments in the final bottom-width for the dam failure analysis of the Lago El Guineo Dam, Orocovis, Puerto Rico.

[HEC-RAS, Hydrologic Engineering Center- River Analysis System; hr, hour; PMP, probable maximum precipitation; PP, piping; ws, water surface; N/A, not applicable]

Breach parameters	HEC-RAS simulation plan identification				
	6hr_PMP_PP	6hr_PMP_PP1	6hr_PMP_PP2	6hr_PMP_PP3	6hr_PMP_PP4
Center station in meters (feet)	146.30 (480)	146.30 (480)	146.30 (480)	146.30 (480)	146.30 (480)
Final bottom width in meters (feet)	60.96 (200)	48.77 (160)	73.15 (240)	60.96 (200)	60.96 (200)
Final bottom elevation in meters (feet)	882.05 (2,894)	882.05 (2,894)	882.05 (2,894)	882.05 (2,894)	882.05 (2,894)
Left side slope	0.5	0.5	0.5	0.5	0.5
Right side slope	0.5	0.5	0.5	0.5	0.5
Breach weir coefficient	2.6	2.6	2.6	2.6	2.6
Full formation time (hour)	0.80	0.80	0.80	0.6	1
Failure mode	Piping	Piping	Piping	Piping	Piping
Trigger at	Set time	Set time	Set time	Set time	Set time
Piping coefficient	0.8	0.8	0.8	0.8	0.8
Initial piping elevation in meters (feet)	896.07 (2,940)	896.07 (2,940)	896.07 (2,940)	896.07 (2,940)	896.07 (2,940)
Trigger failure time	1:54	1:54	1:54	1:54	1:54
Peak discharge at Lago El Guineo Dam, in cubic meters per second (in cubic feet per second)	1, 342.43 (47,414)	1,310.67 (46,293)	1,344.61 (47,491)	1,697.73 (59,963)	1,136.1 (40,127)
Percent difference	N/A	–2.4	0.2	26.5	–15.4

analysis modifications to the side slope of the breach were also completed, but they are not presented herein because results indicated that this parameter did not substantially affect peak discharge at the dam.

Inundation Maps

For each simulated flood condition, inundation maps were prepared to depict the areas that would be affected as a result of the hypothetical failure of the Lago El Guineo Dam. The flood boundaries are based on the maximum water-surface elevations resulting from the simulated dam breaches. Inundation maps were delineated for the Río Grande de Manatí lower reach, but because the inundation boundaries are estimated, the results may not include areas where there would be shallow flooding.

The delineation of the flood boundaries near Barceloneta considered the effects of the levee recently constructed (2000) in the flood plain of the Río Grande de Manatí to provide flood protection to the low-lying populated areas of Barceloneta (Carmen Delgado, Federal Emergency Management Agency, oral commun., 2014). Other valuable information presented in the inundations maps includes the distance from the Lago El Guineo Dam, peak flow or peak elevation, and time elapsed between the dam failure and the time at which the maximum water level is reached (wave peak travel time). The dam failure results at selected locations along the lower reach of the Río Grande de Manatí for the 6- and 24-hour PMP events are shown in plates 1 and 2, respectively. The dam failure results for the 24-hour, 100-year recurrence rainfall event are shown in plate 3. Results for a dam failure under sunny-day conditions are shown on plate 4. Spatial data for the dam failure analysis are provided in Gómez-Fragoso and Torres-Sierra (2016).

Model results indicate that a dam failure of the Lago El Guineo Dam under any of the simulated flood conditions would result in severe flooding of downstream populated urban and rural areas and farmlands. The levee built near Barceloneta would be overtopped for the hypothetical 6-and 24-hour PMP events; the levee would not be overtopped for the 24-hour, 100-year recurrence rainfall event or sunny-day conditions. The most affected areas include, among others, the low-lying areas of Ciales, Manatí, and Barceloneta, Puerto Rico.

Uncertainties in the Flood Inundation Maps

Several uncertainties are inherent in the preparation of flood-inundation maps used to represent the flooding caused by simulated dam failure. Sources of uncertainty include the available topographic and hydraulic data, as well as the modeling assumptions used in the analysis. These uncertainties and assumptions can lead to results that differ from those that would happen during an actual event. In addition, not all physical processes, such as sediment transport and scour that may happen during dam failure and flood-wave propagation, are considered in the model. Both processes may cause changes in the channel geometry. Another assumption made as part of the analysis was that hydraulic structures such as bridges that are exposed to potential hazards during flood events, such as scour and debris jams that can block bridges openings, would not collapse as a result of flooding. Another source of uncertainty is in the breach development model used because even though it is based on specific dam characteristics and empirical relations, the models simulate only hypothetical dam failure scenarios. As indicated by the sensitivity analysis results, peak discharge is strongly affected by variations in the breach model parameters, specifically final breach width and breach-formation time; thus, the peak discharge and flood-wave travel time represented in the inundation map can vary greatly depending on the actual nature of the dam breach.

Summary and Conclusions

Hydrologic and hydraulic analyses were completed to assess the potential hazard to human life and property downstream from the Lago El Guineo Dam associated with four hypothetical dam failure scenarios: (1) a 6-hour probable maximum precipitation (PMP) event, a 24-hour PMP event, a 24-hour, 100-year recurrence rainfall event, and “sunny-day conditions”(nonflood conditions). These analyses were completed in order to prepare flood-inundation maps that delineate the areas that would likely be flooded as a result of dam failure. The dam failure analysis was completed by the U.S. Geological Survey, in cooperation with the Puerto Rico Electric Power Authority, to provide the data needed to prepare an Emergency Action Plan (EAP) for the Lago El Guineo Dam.

The hydrologic analyses consisted of defining runoff hydrographs and peak discharges for the Lago El Guineo drainage basin and other subbasins within the Río Grande de Manatí hydrographic basin for the 6- and 24-hour PMP events and 24-hour 100-year recurrence rainfall event. The Hydrologic Engineering Center’s Hydrologic Modeling System (HEC–HMS) developed by the U.S. Army Corps of Engineers was used to determine these hydrographs and peak discharges. The peak inflow discharges at the Lago El Guineo Dam for the 6- and 24-hour PMP storms were estimated to be 550 and 414 cubic meters per second (m^3/s), respectively. The 24-hour 100-year recurrence rainfall event produced a peak inflow discharge of about 216 m^3/s.

Results from the hydrologic analysis under nonfailure conditions indicate that the 6- and 24-hour PMP events, as well as the 24-hour 100-year recurrence rainfall event would not overtop the Lago El Guineo Dam. The Hydrologic Engineering Center’s River Analysis System (HEC–RAS) developed by the U.S. Army Corps of Engineers was used to determine flood level, flood peak, and time to peak since dam failure at specific locations downstream from the Lago El Guineo Dam for each simulated breach condition. The dam failure analysis was completed using the unsteady flow module available in HEC–RAS.

The failure criteria applied to all the hydrologic conditions was piping. The dam failure for the 6- and 24-hour PMP events was set to begin at the time of the peak of the inflow hydrograph. At the toe of the Lago El Guineo Dam, the peak discharges produced by the dam failure were 1,342.43 m^3/s for the 6-hour PMP event and 1,434.69 m^3/s for the 24-hour PMP event. The flood wave was routed downstream along the lower reaches of the Río Toro Negro and Río Grande de Manatí. Along the Río Grande de Manatí, about 0.6 kilometers upstream from the PR–145 bridge, the peak discharges were 11,524.35 m^3/s for the 6-hour PMP event and 13,281.63 m^3/s for the 24-hour PMP event. Near Barceloneta, Puerto Rico, at the PR–22 bridge, the peak discharge was 12,618.97 m^3/s for the 6-hour PMP event and 14,441.60 m^3/s for the 24-hour PMP event. The flood wave arrival times near Barceloneta at PR–22 bridge were 3.75 and 3.5 hours for the 6- and 24-hour PMP events, respectively.

The dam failure for the 24-hour, 100-year recurrence rainfall event began when the peak discharge arrived at the Lago El Guineo Dam, and the selected failure criteria were either piping failure or internal erosion. The reservoir pool elevation when the breach begins is 906.43 meters. At the toe of the Lago El Guineo Dam, the peak discharge produced by the dam failure was 1,183.12 m^3/s. The peak discharges along the Río Grande de Manatí lower reach were 4,850.19 m^3/s about 0.6 kilometers upstream from the PR–145 bridge, and 4,641.95 m^3/s near Barceloneta at PR–22 bridge.

Failure of the Lago El Guineo Dam under sunny-day conditions began at a reservoir pool elevation of 902.16 meters, which is the morning-glory spillway crest elevation. The peak discharge simulated directly downstream from the Lago de Guineo Dam was 1,015.31 m^3/s. Along the Río Grande de Manatí, the peak discharge about 0.6 kilometers upstream from the bridge crossing at PR–145 was 568.66 m^3/s. The flood wave near Barceloneta at PR–22 bridge had a peak discharge of 229.28 m^3/s, and the flood-wave arrival time was about 6 hours.

Model results indicate that a failure of the Lago El Guineo Dam during any of the simulated flow conditions would result in flooding of downstream populated areas and farmlands. The hydraulic analysis also included effects of the flood control (levee) structure constructed to provide protection to the low-lying populated areas of Barceloneta, Puerto Rico. The results indicated that the most affected areas owing to failure of the Lago El Guineo Dam were the low-lying areas of Ciales, Manatí, and Barceloneta. The results indicated that several bridges along the Río Grande de Manatí lower reach would experience overtopping during the simulated failure for the hydrologic conditions of 6- and 24-hour PMP events, and the 24-hour 100-year recurrence rainfall event. Dam failure simulation under sunny-day conditions showed no bridge overtopping along the lower reach of the Río Grande de Manatí.

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Appendix 1. Hydrologic Engineering Center's Hydrologic Modeling System Output Hydrographs for the Dam Failure Analysis of the Lago El Guineo Dam, Orocovis, Puerto Rico

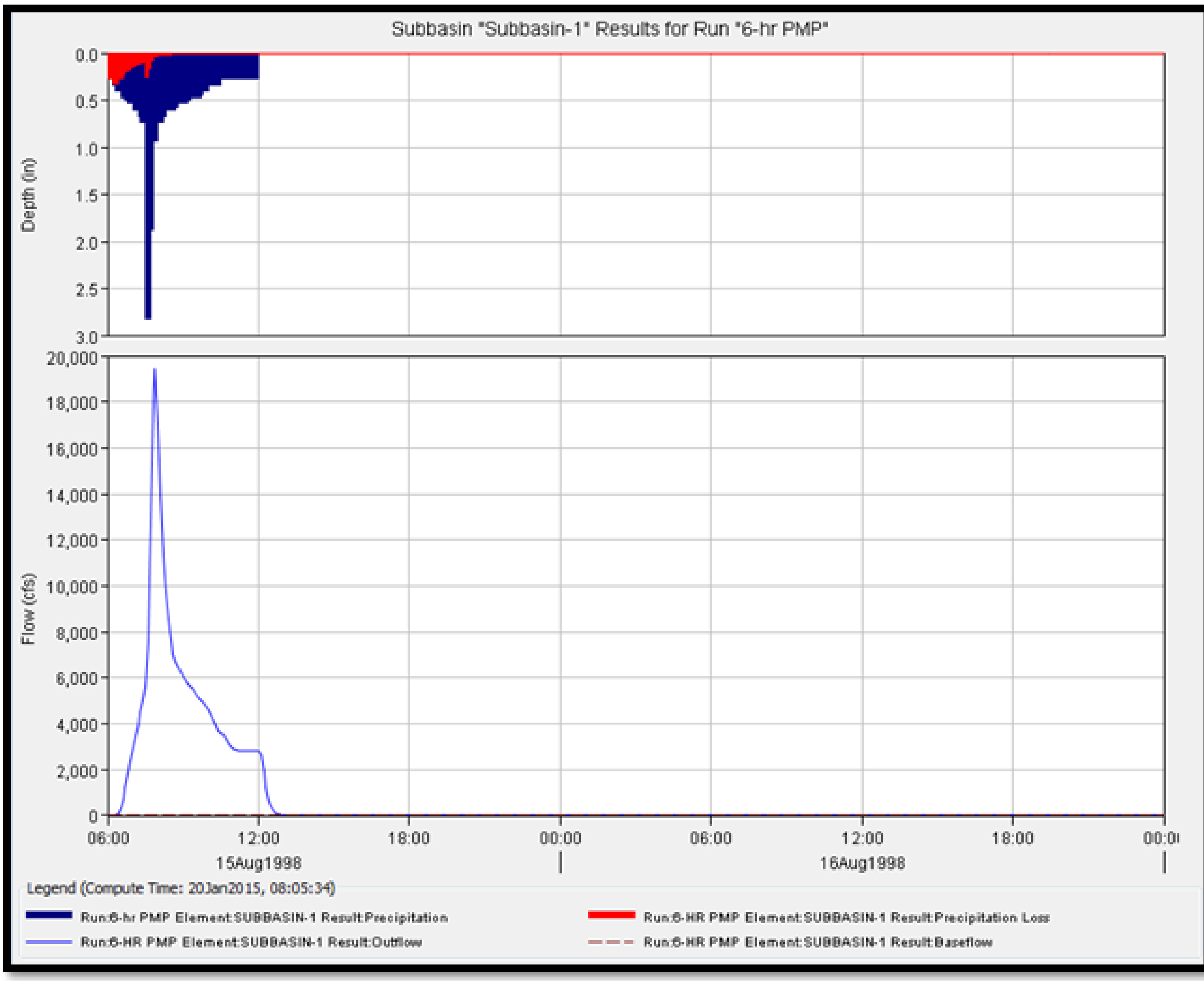

Figure 1–1. Output hydrograph screenshot for subbasin 1 from the 6-hour probable maximum precipitation (PMP) event.

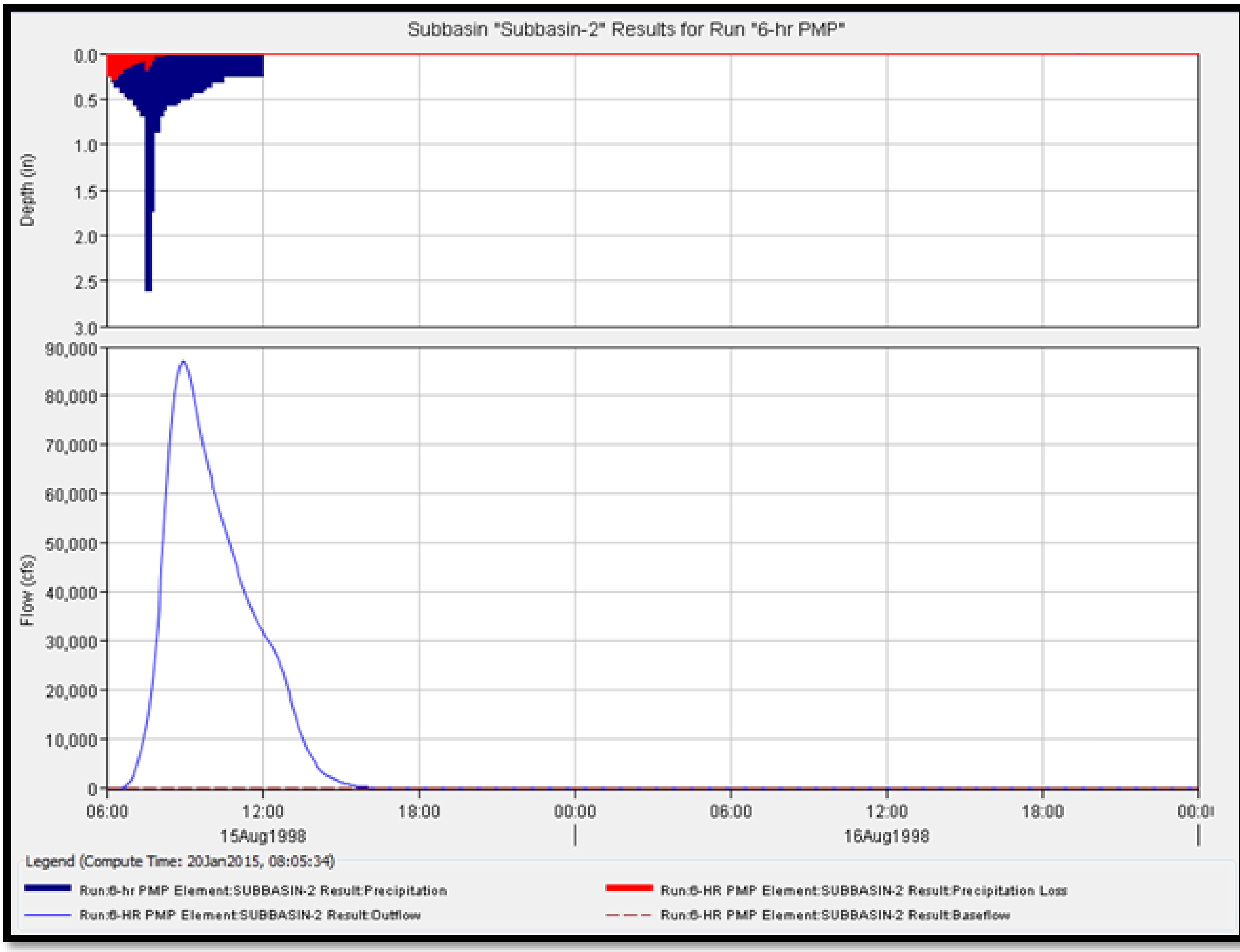

Figure 1–2. Output hydrograph screenshot for subbasin 2 from the 6-hour probable maximum precipitation (PMP) event.

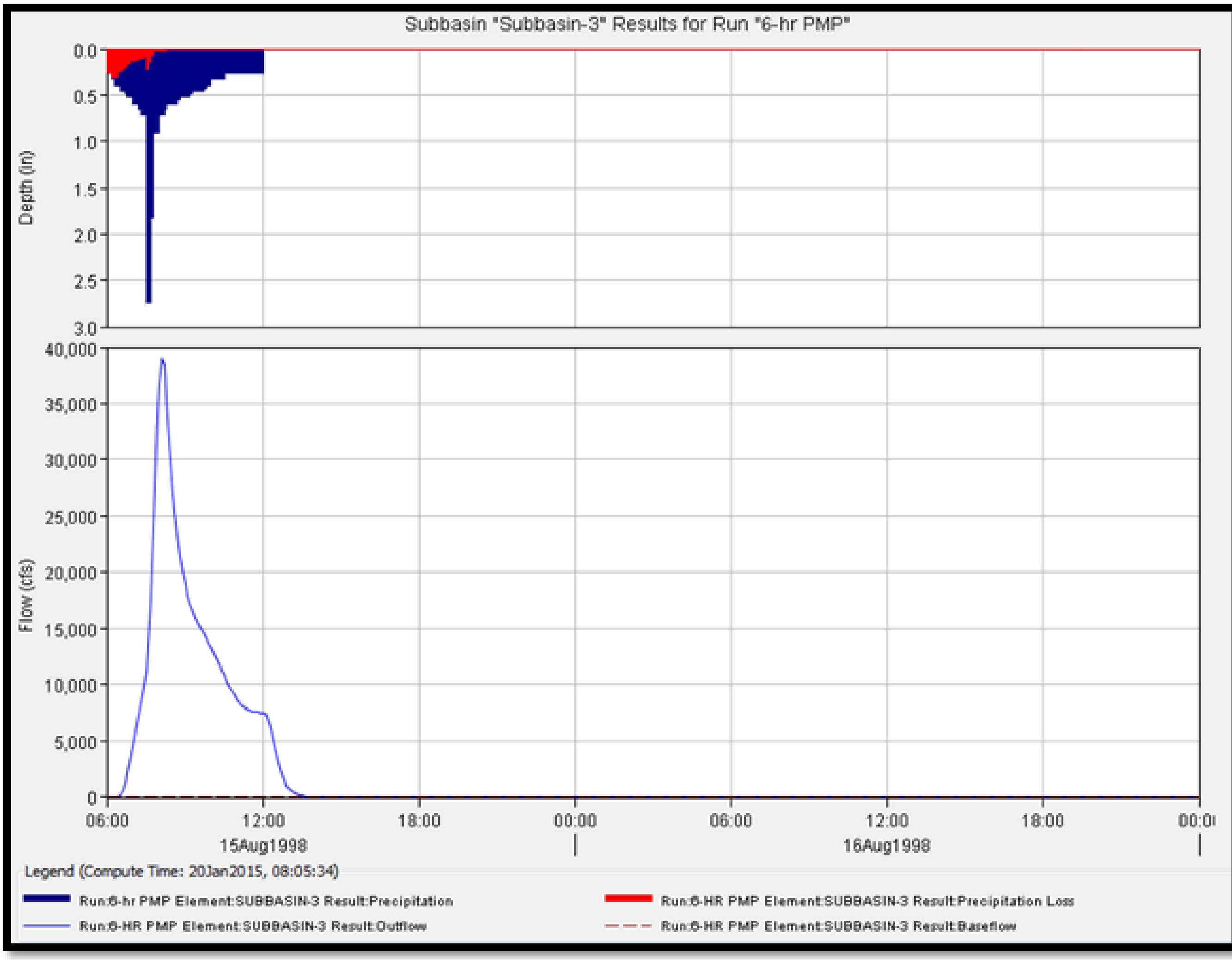

Figure 1–3. Output hydrograph screenshot for subbasin 3 from the 6-hour probable maximum precipitation (PMP) event.

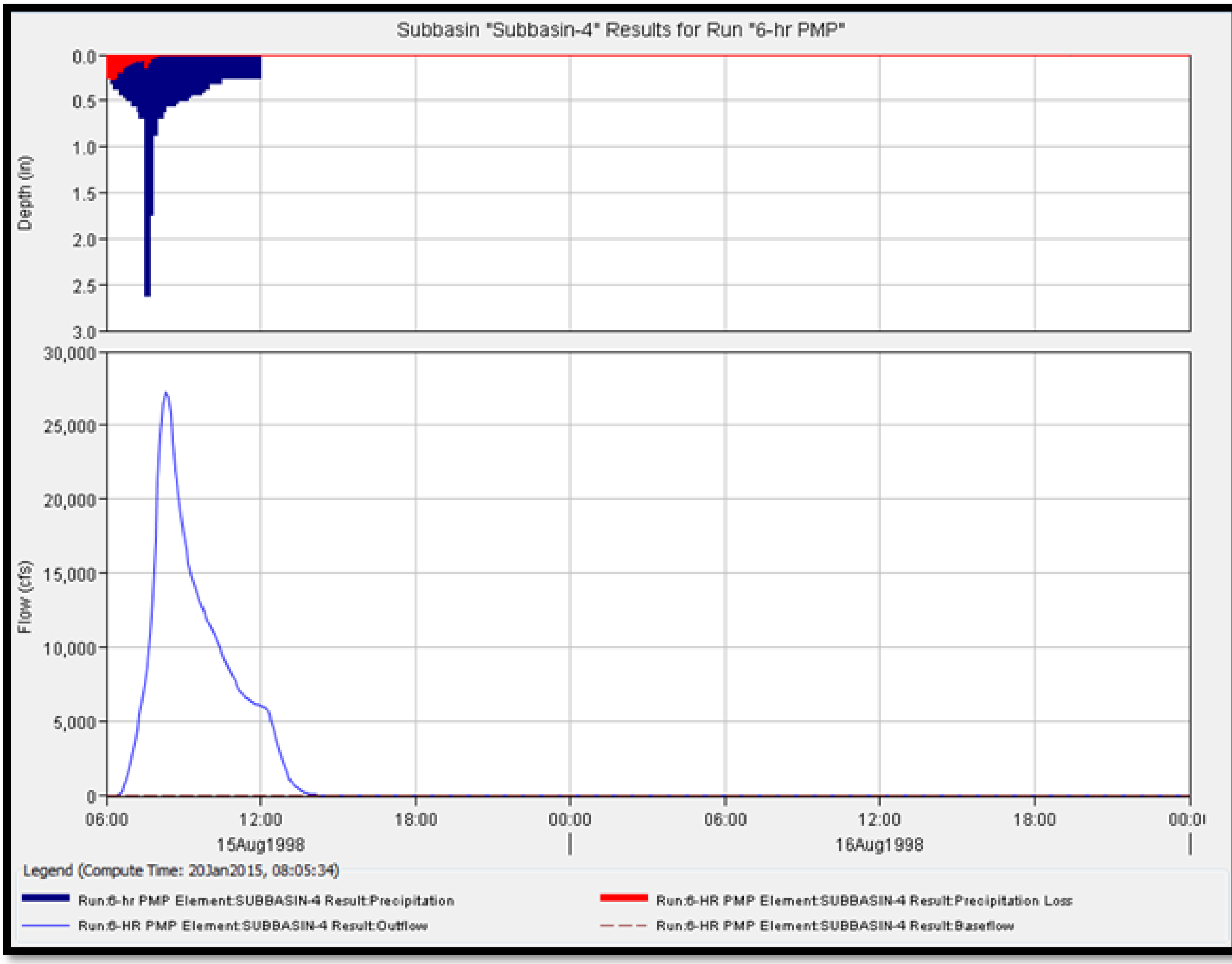

Figure 1–4. Output hydrograph screenshot for subbasin 4 from the 6-hour probable maximum precipitation (PMP) event.

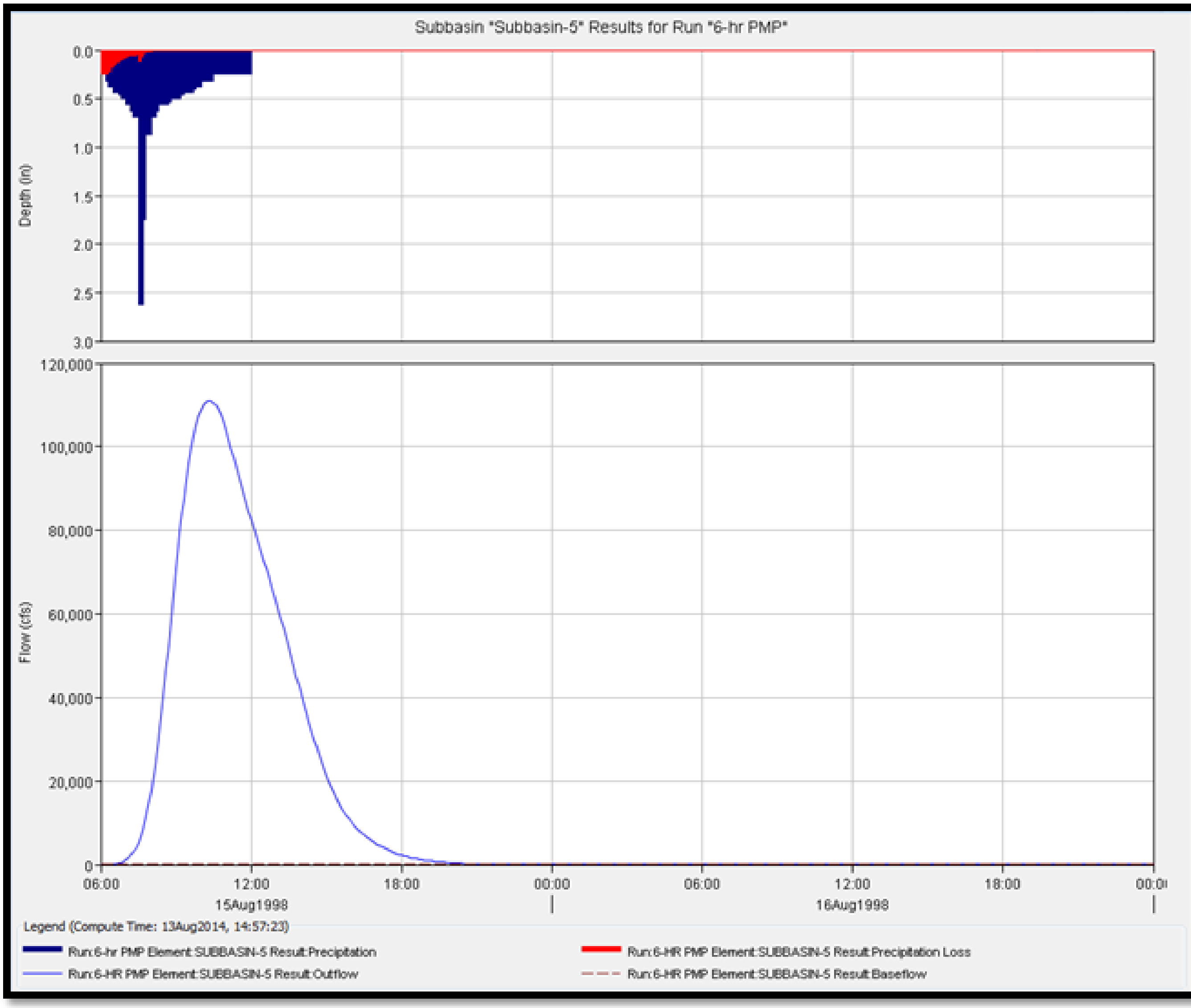

Figure 1–5. Output hydrograph screenshot for subbasin 5 from the 6-hour probable maximum precipitation (PMP) event.

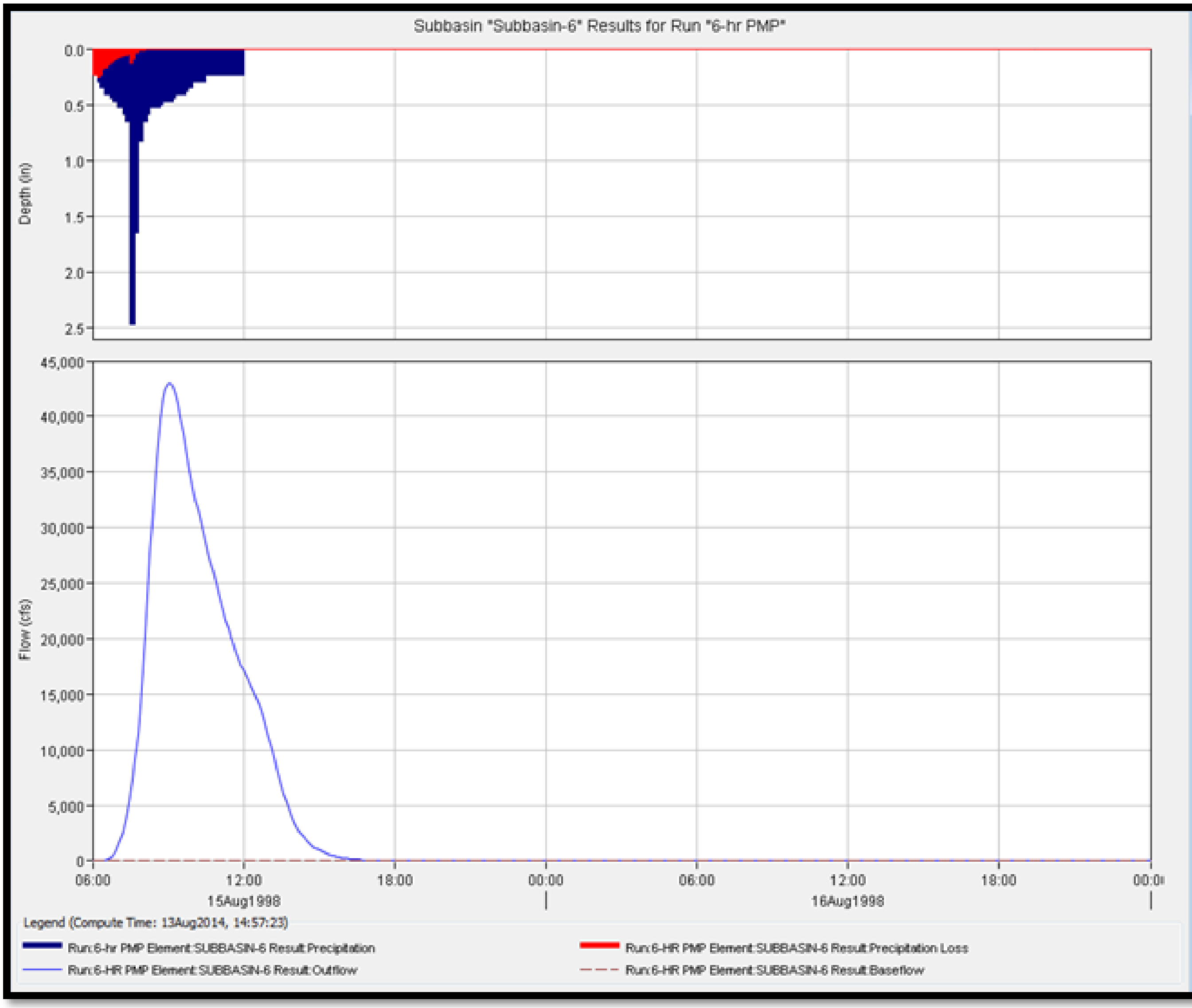

Figure 1–6. Output hydrograph screenshot for subbasin 6 from the 6-hour probable maximum precipitation (PMP) event.

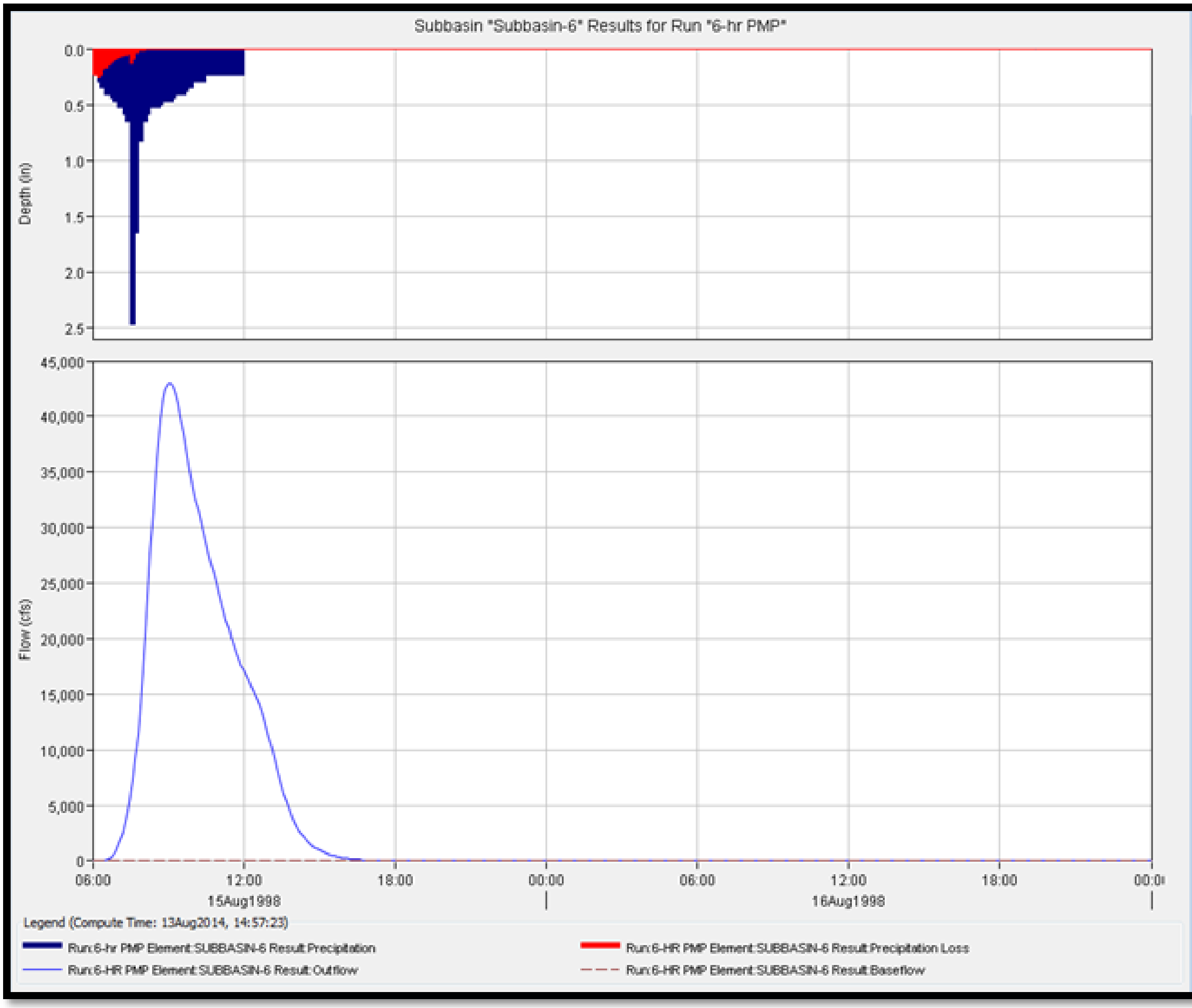

Figure 1–7. Output hydrograph screenshot for subbasin 7 from the 6-hour probable maximum precipitation (PMP) event.

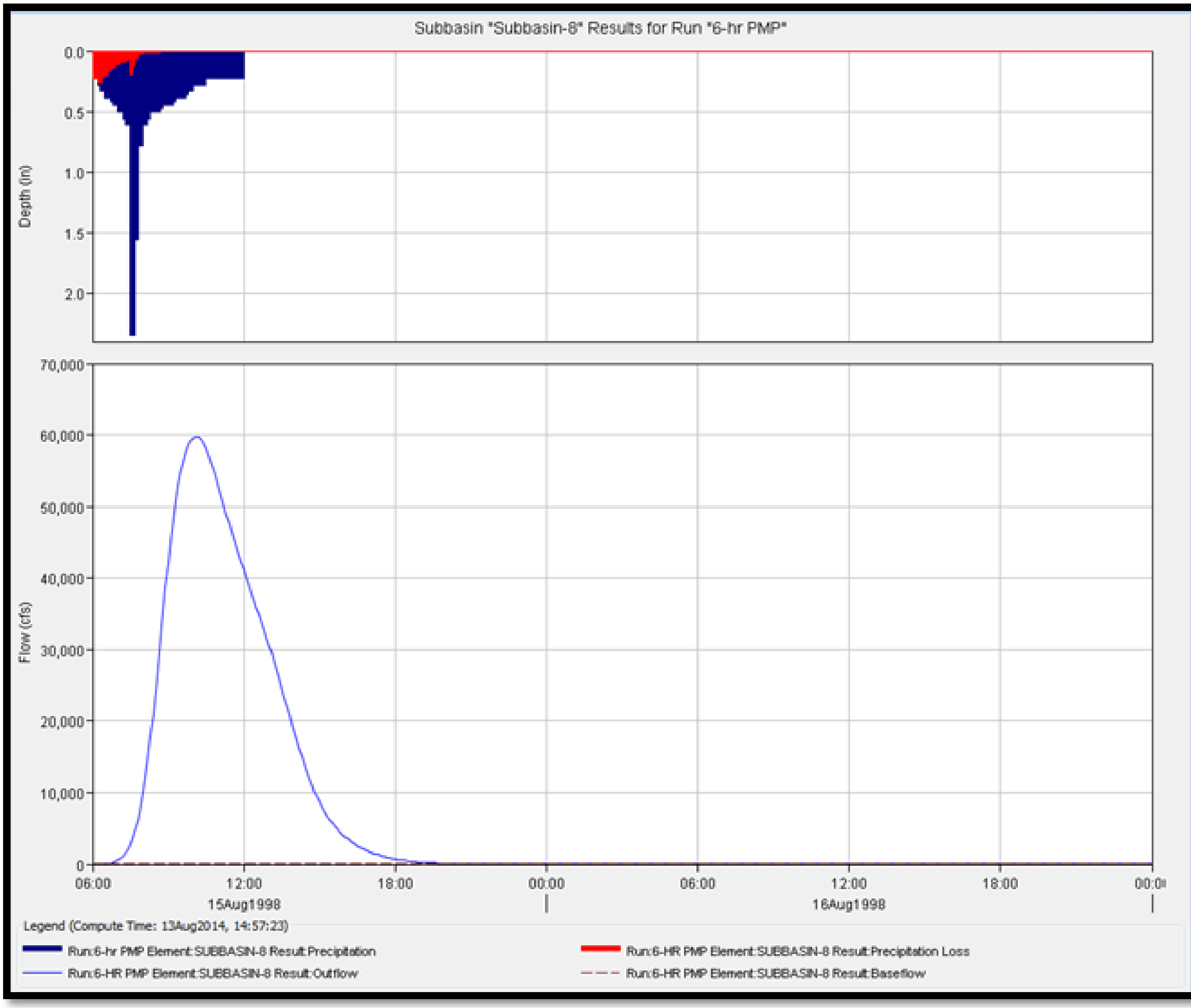

Figure 1–8. Output hydrograph screenshot for subbasin 8 from the 6-hour probable maximum precipitation (PMP) event.

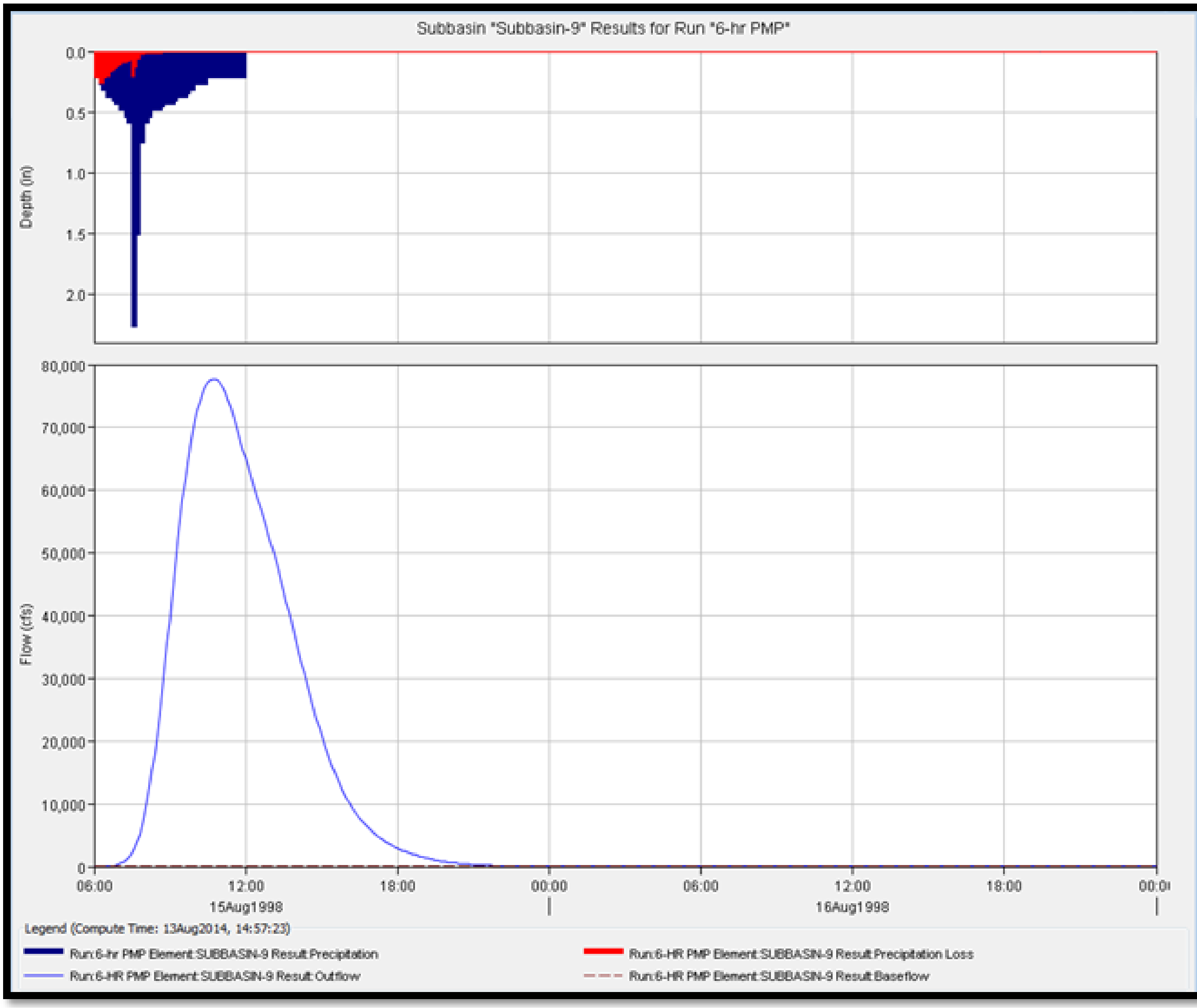

Figure 1–9. Output hydrograph screenshot for subbasin 9 from the 6-hour probable maximum precipitation (PMP) event.

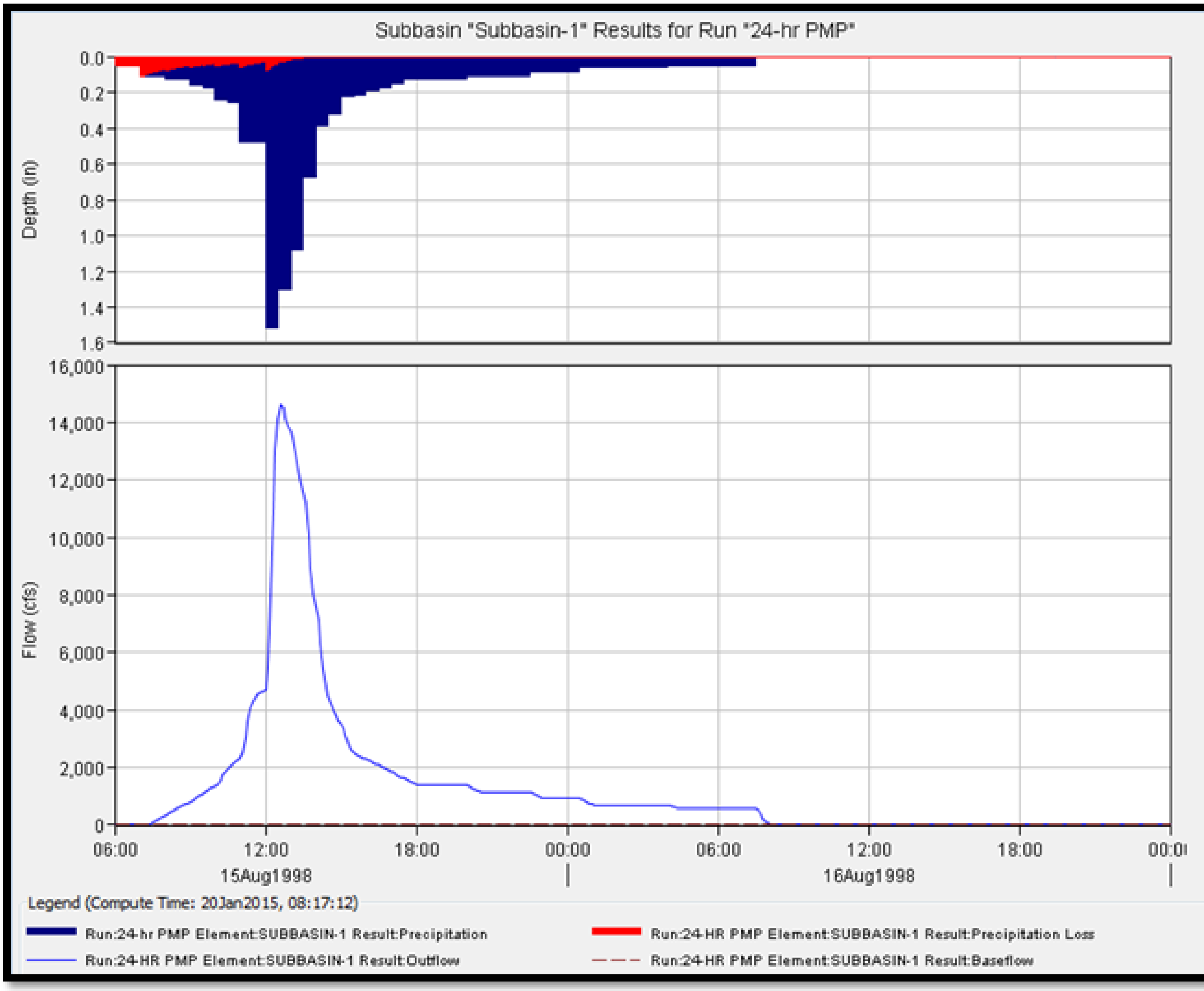

Figure 1–10. Outflow hydrograph screenshot for subbasin 1 from the 24-hour probable maximum precipitation (PMP) event.

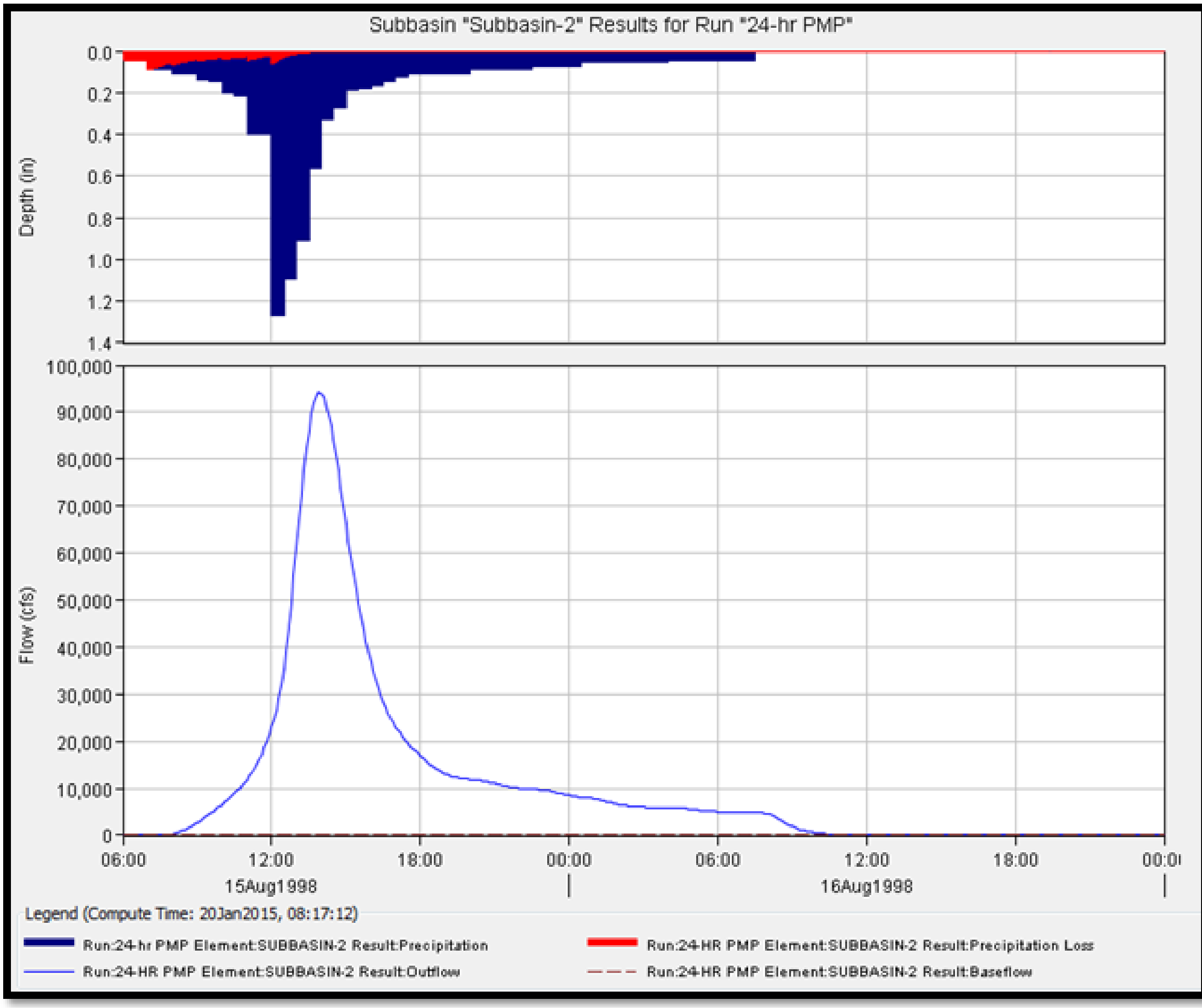

Figure 1–11. Outflow hydrograph screenshot for subbasin 2 from the 24-hour probable maximum precipitation (PMP) event.

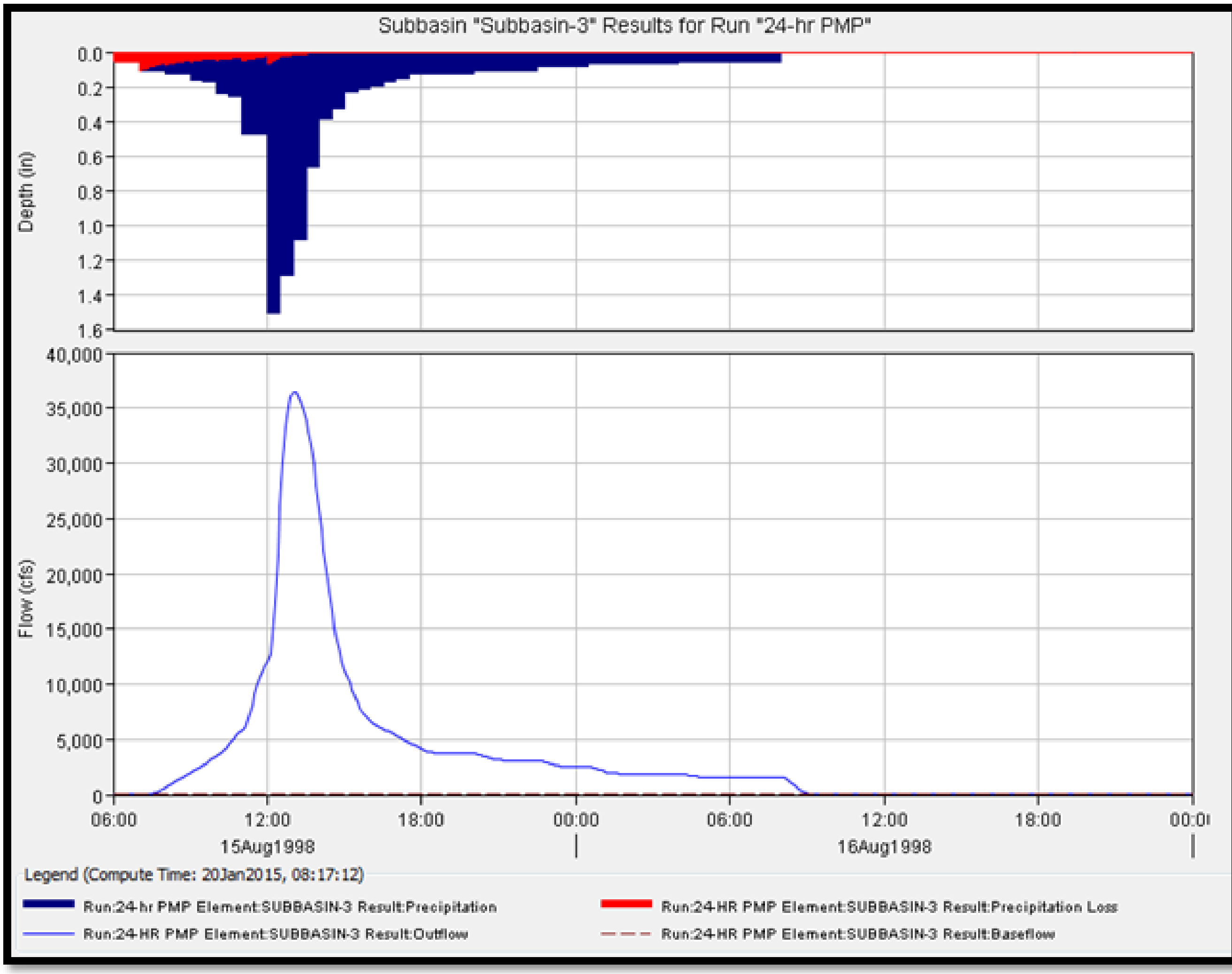

Figure 1–12. Outflow hydrograph screenshot for subbasin 3 from the 24-hour probable maximum precipitation (PMP) event.

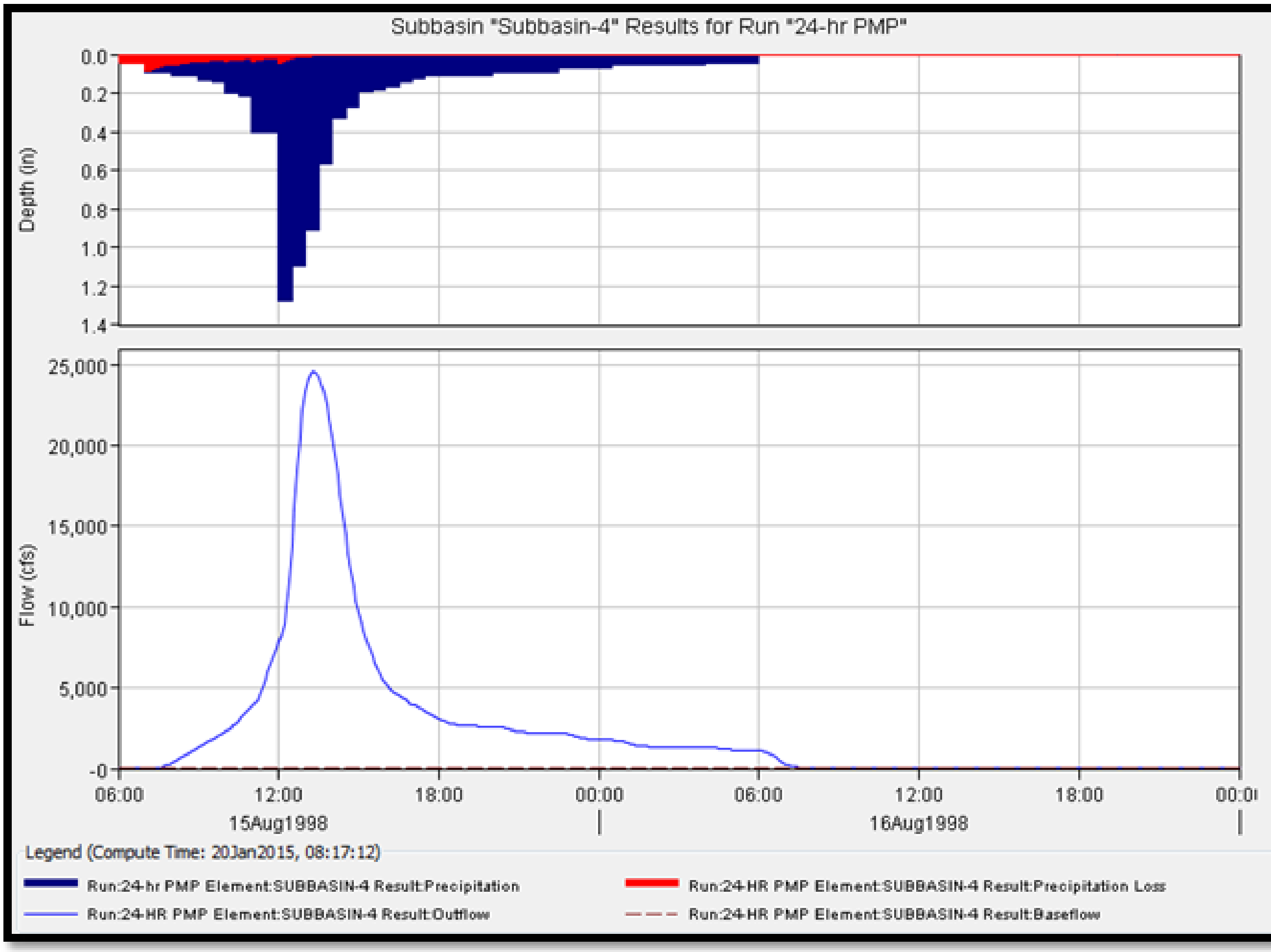

Figure 1–13. Outflow hydrograph screenshot for subbasin 4 from the 24-hour probable maximum precipitation (PMP) event.

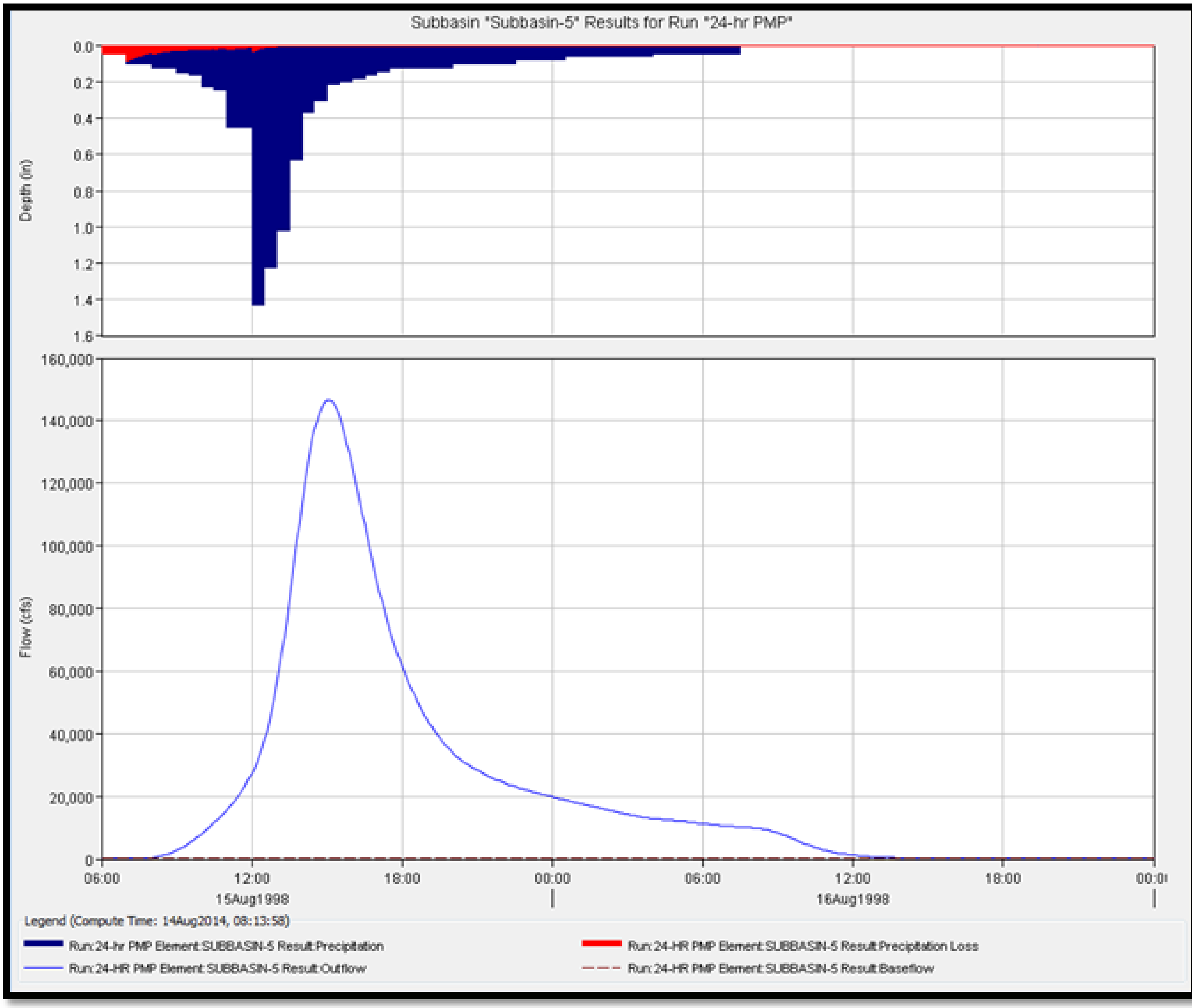

Figure 1–14. Outflow hydrograph screenshot for subbasin 5 from the 24-hour probable maximum precipitation (PMP) event.

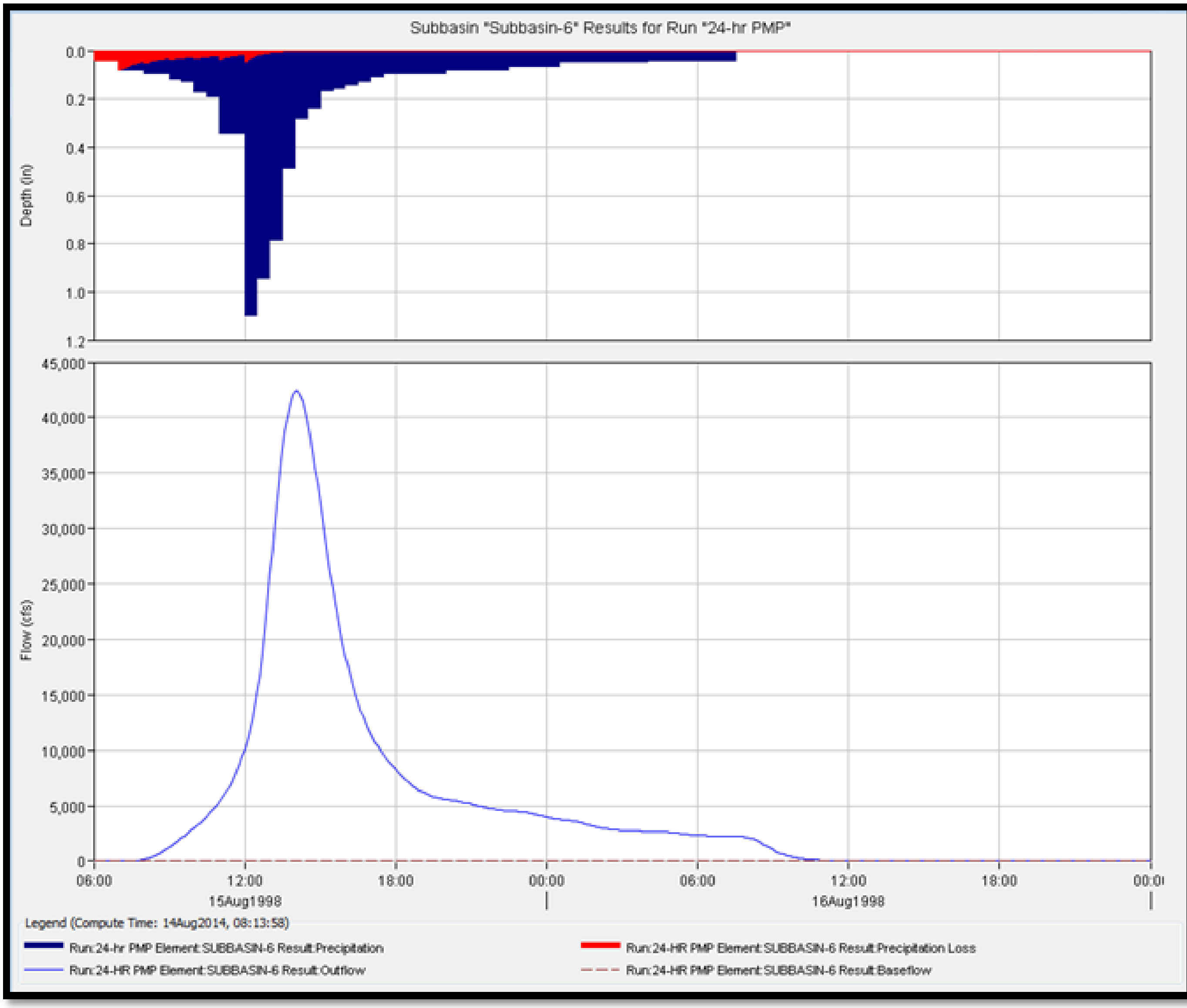

Figure 1–15. Outflow hydrograph screenshot for subbasin 6 from the 24-hour probable maximum precipitation (PMP) event.

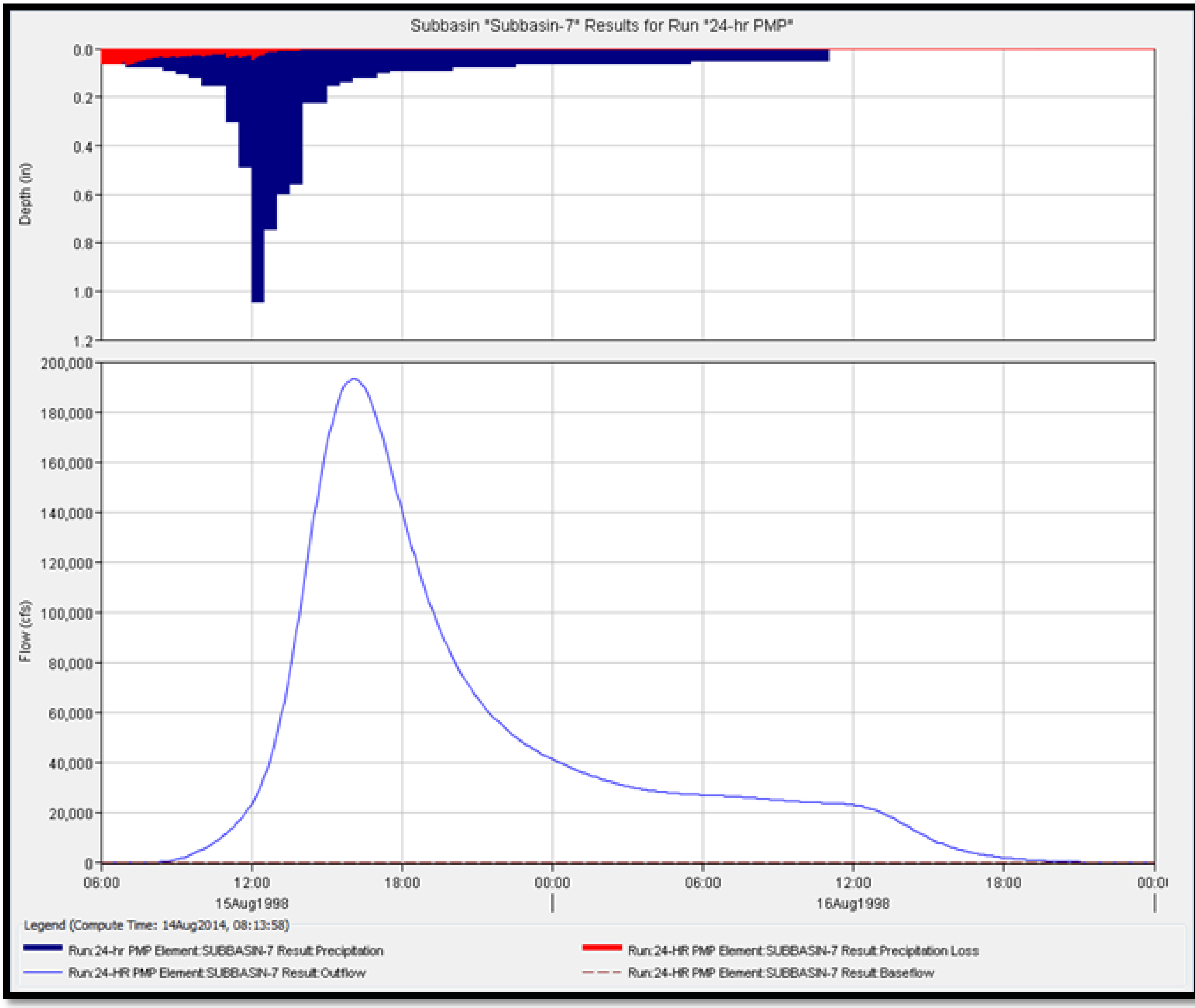

Figure 1–16. Outflow hydrograph screenshot for subbasin 7 from the 24-hour probable maximum precipitation (PMP) event.

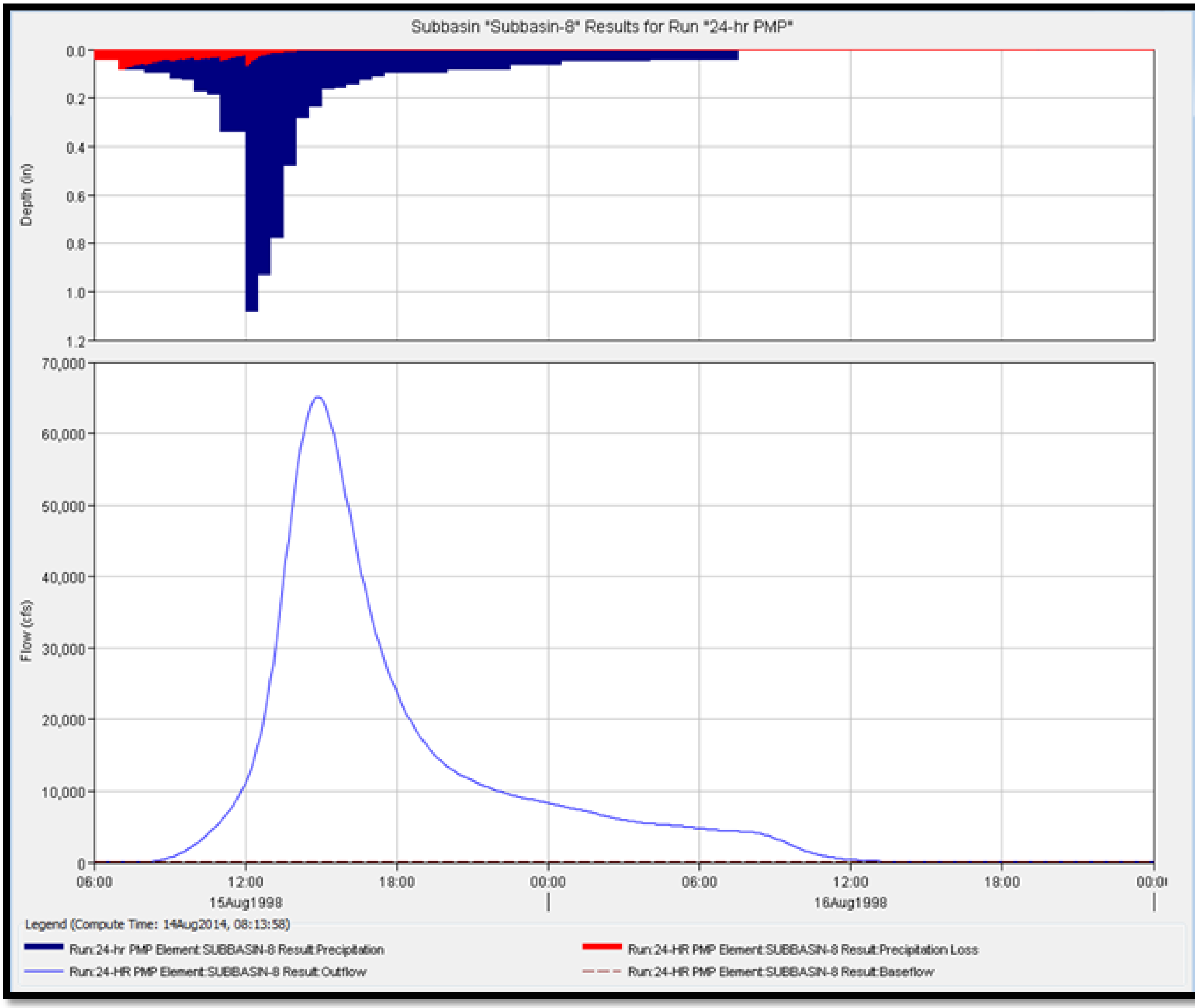

Figure 1–17. Outflow hydrograph screenshot for subbasin 8 from the 24-hour probable maximum precipitation (PMP) event.

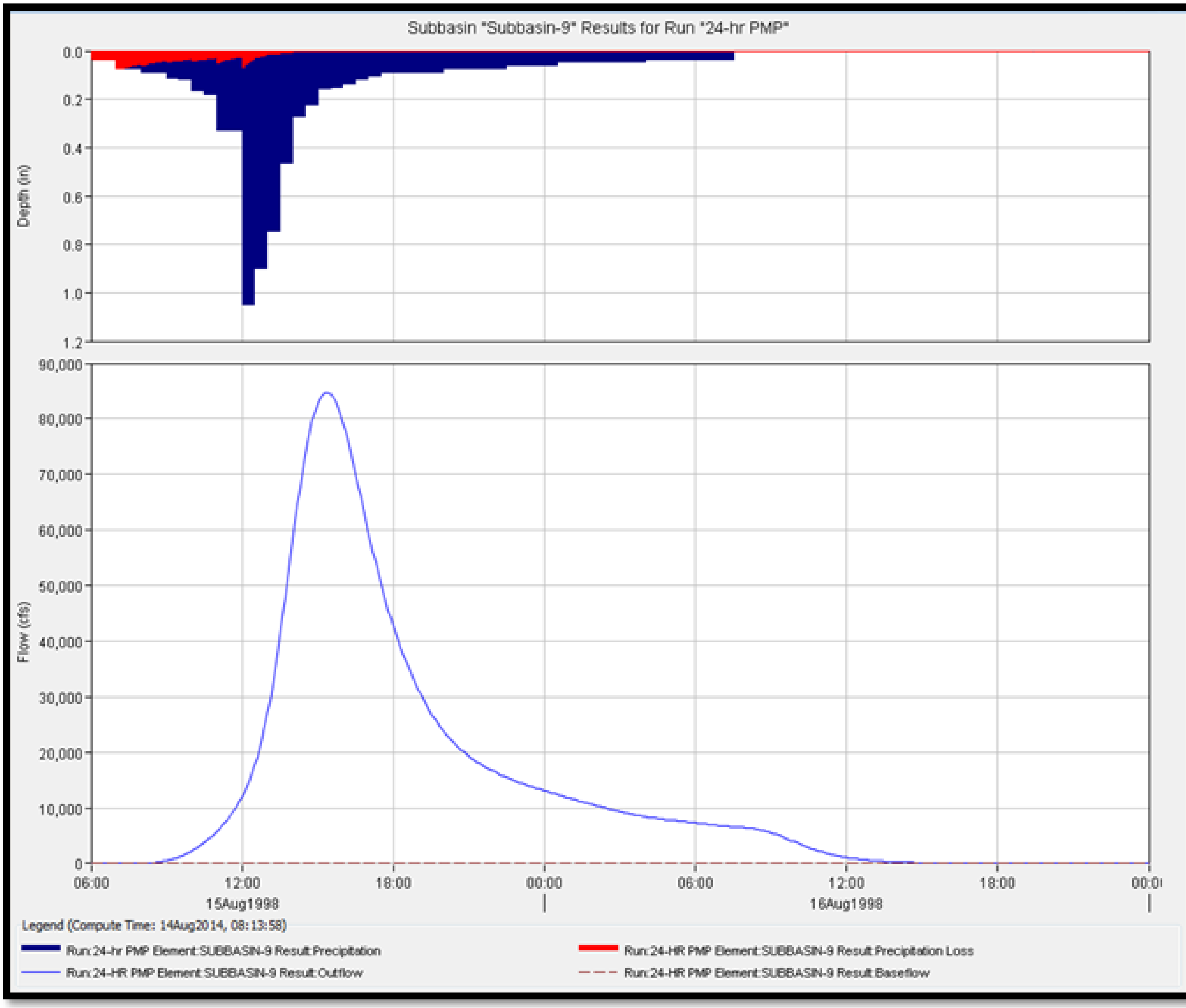

Figure 1–18. Outflow hydrograph screenshot for subbasin 9 from the 24-hour probable maximum precipitation (PMP) event.

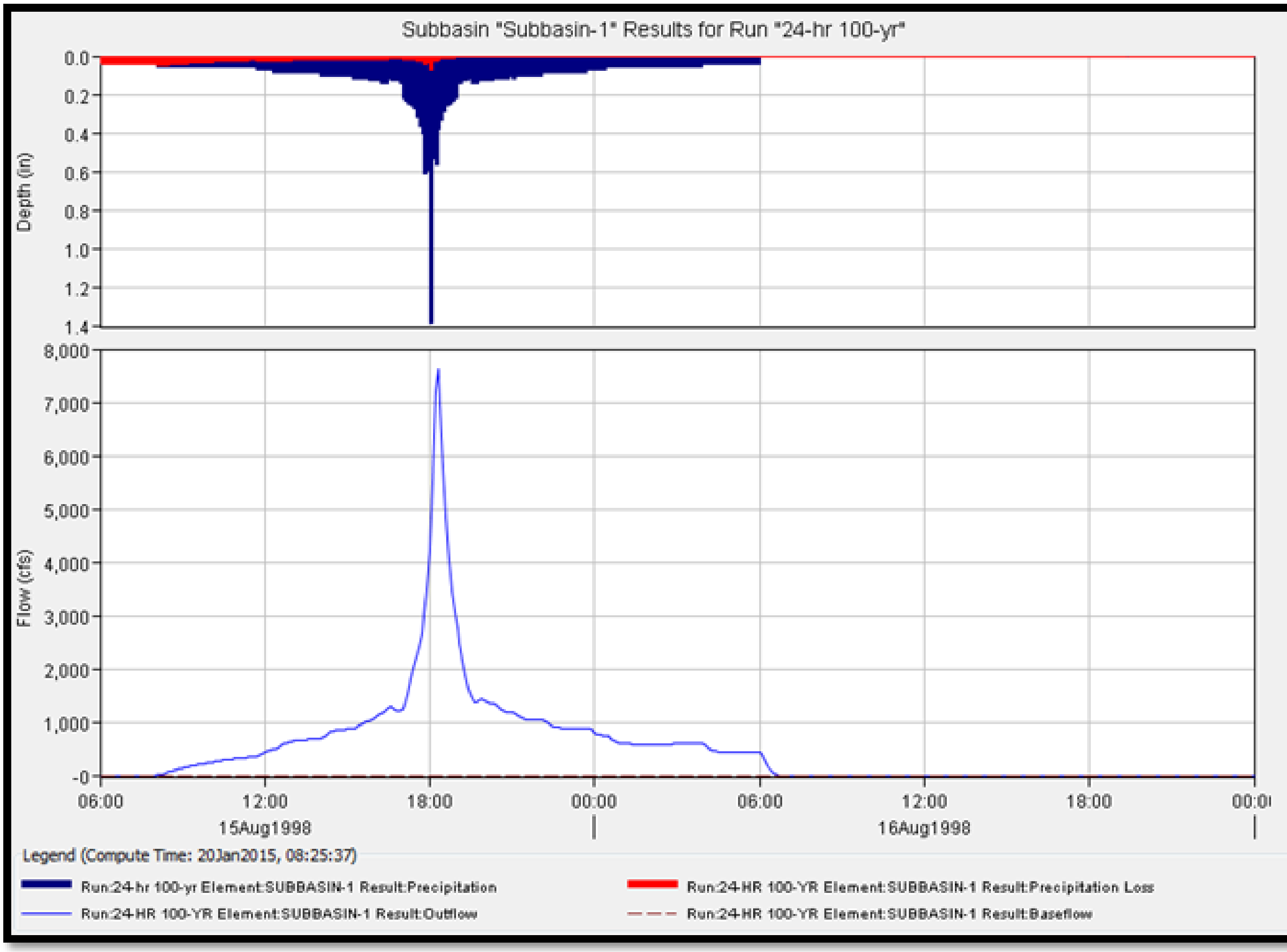

Figure 1–19. Output hydrograph screenshot for subbasin 1 from the 100-year-recurrence, 24-hour rainfall event.

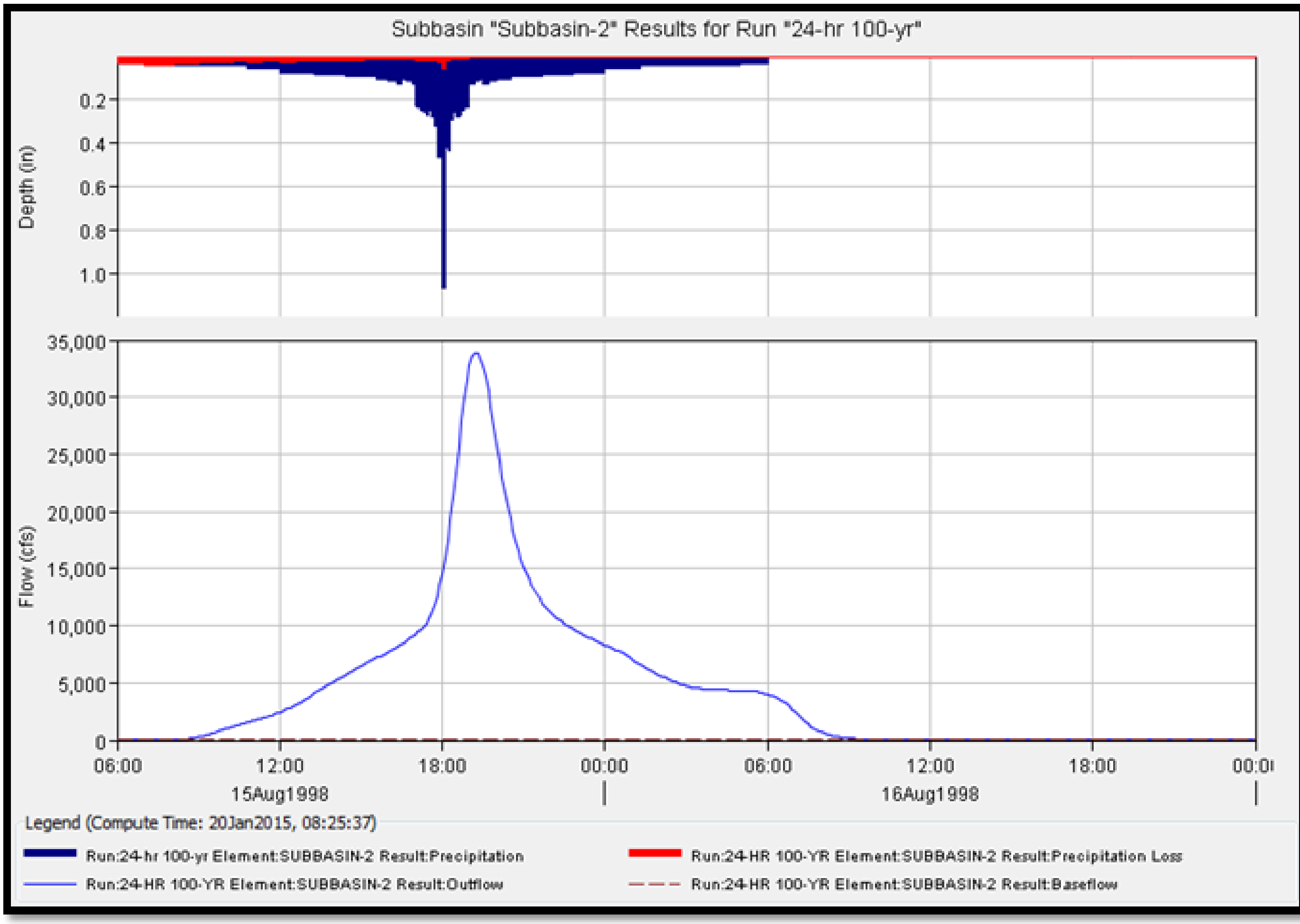

Figure 1–20. Output hydrograph screenshot for subbasin 2 from the 100-year-recurrence, 24-hour rainfall event.

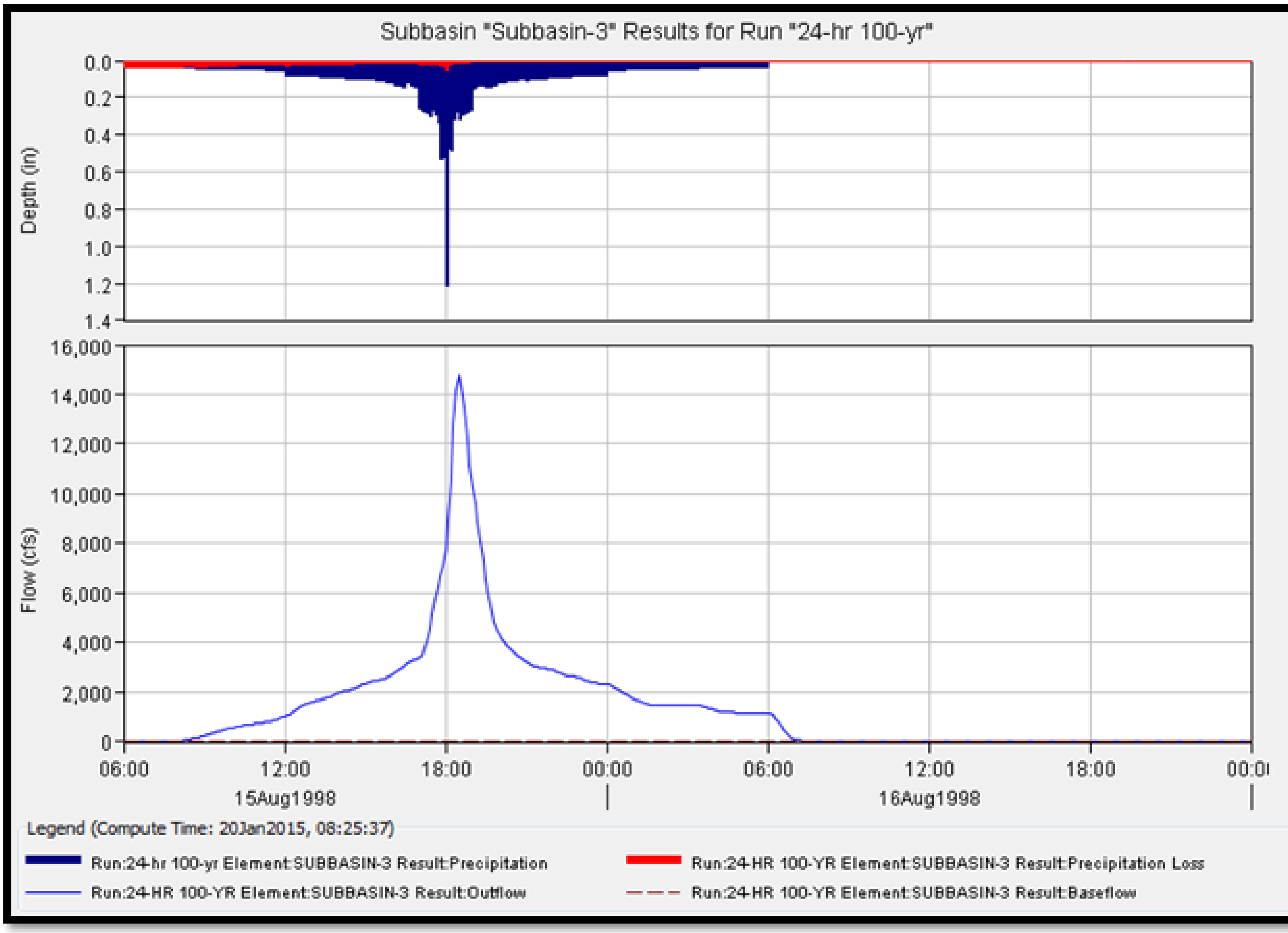

Figure 1–21. Output hydrograph screenshot for subbasin 3 from the 100-year-recurrence, 24-hour rainfall event.

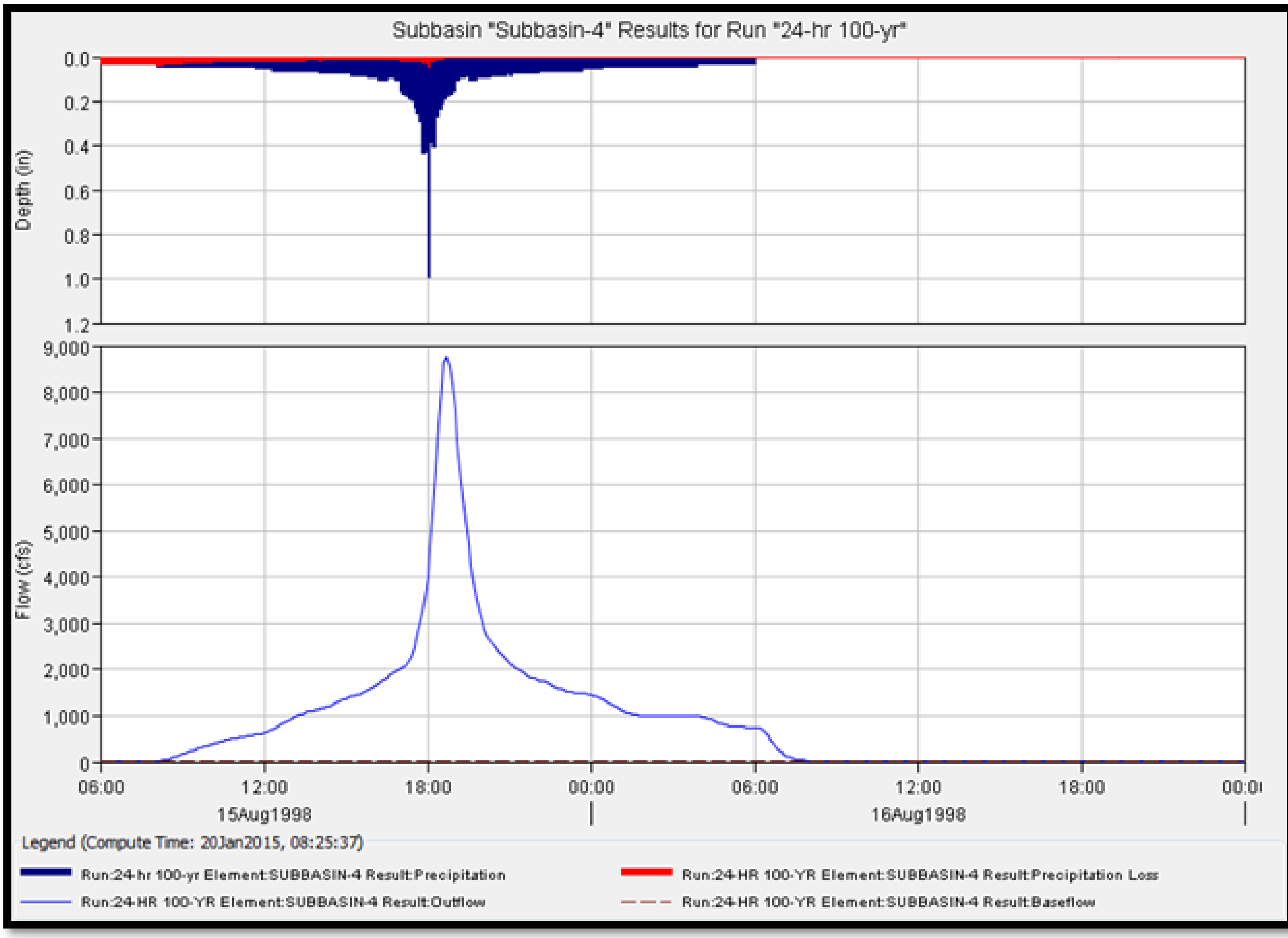

Figure 1–22. Output hydrograph screenshot for subbasin 4 from the 100-year-recurrence, 24-hour rainfall event.

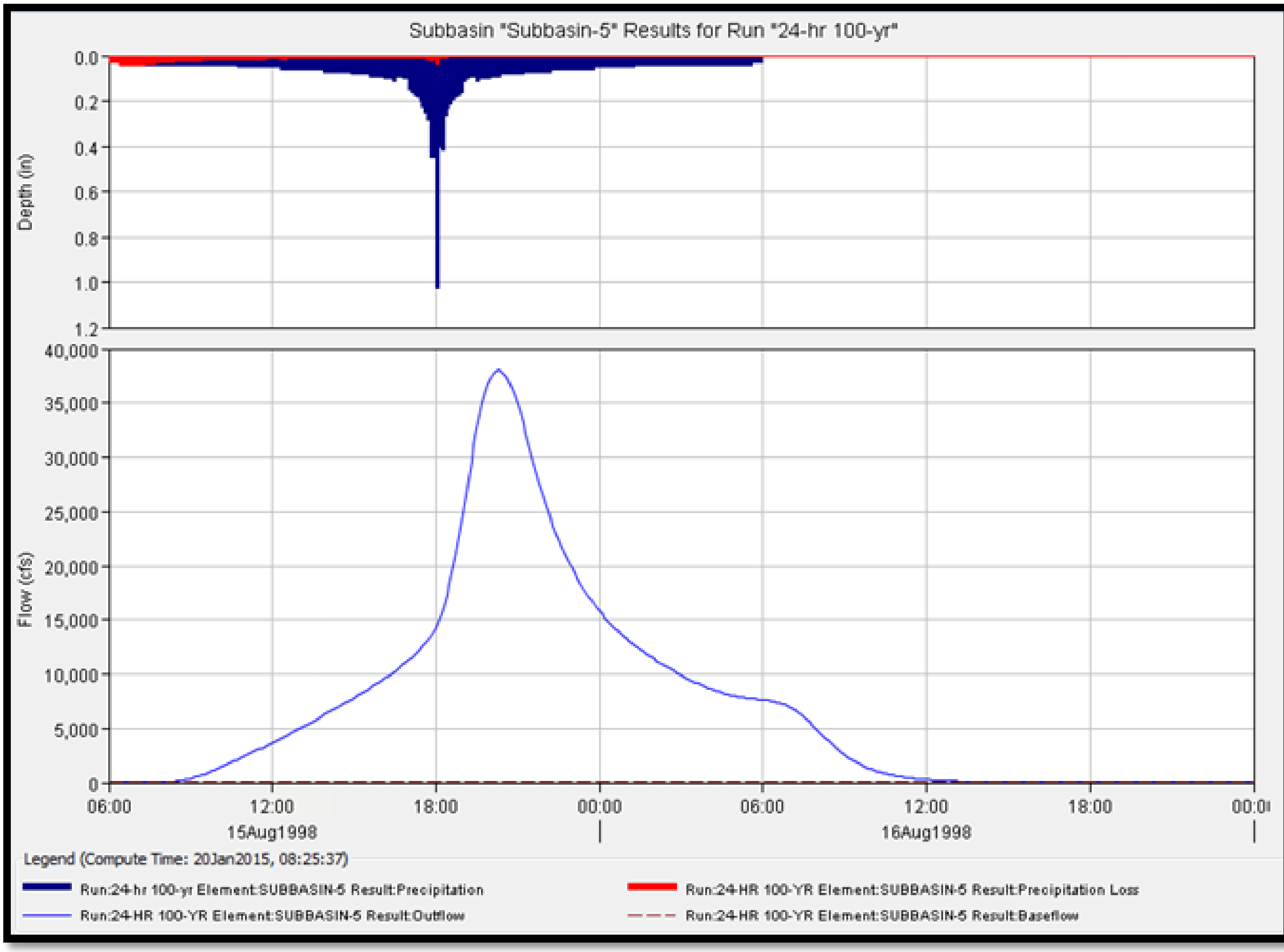

Figure 1–23. Output hydrograph screenshot for subbasin 5 from the 100-year-recurrence, 24-hour rainfall event.

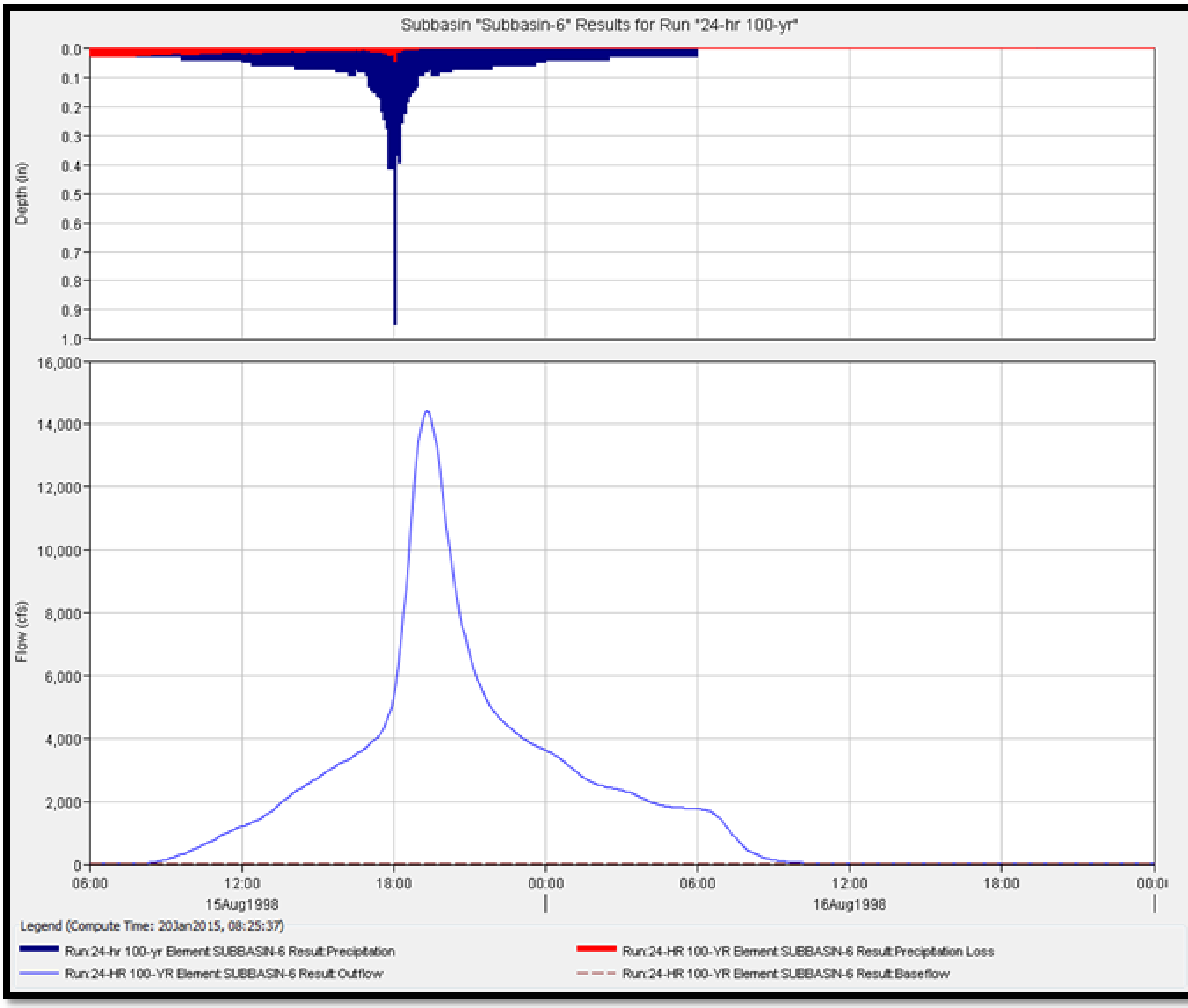

Figure 1–24. Output hydrograph screenshot for subbasin 6 from the 100-year-recurrence, 24-hour rainfall event.

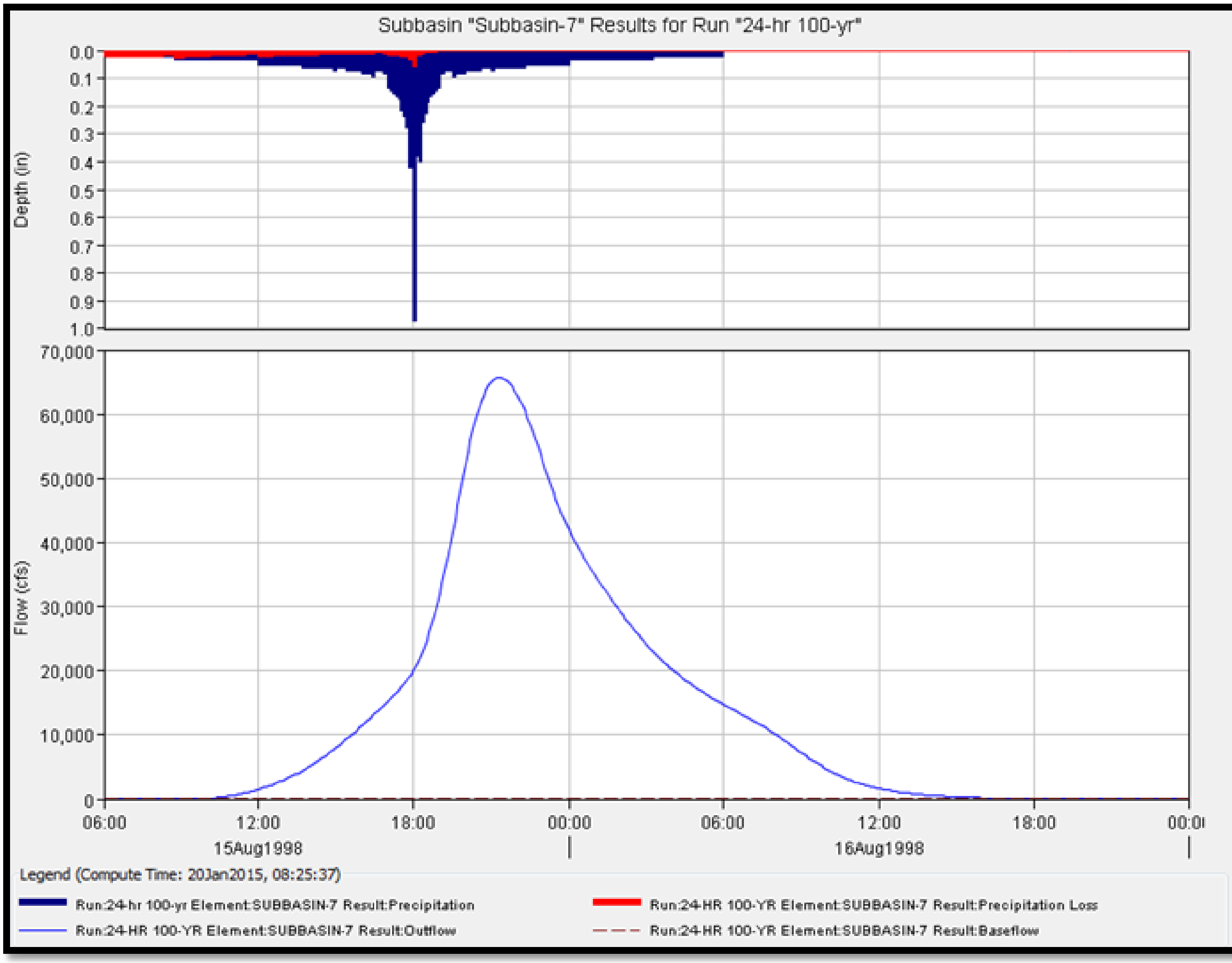

Figure 1–25. Output hydrograph screenshot for subbasin 7 from the 100-year-recurrence, 24-hour rainfall event.

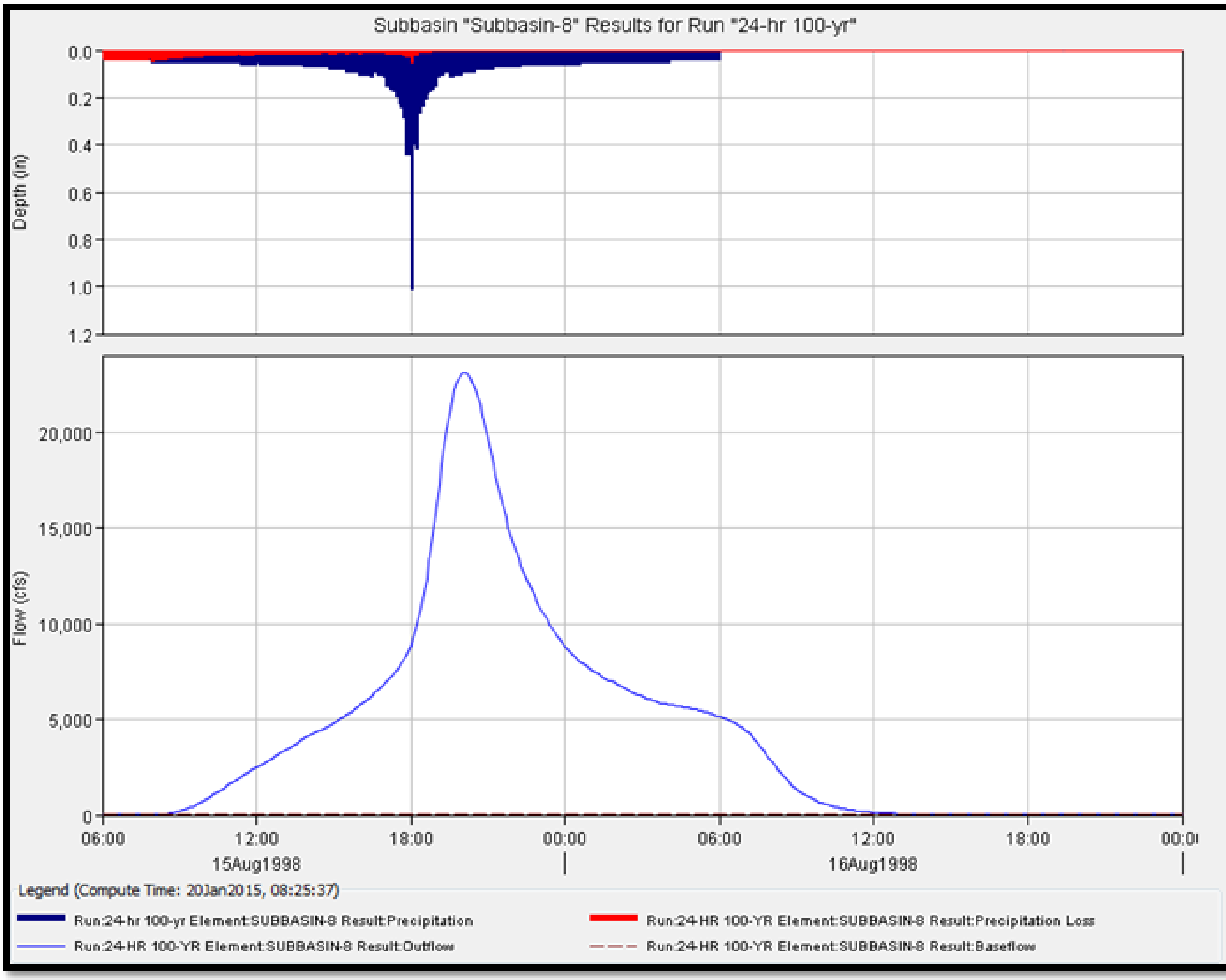

Figure 1–26. Output hydrograph screenshot for subbasin 8 from the 100-year-recurrence, 24-hour rainfall event.

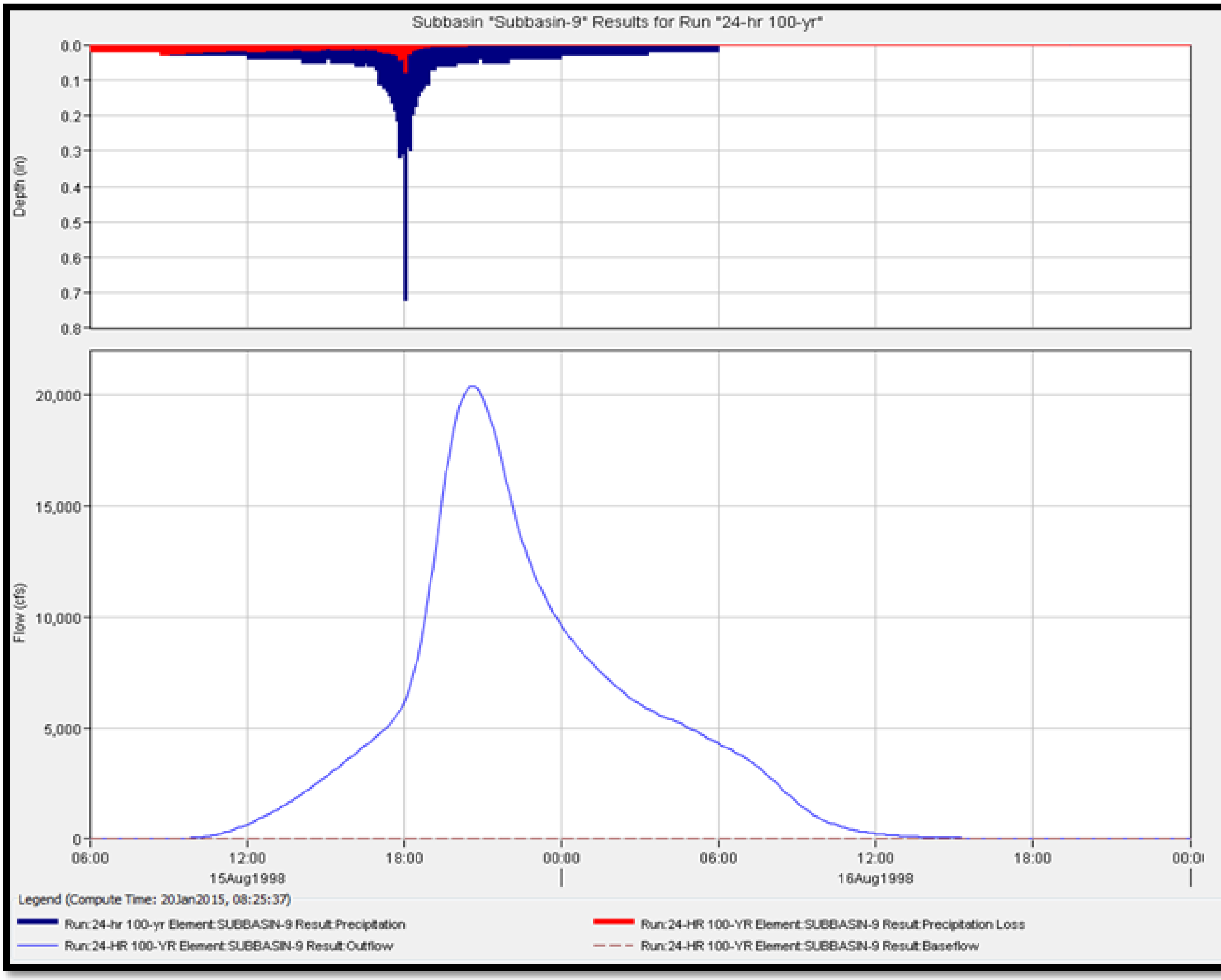

Figure 1–27. Output hydrograph screenshot for subbasin 9 from the 100-year-recurrence, 24-hour rainfall event.

Manuscript approved May 10, 2016

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Gómez-Fragoso and Torres-Sierra—**Dam Failure Analysis for the Lago El Guineo Dam, Orocovis, Puerto Rico**—Scientific Investigations Report 2016-5070

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20165070