

Prepared in cooperation with the Federal Emergency Management Agency

Monitoring Storm Tide, Flooding, and Precipitation From Hurricane Maria in Puerto Rico and the U.S. Virgin Islands, September 2017



Open-File Report 2019–1065

Front cover. U.S. Army helicopter installing sandbags to the breached spillway of the Guajataca Dam in Quebradillas, Puerto Rico, October 9, 2017. Photograph courtesy of Staff Sgt. Mark Scovell, U.S. Army.

Back cover. Destruction of boat pier in Patillas Municipality, Puerto Rico, September 18 and October 10, 2017. Storm-surge sensor PAPAT2231 attached to left nearshore piling. Photographs by David Rivera, U.S. Geological Survey

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By Michael J. Byrne, Sr.

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

U.S. Department of the Interior
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U.S. Geological Survey
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This mission could only be accomplished with U.S. Geological Survey personnel in Puerto Rico and the continental United States and the help of U.S. Military, first responders and other Federal agency partners.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Velocity		
mile per hour (mi/h)	1.609	kilometer per hour (km/h)

Datum

Vertical coordinate information is referenced to the Puerto Rico Vertical Datum of 2002 (PRVD02), unless otherwise noted.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

Abbreviations

ASCII	American Standard Code for Information Interchange
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite Systems
HWM	high-water mark
NetCDF	Network Common Data Form
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NWIS	National Water Information System
USGS	U.S. Geological Survey

Monitoring Storm Tide, Flooding, and Precipitation From Hurricane Maria in Puerto Rico and the U.S. Virgin Islands, September 2017

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Abstract

Hurricane Maria made landfall south of Yabucoa Harbor, Puerto Rico, as a category 4 hurricane with maximum sustained winds of 155 miles per hour on September 20, 2017. The hurricane devastated much of the U.S. Virgin Islands and Puerto Rico. The U.S. Geological Survey (USGS), in cooperation with Federal Emergency Management Agency, installed a temporary monitoring network of 13 water-level and barometric pressure sensors along the coast of Puerto Rico prior to the storm. In addition to the temporary sensors, the USGS maintains 99 permanent real-time streamgages and 36 real-time precipitation stations in Puerto Rico. The real-time data, updated hourly, during and after the hurricane are displayed in the USGS Flood Event Viewer (<https://stn.wim.usgs.gov/FEV/#MariaSeptember2017>) and in the USGS National Water Information System.

The USGS measured 181 coastal and riverine high-water marks throughout Puerto Rico after the storm. Water elevations are referenced to the Puerto Rico Vertical Datum of 2002 (PRVD02) and local datums in Puerto Rico and to the U.S. Virgin Islands Vertical Datum of 2009 (VIVD09) in the U.S. Virgin Islands. Data from the Hurricane Maria storm-tide network are available in tab-delimited, American Standard Code for Information Interchange (ASCII) format and Network Common Data Form (NetCDF) format by site for each sensor through the USGS Flood Event Viewer.

Introduction

Hurricane Maria made landfall south of Yabucoa Harbor, Puerto Rico (fig. 1) as a category 4 hurricane on the Saffir-Simpson Hurricane Wind Scale (table 1) with maximum sustained winds of 155 miles per hour (mi/h) on September 20, 2017 (Pasch and others, 2018). The hurricane passed over the mountains, weakened, and exited the island the same day near the Isabela Municipality as a category 3 hurricane with maximum sustained winds of 115 mi/h. Puerto Rico and the U.S. Virgin Islands (St. Thomas, St. Croix,

and St. John) sustained catastrophic damage because of the high winds, storm tide, flooding, and precipitation. Prior to Hurricane Maria landfall, Hurricane Irma skirted the coast of the islands on September 7, 2017, as a category 5 hurricane with maximum sustained winds of 185 mi/h (Cangialosi and others, 2018), causing 55 percent of the 3.3 million people living in Puerto Rico (U.S. Census Bureau, 2017) and 100 percent of the 106,000 people living in the U.S. Virgin Islands (U.S. Census Bureau, 2010) to lose electrical power (U.S. Department of Energy, 2017). Hurricane Maria devastated much of the remaining electrical grid, leaving most of the islands without electricity. As of February 2018, power had been restored to 70 percent of Puerto Rico and 100 percent of the U.S. Virgin Islands (U.S. Department of Energy, 2018). On August 14, 2018, the Puerto Rico Electric Power Authority announced power was restored to 100 percent of Puerto Rico (Autoridad de Energía Eléctrica, 2018).

In advance of landfall of Hurricane Maria, the U.S. Geological Survey (USGS), in cooperation with the Federal Emergency Management Agency, deployed a temporary monitoring network of water-level sensors and barometric pressure sensors at 13 locations along the Puerto Rico coast to record the timing, areal extent, and magnitude of hurricane-generated storm tide and coastal flooding (fig. 2). The deployment of Hurricane Maria water-level sensors was completed as part of a coordinated Federal emergency response as outlined by the Robert T. Stafford Disaster Relief and Emergency Assistance Act (42 U.S.C. 5121 et seq.) under a directed mission assignment by the Federal Emergency Management Agency. Storm tide is the water-level rise above the astronomical tide during a coastal storm. As noted by Frantz and others (2017), these data are used to improve the performance of storm-tide models used to predict the maximum and incremental water levels and flood extent; these models also predict the site-specific effects of storm tide and flooding on natural and anthropogenic features of the environment.

The permanent USGS monitoring network of real-time streamgages, precipitation stations, and National Oceanic and Atmospheric Administration (NOAA) tide-gages in Puerto Rico and the U.S. Virgin Islands relayed data hourly for display on the USGS Flood Event Viewer (<https://stn.wim.usgs.gov/FEV/#MariaSeptember2017>) and

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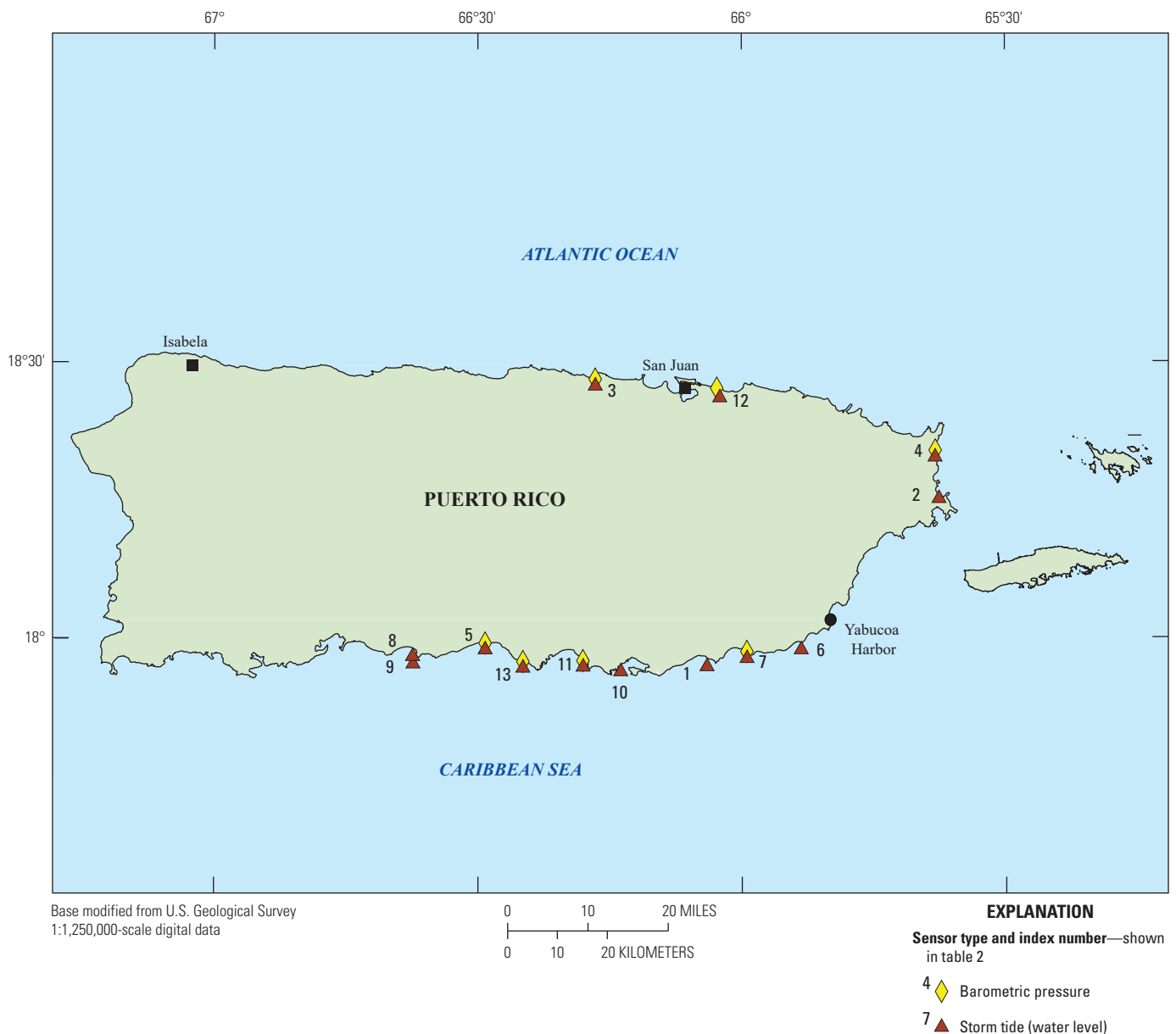


Figure 1. Hurricane Maria path and intensity, September 2017. Map image is the intellectual property of Esri and is used herein under license. Copyright © 2017 Esri and its licensors. All rights reserved.

Table 1. Saffir-Simpson hurricane wind scale.

[National Hurricane Center (2012). mi/h, mile per hour; >, greater than]

Category	Wind speed (mi/h)	Damage
1	74–95	Very dangerous wind will produce some damage.
2	96–110	Extremely dangerous winds will cause extensive damage.
3	111–129	Devastating damage will occur.
4	130–156	Catastrophic damage will occur.
5	>157	Catastrophic damage will occur.

**Figure 2.** Location of water-level sensors for monitoring the timing, areal extent, and magnitude of storm tide and coastal flooding generated by Hurricane Maria, September 2017.

in the National Water Information System (NWIS; U.S. Geological Survey, 2016; NOAA, 2017). These real-time data provided emergency managers and responders with critical information for identifying flood-affected areas and accurately directing assistance to affected communities.

Hurricane Maria Storm Tide, Flood Monitoring, and Precipitation

Water-level sensors were placed at sites in Puerto Rico selected to augment existing tide-gage networks and to ensure adequate monitoring in areas forecast to have substantial storm tide. A total of 13 water-level sensors and seven barometric pressure sensors were deployed at 13 sites on September 18, 2017, two days before hurricane landfall (fig. 2, table 2). The water-level and barometric pressure sensors were programmed to record atmospheric pressure data, in pounds per square inch, at 30-second intervals beginning at 0600 Greenwich Mean Time (GMT) on September 19 through 1800 GMT on September 26. Two water-level sensors

were destroyed during the storm. A typical sensor installation is shown in figure 3.

The water-level and barometric pressure sensor data were collected and processed following protocols established by McGee and others (2006) and McCallum and others (2012). In order to compute the storm-tide time-series datasets in feet above the Puerto Rico Vertical Datum of 2002 (PRVD02) at each site, a post-processing script was used to correct the water-level sensor data for barometric pressure and salinity, and to adjust the data to the elevation of the respective reference point. The script also filtered the water-level data to determine the peak storm tide using the method described in Frantz and others (2017). An example of the water-level data, barometric pressure data, and selected maximum storm-tide elevation are shown in figure 4.

Several permanent USGS real-time streamgages and precipitation stations were destroyed or malfunctioned because of the hurricane-force winds and flooding associated with Hurricane Irma and Hurricane Maria. High flows associated with the hurricanes potentially altered the channel geometry of many rivers, thereby altering the hydraulic rating curves used to estimate river discharge. The USGS conducted direct

Table 2. Hurricane Maria peak storm-tide data for storm-tide stations in Puerto Rico, September 2017.

[Dates shown as month/day/year. Time shown in 24-hour format. PRVD02, Puerto Rico Vertical Datum 2002; UTC, Coordinated Universal Time; ±, plus or minus; ft, foot; --, not applicable; n.d., no data (sensor destroyed during storm)]

Site identification	Figure 2 index number	Municipality	Latitude	Longitude	Sensor deployment type	Peak storm-tide elevation (ft above PRVD02)	Peak storm-tide elevation date and time (UTC)	Surveyed sensor elevation uncertainty (± ft)
			Decimal degrees					
PRARR22313	1	Arroyo	17.9619	−66.0643	Water level	3.93	9/20/2017 1158	0.12
PRCEI22309	2	Ceiba	18.2705	−65.6306	Water level	4.21	9/20/2017 1007	0
PRDOR20633	3	Dorado	18.4762	−66.2773	Barometric pressure	--	--	--
PRDOR20633	3	Dorado	18.4764	−66.2772	Water level	3.24	9/20/2017 1208	0.06
PRFAJ20587	4	Fajardo	18.3459	−65.6365	Barometric pressure	--	--	--
PRFAJ20587	4	Fajardo	18.3459	−65.6365	Water level	3.66	9/20/2017 1027	0.05
PRJUA22307	5	Juana Diaz	17.9898	−66.4822	Barometric pressure	--	--	--
PRJUA22307	5	Juana Diaz	17.9898	−66.4822	Water level	4.24	9/20/2017 1417	0.13
PRMAU22311	6	Maunabo	17.9913	−65.8889	Water level	4.26	9/20/2017 1148	0.15
PRPAT22312	7	Patillas	17.9755	−65.9900	Barometric pressure	--	--	--
PRPAT22312	7	Patillas	17.9755	−65.9900	Water level	4.13	9/20/2017 1138	0.12
PRPON22310	8	Ponce	17.9780	−66.6181	Water level	2.69	9/20/2017 1421	0.01
PRPON22317	9	Ponce	17.9642	−66.6183	Water level	n.d.	n.d.	--
PRSAL22314	10	Salinas	17.9515	−66.2264	Water level	3.84	9/20/2017 1259	0.08
PRSAL22315	11	Salinas	17.9609	−66.2989	Barometric pressure	--	--	--
PRSAL22315	11	Salinas	17.9609	−66.2989	Water level	n.d.	n.d.	--
PRSAN20648	12	San Juan	18.4530	−66.0437	Barometric pressure	--	--	--
PRSAN20648	12	San Juan	18.4530	−66.0437	Water level	7.95	9/20/2017 1359	0.05
PRSAN22316	13	Santa Isabel	17.9563	−66.4110	Barometric pressure	--	--	--
PRSAN22316	13	Santa Isabel	17.9563	−66.4110	Water level	3.62	9/20/2017 1304	0.18



Figure 3. U.S. Geological Survey (USGS) technicians Belytza Velez-Gamez and Dennis Rivera surveying a water-level sensor in the Arroyo Municipality, Puerto Rico, September 2017. Photograph by James Torres, USGS.

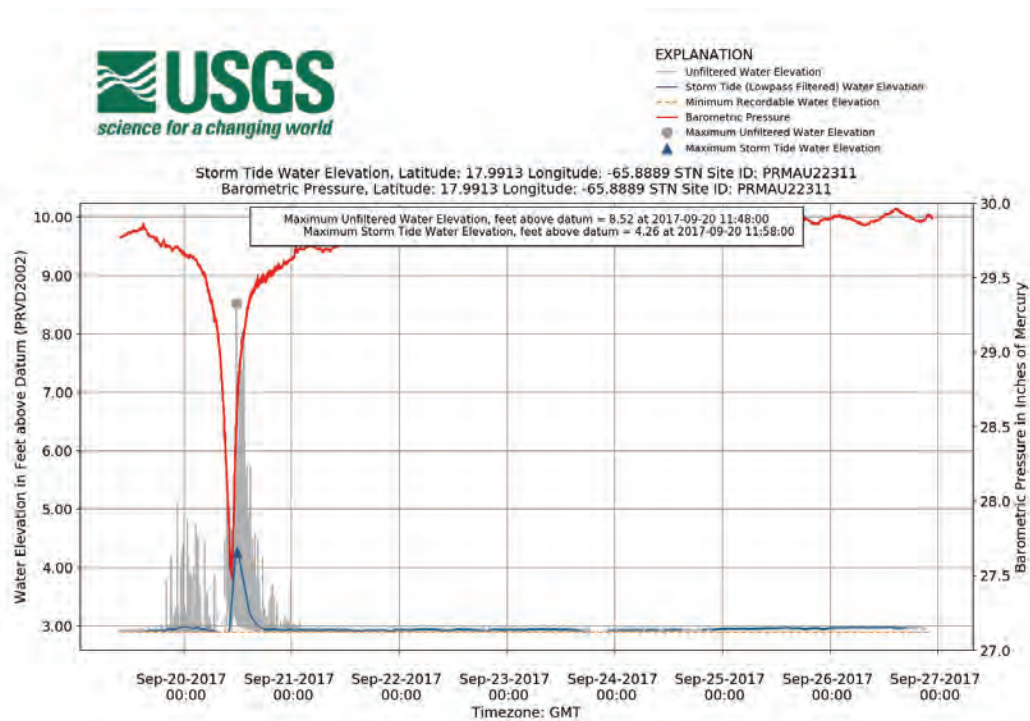


Figure 4. Hydrograph from the U.S. Geological Survey Flood Event Viewer (<https://stn.wim.usgs.gov/FEV/#MariaSeptember2017>) showing storm-tide elevation and barometric pressure data recorded during Hurricane Maria in Puerto Maunabo, September 2017.

discharge measurements, indirect discharge measurements (Matthai, 1967), and step backwater analyses (Davidian, 1976) in Puerto Rico in the months following the hurricane to guide development of new rating curves appropriate to post-hurricane hydraulic conditions. The top priorities of the USGS, following the hurricane, were retrieving the water-level sensors, repairing the permanent gages, making discharge measurements, and flagging high-water marks. Progress to repair and rebuild the sites was hampered by flooded roadways, fuel shortages, collapsed bridges, shortage of construction material, equipment, power outages, and mudslides (fig. 5). Assistance from USGS personnel in the contiguous United States was delayed more than a week after the hurricane because of limited commercial flights (Federal Aviation Administration, 2017).

In total, 181 coastal and riverine high-water marks (HWMs) located in Puerto Rico were recovered and surveyed following the techniques described in Koenig and others (2016). The high-water mark and storm-tide sensor data were disseminated on the USGS Flood Event Viewer website (<https://stn.wim.usgs.gov/FEV/#MariaSeptember2017>).

Elevation Surveys

National Geodetic Survey (NGS) benchmarks were used to determine vertical control at permanent and storm-tide monitoring stations throughout the study area. At the majority of the sites, survey-grade Global Navigation Satellite



Figure 5. Puerto Rico National Guard patrolling a main highway in downtown San Juan on September 22, 2017, two days after Hurricane Maria. Photograph courtesy of Sgt. Jose Ahiham Diaz-Ramos, U.S. National Guard.

System (GNSS) equipment (fig. 6) was used to determine the elevation above PRVD02 of the reference points and HWMs, in accordance with USGS technical guidance (Rydland and Densmore, 2012); all GNSS-determined elevations in this report were derived using the GEOID12A model (NGS, 2017). Vertical control was established on permanent objects near the stations to convert the recorded water-surface elevations to the PRVD02 datum. The survey uncertainty was calculated using the methods described in Rydland and Densmore (2012). At the storm-tide stations, graduated steel tapes were used to relate the elevations of the reference points to those of the water-level sensors.

Data Presentation

The data from the Hurricane Maria storm-tide network are available in tab-delimited, American Standard Code for Information Interchange (ASCII) format and Network Common Data Form (NetCDF) format by site for each sensor from the USGS Flood Event Viewer (<https://stn.wim.usgs.gov/FEV/#MariaSeptember2017>). Digital photographs for selected locations are available on the viewer. Data for each sensor include location, date, time, water level, and barometric pressure. Data for HWMs include location, description and quality of the mark, and elevation.

The peak storm tide was recorded at 11 water-level sensors (table 2). All HWM data collected by the USGS immediately after Hurricane Maria are listed in table 3. The survey uncertainty for the water-level sensors and high-water mark elevations is reported in tables 2 and 3, respectively. The peak riverine stage was recorded at 70 permanent stations (table 4); 24 canal and lake station peaks were excluded from this report. Some data are considered provisional, as denoted by an asterisk, until they receive a formal review by the USGS. Peak storm-tide data also were compiled for 8 of 13 functioning NOAA tide-gages, which have instrumentation to measure coastal water levels located in Puerto Rico and the U.S. Virgin Islands (table 5; NOAA, 2017). Precipitation was recorded at 17 permanent stations (table 6).



Figure 6. Global Navigation Satellite System equipment used for elevation survey near Puerto Chico, Fajardo, Puerto Rico, October 2017. Photograph by Ryan Hollins, U.S. Geological Survey.

Table 3. Hurricane Maria high-water marks recorded by the U.S. Geological Survey in Puerto Rico, September 2017.

[Peak assumed to occur on September 20, 2017. HWM, high-water mark; ft, foot; PRVD02, Puerto Rico Vertical Datum of 2002; ±, plus or minus]

Site identification	Municipality	Latitude	Longitude	HWM surveyed elevation	HWM survey uncertainty
		Decimal degrees		(ft above PRVD02)	(± ft)
PRPAT22312	Patillas	17.9755	−65.9900	4.62	0.12
PRPAT22312	Patillas	17.9755	−65.9900	4.99	0.12
PRCEI22309	Ceiba	18.2705	−65.6306	5.23	0.12
PRFAJ20587	Fajardo	18.3459	−65.6365	5.51	0.14
PRDOR20633	Dorado	18.4762	−66.2773	7.44	0.06
PRDOR20633	Dorado	18.4764	−66.2772	7.03	0.06
PRJUA22307	Juana Diaz	17.9898	−66.4822	4.74	0.13
PRPON22310	Ponce	17.9780	−66.6181	5.06	0.01
PRSAL22315	Salinas	17.9609	−66.2989	5.18	0.09
PRYAB20635	Yabucoa	18.0639	−65.8163	8.70	0.13
PRYAB20635	Yabucoa	18.0640	−65.8165	8.37	0.13
PRHUM20650	Humacao	18.1644	−65.7439	5.93	0.13
PRSAN22316	Santa Isabel	17.9563	−66.4110	5.19	0.18
PRCOR23569	Corozal	18.3417	−66.3212	257.60	0.08
PRCOR23571	Corozal	18.3420	−66.3198	260.93	0.08
PRGUR23573	Gurabo	18.2571	−65.9733	161.91	0.03
PRGUR23574	Gurabo	18.2570	−65.9712	162.28	0.03
PRTOA23575	Toa Baja	18.4437	−66.2314	14.15	0.03
PRTOA23577	Toa Baja	18.4463	−66.2437	13.81	0.03
PRTOA23578	Toa Baja	18.4431	−66.2515	17.37	0.03
PRTOA23579	Toa Baja	18.4398	−66.2531	23.41	0.03
PRCAR23570	Carolina	18.3800	−65.9558	35.19	0.01
PRCOR23598	Corozal	18.3419	−66.3216	257.65	0.08
PRGUR23572	Gurabo	18.2592	−65.9733	162.17	0.03
PRTOA23576	Toa Baja	18.4460	−66.2391	13.74	0.03
PRTOA23599	Toa Baja	18.4438	−66.1784	9.56	0.11
PRTOA23600	Toa Baja	18.4451	−66.1814	9.49	0.11
PRTOA23601	Toa Baja	18.4471	−66.1838	8.72	0.11
PRTOA23602	Toa Baja	18.4501	−66.1860	9.62	0.11
PRCAR23603	Carolina	18.3786	−65.9473	33.77	0.01
PRCAR23604	Carolina	18.4003	−65.9458	30.91	0.01
PRCAR23605	Carolina	18.3936	−65.9306	29.58	0.01
PRCAR23606	Carolina	18.3876	−65.9205	31.72	0.01
PRCAR23607	Carolina	18.3785	−65.9531	36.95	0.01
PRCAR23607	Carolina	18.3785	−65.9531	36.76	0.01
PRCOR23608	Corozal	18.3338	−66.3144	298.01	0.08
PRCOR23609	Corozal	18.3392	−66.3169	267.27	0.08
PRCOR23610	Corozal	18.3383	−66.3194	265.29	0.08
PRGUR23611	Gurabo	18.2631	−65.9668	144.34	0.03

Table 3. Hurricane Maria high-water marks recorded by the U.S. Geological Survey in Puerto Rico, September 2017.—Continued

[Peak assumed to occur on September 20, 2017. HWM, high-water mark; ft, foot; PRVD02, Puerto Rico Vertical Datum of 2002; ±, plus or minus]

Site identification	Municipality	Latitude	Longitude	HWM surveyed elevation (ft above PRVD02)	HWM survey uncertainty (± ft)
		Decimal degrees			
PRTOA23612	Toa Baja	18.4537	−66.1879	9.82	0.11
PRTOA23613	Toa Baja	18.4515	−66.1911	9.94	0.11
PRARE23614	Arecibo	18.4633	−66.7220	16.89	0.07
PRARE23615	Arecibo	18.4636	−66.7237	16.86	0.07
PRMAN23618	Manati	18.4671	−66.5256	17.47	0.10
PRMAN23619	Manati	18.4476	−66.5264	21.47	0.10
PRBAR23620	Barceloneta	18.4798	−66.5353	5.72	0.10
PRBAR23620	Barceloneta	18.4798	−66.5353	5.77	0.10
PRSAN23621	San Juan	18.4120	−66.0744	16.02	0.05
PRBAR23622	Barceloneta	18.4648	−66.5319	17.03	0.10
PRBAR23622	Barceloneta	18.4648	−66.5319	16.96	0.10
PRCOM23624	Comerio	18.2173	−66.2273	655.83	0.16
PRCOM23625	Comerio	18.2157	−66.2300	658.15	0.16
PRCOM23626	Comerio	18.2150	−66.2276	655.89	0.16
PRCOM23627	Comerio	18.2155	−66.2255	652.26	0.16
PRCAN23628	Canovanas	18.3886	−65.9225	24.98	0.01
PRCAN23629	Canovanas	18.3880	−65.9213	30.40	0.01
PRCAN23630	Canovanas	18.3713	−65.8973	52.53	0.05
PRCAN23631	Canovanas	18.3811	−65.8999	26.00	0.05
PRDOR23632	Dorado	18.4565	−66.2595	15.74	0.08
PRDOR23633	Dorado	18.4567	−66.2647	16.86	0.08
PRDOR23634	Dorado	18.4588	−66.2699	15.55	0.08
PRDOR23635	Dorado	18.4328	−66.2745	29.38	0.08
PRMAN23623	Manati	18.4261	−66.4963	43.69	0.10
PRDOR23636	Dorado	18.4293	−66.2653	29.47	0.08
PRBAR23637	Barceloneta	18.4792	−66.5373	9.64	0.10
PRBAR23638	Barceloneta	18.4710	−66.5316	15.48	0.10
PRBAR23638	Barceloneta	18.4710	−66.5316	15.34	0.10
PRUTU23639	Utuado	18.2666	−66.6978	462.78	0.06
PRUTU23640	Utuado	18.2529	−66.6776	597.31	0.06
PRARE23641	Arecibo	18.4103	−66.0758	15.59	0.00
PRUTU23640	Utuado	18.2528	−66.6777	597.79	0.06
PRSAN23642	San Juan	18.4020	−66.0659	28.42	0.00
PRSAL23473	Salinas	17.9559	−66.2189	2.12	0.09
PRSAL23473	Salinas	17.9559	−66.2189	1.90	0.09
PRUTU23643	Utuado	18.2671	−66.7030	449.08	0.06
PRMAN23644	Manati	18.4248	−66.4945	46.81	0.10
PRMAN23646	Manati	18.4249	−66.4947	46.29	0.10
PRUTU23645	Utuado	18.2667	−66.7068	443.64	0.06

Table 3. Hurricane Maria high-water marks recorded by the U.S. Geological Survey in Puerto Rico, September 2017.—Continued

[Peak assumed to occur on September 20, 2017. HWM, high-water mark; ft, foot; PRVD02, Puerto Rico Vertical Datum of 2002; ±, plus or minus]

Site identification	Municipality	Latitude	Longitude	HWM	HWM survey
		Decimal degrees		surveyed elevation (ft above PRVD02)	uncertainty (± ft)
PRSAN23647	San Juan	18.4065	−66.0670	25.45	0.00
PRSAN23648	San Juan	18.4125	−66.0733	16.79	0.00
PRSAN23649	San Juan	18.4153	−66.0785	15.33	0.00
PRSAN23650	San Juan	18.4052	−66.0741	20.99	0.00
PRSAN23652	San Juan	18.4026	−66.0766	23.12	0.00
PRUTU23651	Utua	18.2667	−66.7102	439.48	0.06
PRUTU23651	Utua	18.2667	−66.7102	439.74	0.06
PRARE23653	Arecibo	18.4703	−66.7165	15.49	0.07
PRARE23654	Arecibo	18.4705	−66.7050	12.38	0.07
PRCAN23655	Canovanas	18.3739	−65.9159	31.68	0.05
PRCAN23656	Canovanas	18.3720	−65.9016	39.19	0.05
PRCOM23658	Comerio	18.2240	−66.2176	637.34	0.16
PRCAN23659	Canovanas	18.3934	−65.8886	24.78	0.09
PRMAN23660	Manati	18.4283	−66.5235	32.54	0.10
PRMAN23661	Manati	18.4282	−66.5056	40.82	0.10
PRCOM23662	Comerio	18.2209	−66.2255	648.16	0.16
PRMAN23663	Manati	18.4273	−66.4974	43.75	0.10
PRCOM23664	Comerio	18.2181	−66.2259	652.83	0.16
PRCOM23665	Comerio	18.2355	−66.2149	618.68	0.16
PRCOM23666	Comerio	18.2496	−66.2064	594.67	0.16
PRHUM23667	Humacao	18.1637	−65.7461	8.48	0.14
PRUTU23668	Utua	18.2736	−66.7102	427.21	0.06
PRUTU23669	Utua	18.2694	−66.7089	433.99	0.06
PRUTU23670	Utua	18.2725	−66.7085	429.16	0.06
PRUTU23671	Utua	18.2829	−66.7029	409.70	0.06
PRUTU23672	Utua	18.2604	−66.6913	492.48	0.06
PRSAL23673	Salinas	17.9775	−66.3024	26.22	0.05
PRSAL23674	Salinas	17.9761	−66.3029	25.36	0.05
PRRIO23676	Rio Grande	18.3788	−65.8290	14.98	0.08
PRRIO23677	Rio Grande	18.3853	−65.8284	12.53	0.02
PRRIO23678	Rio Grande	18.3853	−65.8278	11.96	0.02
PRRIO23679	Rio Grande	18.3866	−65.8284	9.21	0.02
PRRIO23680	Rio Grande	18.3939	−65.8235	8.49	0.02
PRHUM23681	Humacao	18.1684	−65.7416	9.52	0.14
PRRIO23682	Rio Grande	18.3938	−65.8234	8.46	0.02
PRRIO23684	Rio Grande	18.3782	−65.8292	15.15	0.08
PRHUM23683	Humacao	18.1693	−65.7467	6.97	0.14
PRHUM23683	Humacao	18.1693	−65.7467	7.21	0.14
PRHUM23685	Humacao	18.1671	−65.7522	6.19	0.14

Table 3. Hurricane Maria high-water marks recorded by the U.S. Geological Survey in Puerto Rico, September 2017.—Continued

[Peak assumed to occur on September 20, 2017. HWM, high-water mark; ft, foot; PRVD02, Puerto Rico Vertical Datum of 2002; ±, plus or minus]

Site identification	Municipality	Latitude	Longitude	HWM surveyed elevation (ft above PRVD02)	HWM survey uncertainty (± ft)
		Decimal degrees			
PRSAL23686	Salinas	17.9867	−66.2803	61.70	0.05
PRHUM23685	Humacao	18.1671	−65.7522	6.32	0.14
PRHUM23687	Humacao	18.1622	−65.7585	7.38	0.14
PRARE23616	Arecibo	18.4667	−66.7207	16.50	0.07
PRCAR23688	Carolina	18.3755	−65.9175	28.99	0.05
PRCAR23688	Carolina	18.3755	−65.9175	29.33	0.05
PRUTU23689	Utuado	18.2550	−66.6800	567.60	0.06
PRUTU23690	Utuado	18.2662	−66.6966	463.94	0.06
PRCAN23691	Canovanas	18.3779	−65.8921	43.37	0.05
PRCAN23692	Canovanas	18.3450	−65.8961	122.75	0.09
PRRIO23693	Rio Grande	18.3930	−65.8126	8.45	0.02
PRRIO23694	Rio Grande	18.3786	−65.8296	15.11	0.08
PRRIO23695	Rio Grande	18.3749	−65.8239	23.65	0.08
PRSAL23696	Salinas	17.9627	−66.3005	2.09	0.05
PRHUM23697	Humacao	18.1849	−65.7081	8.75	0.14
PRHUM23697	Humacao	18.1849	−65.7081	8.98	0.14
PRHUM23698	Humacao	18.1873	−65.7109	7.73	0.14
PRHUM23699	Humacao	18.1594	−65.7641	7.92	0.14
PRHUM23700	Humacao	18.1640	−65.7615	7.81	0.14
PRHUM23701	Humacao	18.1592	−65.7589	7.88	0.14
PRYAU23702	Yauco	18.0329	−66.8440	98.80	0.60
PRYAU23703	Yauco	18.0368	−66.8446	104.43	0.60
PRYAU23704	Yauco	18.0351	−66.8460	99.31	0.60
PRCAN23657	Canovanas	18.3386	−65.8903	146.46	0.05
PRYAU23706	Yauco	18.0388	−66.8443	115.39	0.60
PRHUM23708	Humacao	18.1879	−65.7261	8.76	0.14
PRHUM23709	Humacao	18.1893	−65.7273	7.84	0.14
PRHUM23710	Humacao	18.1879	−65.7272	7.40	0.14
PRYAU23711	Yauco	18.0385	−66.8439	110.31	0.60
PRYAU23712	Yauco	18.0337	−66.8477	99.37	0.60
PRGUA23713	Guayama	17.9760	−66.0935	57.97	0.10
PRGUA23714	Guayama	17.9744	−66.1252	129.54	0.10
PRGUA23715	Guayama	17.9771	−66.1242	145.12	0.06
PRSAN23716	Santa Isabel	17.9552	−66.4098	4.59	0.02
PRYAU23717	Yauco	18.0318	−66.8473	96.55	0.60
PRYAU23718	Yauco	18.0299	−66.8463	92.45	0.60
PRSAN23719	Santa Isabel	17.9564	−66.4090	7.17	0.02
PRTOA23720	Toa Alta	18.3959	−66.2529	48.11	0.08
PRTOA23728	Toa Alta	18.3934	−66.2471	52.57	0.08

Table 3. Hurricane Maria high-water marks recorded by the U.S. Geological Survey in Puerto Rico, September 2017.—Continued

[Peak assumed to occur on September 20, 2017. HWM, high-water mark; ft, foot; PRVD02, Puerto Rico Vertical Datum of 2002; ±, plus or minus]

Site identification	Municipality	Latitude	Longitude	HWM surveyed elevation (ft above PRVD02)	HWM survey uncertainty (± ft)
		Decimal degrees			
PRTOA23738	Toa Alta	18.3911	−66.2537	49.91	0.08
PRCAG23739	Caguas	18.1840	−66.0551	359.37	0.03
PRCAG23740	Caguas	18.2336	−66.0423	210.61	0.03
PRVEG23741	Vega Baja	18.4620	−66.3716	13.70	0.23
PRCAG23742	Caguas	18.2230	−66.0156	187.87	0.03
PRVEG23743	Vega Baja	18.4605	−66.3569	19.42	0.23
PRVEG23744	Vega Baja	18.4341	−66.3814	42.66	0.23
PRTOA23745	Toa Baja	18.4109	−66.2558	37.04	0.08
PRCAN23746	Canovanas	18.3913	−65.8913	24.77	0.09
PRCAN23747	Canovanas	18.4010	−65.9109	15.97	0.01
PRYAU23748	Yauco	18.0029	−66.8340	47.88	0.60
PRGUA23749	Guayama	17.9796	−66.1232	154.36	0.06
PRGUA23750	Guayama	17.9809	−66.1226	164.15	0.10
PRGUA23751	Guayama	17.9874	−66.1182	200.49	0.10
PRGUA23752	Guayama	17.9889	−66.1168	210.55	0.10
PRVEG23765	Vega Baja	18.4392	−66.3634	35.67	0.27
PRVEG23766	Vega Baja	18.4344	−66.3618	37.35	0.27
PRVEG23767	Vega Baja	18.4302	−66.3563	44.01	0.23
PRYAU23793	Yauco	17.9900	−66.8400	44.58	0.60
PRCAR23794	Carolina	18.3687	−65.9540	39.49	0.09
PRARE23795	Arecibo	18.4562	−66.7241	17.07	0.07
PRCAR23796	Carolina	18.3731	−65.9459	35.55	0.09
PRARE23797	Arecibo	18.4167	−66.7077	43.48	0.07
PRARE23798	Arecibo	18.3931	−66.6823	72.80	0.07
PRRIN23799	Rincon	18.3155	−67.2246	51.43	0.06

Table 4. Hurricane Maria peak riverine stage recorded at U.S. Geological Survey long-term monitoring sites in Puerto Rico, September 2017.

[Dates shown as month, day, year. Time shown in 24-hour format. ft, foot; UTC, Coordinated Universal Time; blw, below; nr, near; abv, above; hwy, highway; *, provisional; >, greater than; E, estimated; PR, Puerto Rico]

Site identification	Station name	Latitude	Longitude	Peak riverine stage (ft above local datum)	Peak date and time (UTC)
		Decimal degrees			
50011200	Rio Guajataca blw Lago Guajataca, PR	18.3983	−66.9274	17.10	9/20/17 2341
50014800	Rio Camuy nr Bayaney, PR	18.3944	−66.8176	25.20	9/21/17 1124
50021700	Rio Grande De Arecibo abv Utuado, PR	18.2422	−66.7219	20.33	9/20/17 1600
50024950	Rio Grande De Arecibo blw Utuado, PR	18.3001	−66.7037	31.84*	9/20/17 1630
50025155	Rio Saliente at Coabey nr Jayuya, PR	18.2108	−66.5628	13.72	9/20/17 1300
50026025	Rio Caonillas at Paso Palma, PR	18.2294	−66.6367	31.12*	9/20/17 1330
50027000	Rio Limon abv Lago Dos Bocas, PR	18.3241	−66.6206	23.93*	9/20/17 1230
50027600	Rio Grande De Arecibo nr San Pedro, PR	18.3968	−66.6912	21.96*	9/20/17 1645
50028000	Rio Tanama nr Utuado, PR	18.2987	−66.7826	18.42	9/20/17 1500
50028400	Rio Tanama at Charco Hondo, PR	18.4121	−66.7143	22.39	9/20/17 1600
50029000	Rio Grande De Arecibo at Central Cambalache, PR	18.4535	−66.7021	20.35*	9/20/17 1807
50031200	Rio Grande De Manati nr Morovis, PR	18.2937	−66.4134	31.57*	9/20/17 1300
50034000	Rio Bauta nr Orocovis, PR	18.2340	−66.4544	22.48*	9/20/17 1337
50035000	Rio Grande De Manati at Ciales, PR	18.3224	−66.4596	43.36	9/20/17 1432
50038100	Rio Grande De Manati at Hwy 2 nr Manati, PR	18.4290	−66.5265	37.07*	9/20/17 1520
50039500	Rio Cibuco at Vega Baja, PR	18.4453	−66.3740	19.98*	9/20/17 2245
50043197	Rio Usabon at Hwy 162 nr Barranquitas, PR	18.1596	−66.3090	20.84	9/20/17 1901
50043800	Rio De La Plata at Comerio, PR	18.2202	−66.2242	34.86*	9/20/17 1317
50043980	Rio Arroyata at Bo. Naranjo, PR	18.2210	−66.2028	12.32*	9/20/17 1230
50044810	Rio Guadiana nr Guadiana, Naranjito PR	18.2994	−66.2282	17.68*	9/20/17 1900
50045010	Rio De La Plata blw La Plata Damsite, PR	18.3440	−66.2384	44.63	9/20/17 1300
50046000	Rio De La Plata at Hwy 2 nr Toa Alta, PR	18.4096	−66.2606	28.56	9/20/17 1445
50047535	Rio De Bayamon at Arenas, PR	18.1672	−66.1216	7.02	9/20/17 1000
50047560	Rio De Bayamon blw Lago De Cidra Dam, PR	18.2008	−66.1388	22.89*	9/20/17 1038
50047850	Rio De Bayamon nr Bayamon, PR	18.3323	−66.1391	13.59	9/20/17 1307
50049100	Rio Piedras at Hato Rey, PR	18.4076	−66.0689	22.91*	9/20/17 1808
50049620	Qda. Margarita at Caparra Inter. nr Guaynabo, PR	18.4135	−66.1030	11.93	9/20/17 1245
50050900	Rio Grande De Loiza at Quebrada Arenas, PR	18.1180	−65.9882	10.89	9/20/17 1255
50051310	Rio Cayaguas at Cerro Gordo, PR	18.1519	−65.9563	17.42	9/20/17 1327
50051800	Rio Grande De Loiza at Hwy 183 San Lorenzo, PR	18.1837	−65.9611	24.18	9/20/17 1430
50053025	Rio Turabo abv Borinquen, PR	18.1602	−66.0396	10.35	9/21/17 0127
50055000	Rio Grande De Loiza at Caguas, PR	18.2407	−66.0092	24.48	9/20/17 1610
50055225	Rio Caguitas at Villa Blanca at Caguas, PR	18.2467	−66.0272	20.65	9/20/17 1051
50055750	Rio Gurabo blw El Mango, PR	18.2322	−65.8849	23.87	9/20/17 1040
50056400	Rio Valenciano nr Juncos, PR	18.2141	−65.9258	18.49*	9/20/17 1300
50057000	Rio Gurabo at Gurabo, PR	18.2565	−65.9677	31.96*	9/20/17 1210
50058350	Rio Canas at Rio Canas, PR	18.2925	−66.0447	22.24	9/20/17 1350
50059050	Rio Grande De Loiza blw Loiza Damsite, PR	18.3403	−66.0056	47.93*	9/20/17 1800
50059210	Quebrada Grande at Bo. Dos Bocas, PR	18.3484	−65.9901	22.78	9/20/17 1327

Table 4. Hurricane Maria peak riverine stage recorded at U.S. Geological Survey long-term monitoring sites in Puerto Rico, September 2017.—Continued

[Dates shown as month, day, year. Time shown in 24-hour format. ft, foot; UTC, Coordinated Universal Time; blw, below; nr, near; abv, above; hwy, highway; *, provisional; >, greater than; E, estimated; PR, Puerto Rico]

Site identification		Station name	Latitude	Longitude	Peak riverine stage (ft above local datum)	Peak date and time (UTC)
			Decimal degrees			
50061800	Rio Canovanas nr Campo Rico, PR		18.3165	−65.8885	17.33*	9/20/17 0945
50063800	Rio Espiritu Santo nr Rio Grande, PR		18.3579	−65.8136	17.24	9/20/17 1146
50064200	Rio Grande nr El Verde, PR		18.3434	−65.8416	18.48	9/20/17 1145
50065500	Rio Mameyes nr Sabana, PR		18.3268	−65.7504	12.10	9/20/17 1300
50067000	Rio Sabana at Sabana, PR		18.3290	−65.7306	16.47	9/20/17 1120
50070900	Rio Fajardo at Paraiso nr Fajardo, PR		18.2808	−65.7007	12.52	9/20/17 0922
50071000	Rio Fajardo nr Fajardo, PR		18.2970	−65.6934	13.90	9/20/17 1205
50075000	Rio Icacos nr Naguabo, PR		18.2752	−65.7854	8.35	9/20/17 1150
50081000	Rio Humacao at Las Piedras, PR		18.1721	−65.8690	6.63	9/20/17 1405
50083500	Rio Guayanes nr Yabucoa, PR		18.0569	−65.9007	24.79	9/20/17 1500
50085100	Rio Guayanes at Central Roig, PR		18.0644	−65.8738	27.29	9/20/17 1455
50090500	Rio Maunabo at Lizas, PR		18.0252	−65.9391	11.86	9/20/17 1301
50092000	Rio Grande De Patillas nr Patillas, PR		18.0322	−66.0321	16.38	9/20/17 1203
50093000	Rio Marin nr Patillas, PR		18.0358	−66.0093	11.50	9/20/17 1015
50093120	Rio Grande De Patillas blw Lago Patillas, PR		18.0144	−66.0232	16.94	9/20/17 1200
50100200	Rio Lapa nr Rabo Del Buey, PR		18.0577	−66.2407	15.37	9/20/17 1155
50100450	Rio Majada at La Plena, PR		18.0427	−66.2071	16.62*	9/20/17 1155
50110650	Rio Jacaguas abv Lago Guayabal		18.1146	−66.5043	17.19*	9/20/17 1242
50110900	Rio Toa Vaca abv Lago Toa Vaca, PR		18.1245	−66.4574	14.36*	9/20/17 1600
50112500	Rio Inabon at Real Abajo, PR		18.0845	−66.5627	>20.76	9/20/17 1331
50113800	Rio Cerrillos abv Lago Cerrillos nr Ponce, PR		18.1148	−66.6045	15.55	9/20/17 1222
50114000	Rio Cerrillos blw Lago Cerrillos nr Ponce, PR		18.0709	−66.5810	7.53	9/20/17 1053
50114900	Rio Portugues nr Tibes, PR		18.0979	−66.6425	14.04	9/20/17 1357
50115240	Rio Portugues at Parque Ceremonial Tibes nr Ponce		18.0416	−66.6211	8.20	9/20/17 1315
50124200	Rio Guayanilla Near Guayanilla, PR		18.0423	−66.7978	21.40	9/20/17 1510
50126150	Rio Yauco abv Diversion Monserrate nr Yauco, PR		18.0472	−66.8415	16.93E	9/20/17 1210
50129254	Rio Loco at Las Latas nr La Joya nr Guanica, PR		18.0072	−66.8763	19.08*	9/20/17 1750
50136400	Rio Rosario nr Hormigueros, PR		18.1581	−67.0854	19.50	9/20/17 1717
50138000	Rio Guanajibo nr Hormigueros, PR		18.1407	−67.1484	28.59	9/21/17 0110
50144000	Rio Grande De Anasco nr San Sebastian, PR		18.2822	−67.0506	35.85*	9/20/17 1904
50148890	Rio Culebrinas at Margarita Damsite nr Aguada, PR		18.3925	−67.1508	21.99*	9/20/17 2130

14 Monitoring Storm Tide, Flooding, and Precipitation From Hurricane Maria in Puerto Rico and the U.S. Virgin Islands

Table 5. Hurricane Maria peak storm-tide data recorded at National Oceanic and Atmospheric Administration real-time tide-gages in Puerto Rico and the U.S. Virgin Islands, September 2017.

[Dates shown as month, day, year. Time shown in 24-hour format. PRVD02, Puerto Rico Vertical Datum of 2002; VIVD09, Virgin Islands Vertical Datum of 2009; UTC, Coordinated Universal Time; ft, foot; P.R., Puerto Rico; V.I., Virgin Islands; NOAA, National Oceanic and Atmospheric Administration; ±, plus or minus]

Site identification	U.S. Territory	Municipality	Latitude	Longitude	Peak storm-tide elevation (ft)	Peak storm-tide date and time (UTC)	Vertical datum
			Decimal degrees				
9751364	V.I.	St. Croix	17.7356	−64.6858	3.18	9/21/2017 1136	VIVD09
9751381	V.I.	St. John	18.3169	−64.7181	1.84	9/21/2017 0718	VIVD09
9752619	P.R.	Vieques Island	18.1503	−65.4350	2.63 ±0.02	9/21/2017 0800	PRVD02
9752235	P.R.	Culebra Island	18.3003	−65.3003	1.89	9/21/2017 0900	PRVD02
9754228	P.R.	Yabucoa	18.0508	−65.8333	5.66 ±0.02	9/20/2017 1118	PRVD02
9755371	P.R.	San Juan	18.4517	−66.1167	3.10	9/20/2017 1200	PRVD02
9757809	P.R.	Arecibo	18.4689	−66.7003	2.63 ±0.02	9/20/2017 1418	PRVD02
9759938	P.R.	Mona Island	18.0844	−67.9342	2.76	9/21/2017 0148	PRVD02

Table 6. Precipitation measured in the U.S. Virgin Islands and Puerto Rico, September 18–22, 2017.

[in., inch; USVI, U.S. Virgin Islands; PR, Puerto Rico; hwy, highway]

Site identification	Station name	Latitude	Longitude	Precipitation (in.)
		Decimal degrees		
174237064474900	Wp 14 well, St. Croix, USVI	17.7083	−64.7965	11.48
50029000	Rio Grande de Arecibo at Central Cambalache, PR	18.4535	−66.7021	17.01
182647066201700	Sabana Hoyos 2 well, Vega Alta, PR	18.4443	−66.3382	9.59
50125780	Lago Lucchetti at damsite near Yauco, PR	18.0919	−66.8647	18.72
50115240	Rio Portugues at Parque Ceremonial Tibes near Ponce	18.0416	−66.6211	12.62
50999963	Jagueyes Abajo raingage, Aguas Buenas PR	18.2872	−66.0757	14.34
50999964	Bairoa Arriba raingage, Aguas Buenas PR	18.2638	−66.0954	6.55
50999965	Vaqueria El Mimo Raingage, Caguas PR	18.2116	−66.0666	21.31
50106100	Rio Coamo at Hwy 14 at Coamo, PR	18.0815	−66.3544	20.94
50010500	Rio Guajataca at Lares, PR	18.2972	−66.8735	7.65
50047550	Lago de Cidra at damsite near Cidra, PR	18.1969	−66.1407	14.43
181529065575200	Gurabo Raingage at Gurabo, PR	18.2561	−65.9641	24.41
50055225	Rio Caguitas at Villa Blanca at Caguas, PR	18.2467	−66.0272	15.72
50999966	Bo. Beatriz raingage, Caguas PR	18.1813	−66.0891	29.34
50999956	Quebrada Blanca raingage, San Lorenzo PR	18.1601	−65.9977	20.85
50999970	Bo. Apeadero raingage near Villalba, PR	18.1566	−66.4591	29.07
50999958	Pueblito del Rio raingage, Las Piedras PR	18.2463	−65.8318	29.25

Conclusion

Hurricane Maria made landfall south of Yabucoa Harbor, Puerto Rico, as a category 4 hurricane with maximum sustained winds of 155 miles per hour on September 20, 2017. The hurricane devastated much of the U.S. Virgin Islands and Puerto Rico. The U.S. Geological Survey (USGS), in cooperation with the Federal Emergency Management Agency, installed a temporary monitoring network of 13 water-level and barometric pressure sensors along the coast of Puerto Rico prior to the storm. In addition to the temporary sensors, the USGS maintains 99 permanent real-time streamgages and 36 real-time precipitation stations in Puerto Rico. The real-time data, updated hourly during and after the hurricane, are displayed in the USGS Flood Event Viewer (<https://stn.wim.usgs.gov/FEV/#MariaSeptember2017>) and in the USGS National Water Information System. The USGS measured 181 coastal and riverine high-water marks throughout Puerto Rico after the storm. Water elevations are referenced to the Puerto Rico Vertical Datum of 2002 (PRVD02) and local datums in Puerto Rico and to the U.S. Virgin Islands Vertical Datum of 2009 (VIVD09) in the U.S. Virgin Islands.

The data from Hurricane Maria storm-tide network are available in tab-delimited, ASCII format and Network Common Data Form (NetCDF) format by site for each sensor through the USGS Flood Event Viewer. The peak storm tide was recorded at 11 water-level sensors, and the peak riverine stage was recorded at 70 permanent stations. Peak storm-tide data also were compiled for National Oceanic and Atmospheric Administration tide-gages, which have instrumentation to measure coastal water levels located in Puerto Rico and the U.S. Virgin Islands. Precipitation was recorded at 17 permanent stations.

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