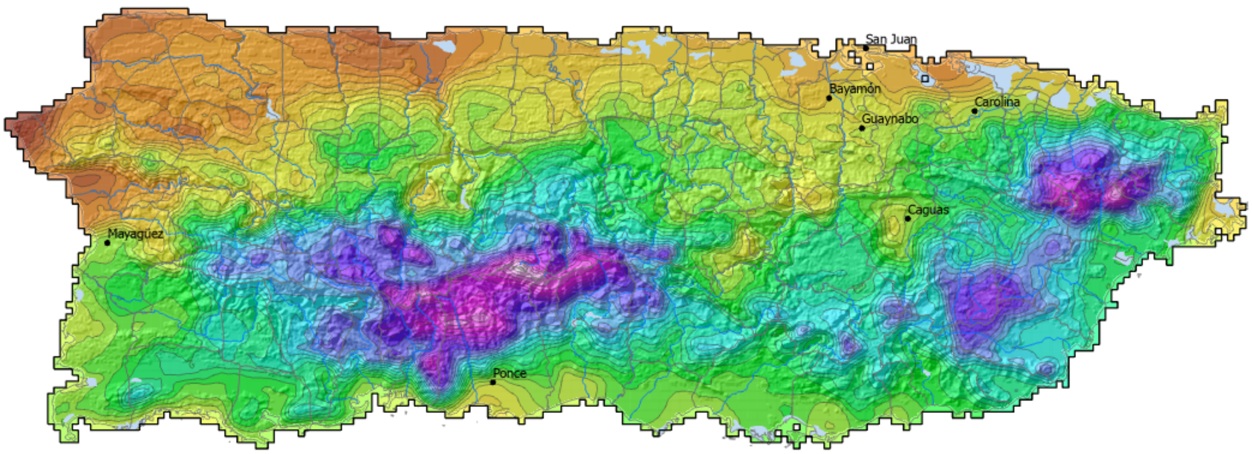
Probable Maximum Precipitation Study for Puerto Rico
Final Report

Prepared for:

Puerto Rico Electric Power Authority
In Partnership with the US Bureau of Reclamation
under Subcontract to AECOM



Prepared by:

Applied Weather Associates
PO Box 175, Monument, CO 80132
(719) 488-4311
www.appliedweatherassociates.com

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Bill Kappel, President/Chief Meteorologist, Applied Weather Associates

Credits and Acknowledgements
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The following staff of Applied Weather Associates participated in this PMP development:

Bill Kappel	Project Manager/Chief Meteorologist
Doug Hultstrand	Senior Hydrometeorologist
Geoff Muhlestein	Senior GIS Analyst
Kristi Steinhilber	Staff Meteorologist
Jake Rodel	GIS Analyst

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Jose Bermudez	PREPA
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Executive Summary

This study produced gridded PMP depths for the entire island of Puerto Rico covering any area size from 1/3rd-square mile (1-square kilometer) through the entire island and for durations from 1-hour through 120-hours. Variations in topography, climate and storm types across the island were explicitly considered in relation to PMP storm design and Probable Maximum Flood (PMF) implementation. An extensive database of PMP-type storm information was analyzed for use in developing the PMP depths and associated meteorological guidance. This included PMP for tropical systems and general storms/easterly waves with embedded convection. The tropical storm type has a distinct seasonality between June through November, while the general storms/easterly waves are most common during the fall and winter seasons. PMP depths developed in this study replace those provided in Technical Paper 42 (TP42).

Results of this analysis reflect the current standard of practice used for defining PMP, including comprehensive storm analyses procedures, extensive use of geographical information systems (GIS), explicit quantification of orographic effects, updated maximum sea surface temperature climatologies, and improved understanding of the weather and climate related to extreme rainfall throughout the region.

The approach used in this study followed the same philosophy used in the numerous site-specific, statewide, and regional PMP studies that AWA has completed. This PMP development utilizes the storm-based approach. This is the same general procedures used by the National Weather Service (NWS) in the development of the various Hydrometeorological Reports (HMR) and TP42. In addition, the World Meteorological Organization (WMO) Manual on Estimation of PMP recommends this same approach when adequate data are available. The storm-based approach identified extreme rainfall events that have occurred in regions considered transpositionable to any location within the study domain. These are storms that had meteorological and topographical characteristics similar to extreme rainfall storms that could occur over any location within the project domain and were deemed to be PMP-type storm events. These were separated by storm type, tropical and general/easterly waves with convection. Detailed storm analyses were completed for the largest of these rainfall events and used for final PMP calculations.

Data, assumptions, and analysis techniques used in this study have been reviewed and accepted by the study participants including meteorologists and hydrologist with the US Bureau of Reclamation and AECOM, as well as independent review by a meteorologist with the US Army Corps of Engineers.

Although this study produced deterministic values, it must be recognized that there is some variability associated with the PMP development procedures. Examples of decisions where meteorological judgment was involved included determining which storms are used for PMP, determination of storm adjustment factors, application of storm transposition limits, and combinations associated with temporal patterns. For areas where uncertainties in data were recognized, conservative assumptions were applied unless sufficient data existed to make a more informed decision. All data and information supporting decisions in the PMP development process have been documented so that results can be reproduced and verified.

A total of 18 unique storms centers were utilized for PMP development. These include 14 tropical storms and four General/easterly wave storms. Each storm center was analyzed using the Storm Precipitation Analysis System (SPAS), which produced several standard products including Depth-Area-Duration values, storm center mass curves, and total storm isohyetal patterns. National Weather Service Next Generation Weather Radar (NEXRAD) data were used in storm analyses when available.

Standard procedures were applied for in-place maximization adjustments (e.g., HMR 51 Section 2.3). Improved techniques and new datasets were used in other procedures to increase accuracy and reliability when justified by utilizing advancements in technology and meteorological understanding, while adhering to the basic approach used in the HMRs and in the WMO PMP Manual. Updated precipitation frequency analyses data available from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 were used for this study.

Precipitation frequency depths were used to calculate Geographic Transposition Factors (GTFs) for each storm. The GTF procedure, through its correlation process of the 100-year precipitation frequency depth provided quantifiable and reproducible analyses of the effects of terrain and all other precipitation processes on rainfall between two locations. Results of these factors (in-place maximization and geographic transposition) were applied for each storm at each grid point for each of the area sizes and durations used in this study. The results of these calculations were used to define the PMP depths.

Maximization factors were computed for each of the analyzed storm events using updated sea surface temperature (SST) climatologies. These were calculated by defining the storm representative SST for each storm, then comparing that to the maximum moisture that could have been available which utilized the +2 sigma SST climatologies developed for each month. HYSPLIT model output were utilized to represent model reanalysis fields of air flow in the atmosphere to help identify moisture source regions and timing of moisture inflow into individual storms. For storm events prior to 1948, when HYSPLIT output became available, NWS synoptic weather maps and previous storm analysis data were used as guidance in identifying the storm representative moisture source regions.

To store, analyze, and produce results from the large datasets developed in the study, the PMP database and calculations were stored and analyzed in individual Excel spreadsheets and a GIS database. This combination of Excel and GIS was used to query, calculate, and derive PMP depths for each grid point for each duration for each storm type. The database allowed PMP to be calculated at any area size and/or duration available in the underlying SPAS data, from 1/3rd-square mile through the entire domain.

When compared to previous PMP depths provided in TP42 the updated values from this study resulted in a wide range of reductions at most area sizes and durations, with some regions resulting in minor increases. PMP depths are highest in the elevated regions in the central portion of the island and the elevated regions the eastern areas around El Yunque. The lowest PMP depths are along the regions in the southwestern, western, and northern parts of the island. These spatial variations in PMP depth match the general weather pattern of the region, including moisture availability, orographic influences, and storm dynamics.

Many watersheds across the island are relatively small in area size, less than 20-square miles. Therefore, a significant amount of emphasis was placed on developing PMP depths and temporal patterns most relevant for smaller area sizes and quick response basins. Providing PMP depths down to area sizes at 1/3rd-square mile by storm type, along with specific temporal accumulation patterns were significant improvements for dam safety evaluations over what was previously available in the TP42.

On average, this updated PMP analysis resulted in a wide range of changes from TP42. Some areas saw increases, especially for the 1-hr duration in the orographically influenced mountainous regions. In general, significant decreases compared to TP42 resulted for the 24-hour duration, with minor increases over the orographically influenced mountainous regions. Figures E.1 and E.2 provide the average percent difference (negative is a reduction) from TP4 across the entire island at the 1-hour and 24-hour durations.

Figure E.1: Percent difference from TP42 1-hour PMP against Puerto Rico 1-hour PMP

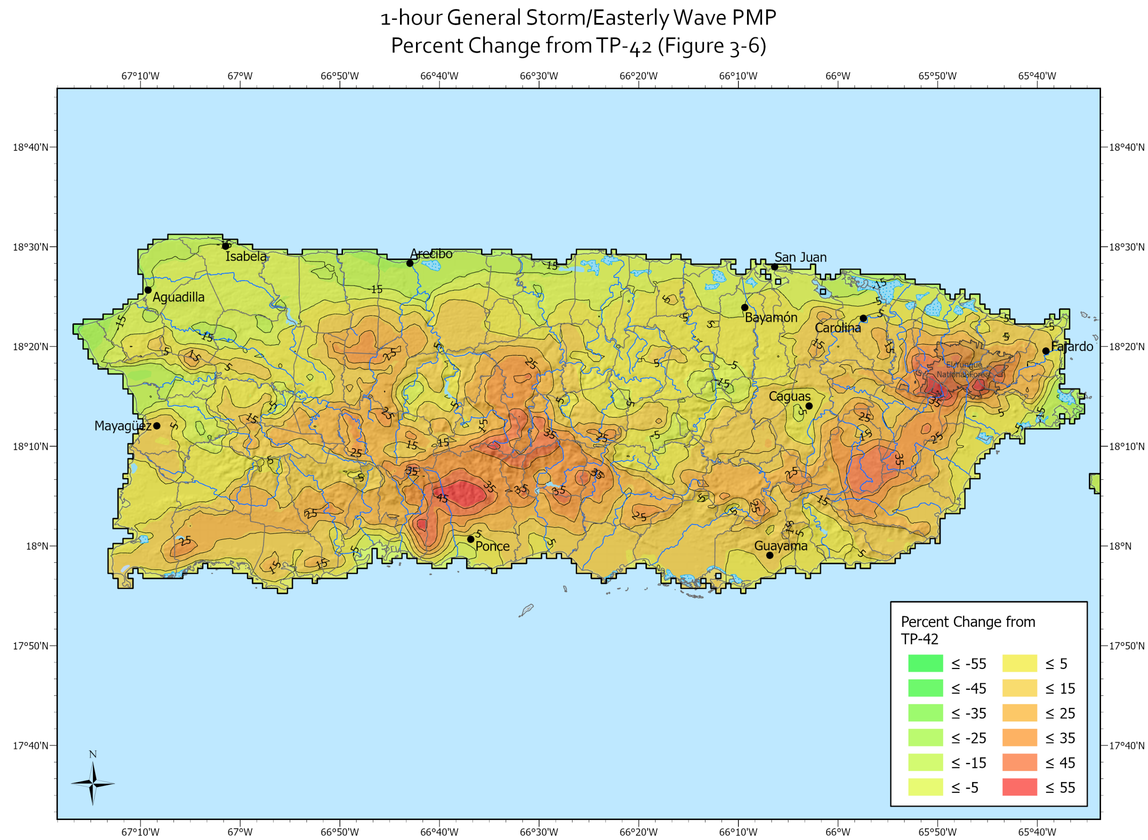
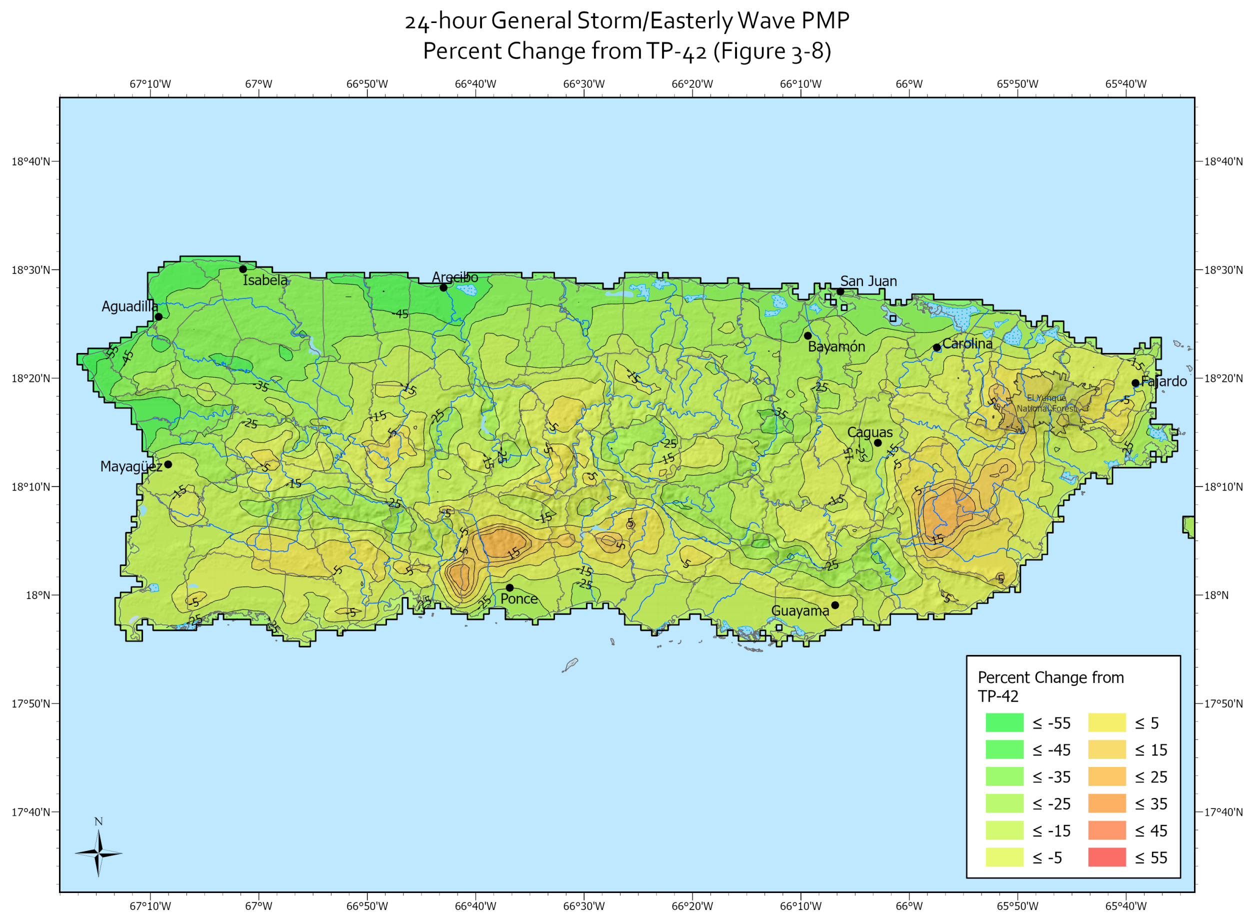


Figure E.2: Percent change from TP 42 24-hour PMP to Puerto Rico 24-hour PMP



Glossary

Adiabat: Curve of thermodynamic change taking place without addition or subtraction of heat. On an adiabatic chart or pseudo-adiabatic diagram, a line showing pressure and temperature changes undergone by air rising or condensation of its water vapor; a line, thus, of constant potential temperature.

Adiabatic: Referring to the process described by adiabat.

Advection: The process of transfer (of an air mass property) by virtue of motion. In particular cases, advection may be confined to either the horizontal or vertical components of the motion. However, the term is often used to signify horizontal transfer only.

Air mass: Extensive body of air approximating horizontal homogeneity, identified as to source region and subsequent modifications.

Basin centroid: The point at the exact center of the drainage basin as determined through geographical information systems calculations using the basin outline.

Basin shape: The physical outline of the basin as determined from topographic maps, field survey, or GIS.

Cold front: Front where relatively colder air displaces warmer air.

Convective rain: Rainfall caused by the vertical motion of an ascending mass of air that is warmer than the environment and typically forms a cumulonimbus cloud. The horizontal dimension of such a mass of air is generally of the order of 12 miles or less. Convective rain is typically of greater intensity than either of the other two main classes of rainfall (cyclonic and orographic) and is often accompanied by thunder. The term is more particularly used for those cases in which the precipitation covers a large area as a result of the agglomeration of cumulonimbus masses.

Convergence: Horizontal shrinking and vertical stretching of a volume of air, accompanied by net inflow horizontally and internal upward motion.

Cooperative station: A weather observation site where an unpaid observer maintains a climatological station for the National Weather Service.

Depth-Area-Duration: The precipitation values derived from Depth-Area and Depth-Duration curves at each time and area size increment analyzed for a PMP evaluation.

Depth-Area curves: Rainfall accumulation at a given area size through time.

Depth-Duration curves: Curve showing, for a given area size, the relation of maximum average depth of precipitation to duration periods within a storm or storms.

Dew point: The temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content for saturation to occur.

Envelopment: A process for selecting the largest value from any set of data. In estimating PMP, the maximum and transposed rainfall data are plotted on graph paper, and a smooth curve is drawn through the largest values.

First-order NWS station: A weather station that is either automated or staffed by employees of the National Weather Service and records observations on a continuous basis.

Front: The interface or transition zone between two air masses of different parameters. The parameters describing the air masses are temperature and dew point.

Frontal system: A boundary between differing air masses. A warm front marks the boundary of an advancing warmer air mass, usually the tropical maritime air that originates from the subtropical Atlantic, while a cold front marks the boundary of a cold air mass.

General storm: A storm event that produces precipitation over areas in excess of 500-square miles, has a duration longer than 6 hours, and is associated with a major synoptic weather feature.

Geographic Transposition Factor: A factor representing the comparison of precipitation frequency relationships between two locations which is used to quantify how rainfall is affected by physical processes related to location and terrain. It is assumed the precipitation frequency data are a combination of what rainfall would have accumulated without topographic affects and what accumulated because of the topography, both at the location and upwind of the location being analyzed.

Hydrologic Unit: A hydrologic unit is a drainage area delineated to nest in a multi-level, hierarchical drainage system. Its boundaries are defined by hydrographic and topographic criteria that delineate an area of land upstream from a specific point on a river, stream or similar surface waters. A hydrologic unit can accept surface water directly from upstream drainage areas, and indirectly from associated surface areas such as remnant, non-contributing, and diversions to form a drainage area with single or multiple outlet points. Hydrologic units are only synonymous with classic watersheds when their boundaries include all the source area contributing surface water to a single defined outlet point

HYSPLIT: Hybrid Single-Particle Lagrangian Integrated Trajectory. A complete system for computing parcel trajectories to complex dispersion and deposition simulations using either puff or particle approaches. Gridded meteorological data, on one of three conformal (Polar, Lambert, or Mercator latitude-longitude grid) map projections, are required at regular time intervals. Calculations may be performed sequentially or concurrently on multiple meteorological grids, usually specified from fine to coarse resolution.

Isohyets: Lines of equal value of precipitation for a given time interval.

Isohyetal pattern: The pattern formed by the isohyets of an individual storm.

Jet Stream: A strong, narrow current concentrated along a quasi-horizontal axis (with respect to the earth's surface) in the upper troposphere or in the lower stratosphere, characterized by strong vertical and lateral wind shears. Along this axis it features at least one velocity maximum (jet streak). Typical jet streams are thousands of kilometers long, hundreds of kilometers wide, and several kilometers deep. Vertical wind shears are on the order of 10 to 20 mph per kilometer of altitude and lateral winds shears are on the order of 10 mph per 100 kilometers of horizontal distance.

Local storm: A storm event that occurs over a small area in a short time period. Precipitation rarely exceeds 6 hours in duration and the area covered by precipitation is less than 500 square miles. Frequently, local storms will last only 1 or 2 hours and precipitation will occur over areas of up to 200 square miles. Precipitation from local storms will be isolated from general-storm rainfall. Often these storms are thunderstorms.

Low Level Jet: A band of strong winds at an atmospheric level well below the high troposphere as contrasted with the jet streams of the upper troposphere.

Mass curve: Curve of cumulative values of precipitation through time.

Moisture maximization: The process of adjusting observed precipitation amounts upward based upon the hypothesis of increased moisture inflow to the storm.

Observational day: The 24-hour time period between daily observation times for two consecutive days at cooperative stations, e.g., 6:00PM to 6:00PM.

One-hundred-year rainfall event: The point rainfall amount that has a one-percent probability of occurrence in any year. Also referred to as the rainfall amount that has a 1 percent chance of occurring in any single year.

Precipitable water: The total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels in the atmosphere; commonly expressed in terms of the height to which the liquid water would stand if the vapor were completely condensed and collected in a vessel of the same unit cross-section. The total precipitable water in the atmosphere at a location is that contained in a column or unit cross-section extending from the earth's surface all the way to the "top" of the atmosphere. The 30,000-foot level (approximately 300mb) is considered the top of the atmosphere in this study.

Probable Maximum Flood: The flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area.

Probable Maximum Precipitation: Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location at a certain time of the year.

Pseudo-adiabat: Line on thermodynamic diagram showing the pressure and temperature changes undergone by saturated air rising in the atmosphere, without ice-crystal formation and without exchange of heat with its environment, other than that involved in removal of any liquid water formed by condensation.

Saturation: Upper limit of water-vapor content in a given space; solely a function of temperature.

Shortwave: Also referred to as a shortwave trough, is an embedded kink in the trough / ridge pattern. This is the opposite of longwaves, which are responsible for synoptic scale systems, although shortwaves may be contained within or found ahead of longwaves and range from the mesoscale to the synoptic scale.

Spatial distribution: The geographic distribution of precipitation over a drainage according to an idealized storm pattern of the PMP for the storm area.

Storm transposition: The hypothetical transfer, or relocation of storms, from the location where they occurred to other areas where they could occur. The transfer and the mathematical adjustment of storm rainfall amounts from the storm site to another location is termed "explicit transposition." The areal, durational, and regional smoothing done to obtain comprehensive individual drainage estimates and generalized PMP studies is termed "implicit transposition" (WMO, 1986).

Synoptic: Showing the distribution of meteorological elements over an area at a given time, e.g., a synoptic chart. Use in this report also means a weather system that is large enough to be a major feature on large-scale maps (e.g., of the continental U.S.).

Temporal distribution: The time order in which incremental PMP amounts are arranged within a PMP storm.

Transposition limits: The outer boundaries of the region surrounding an actual storm location that has similar, but not identical, climatic and topographic characteristics throughout. The storm can be transpositioned within the transposition limits with only relatively minor modifications to the observed storm rainfall amounts.

Tropical Easterly Wave: It is a wave within the broad easterly current and moves from east to west, generally more slowly than the current in which it is embedded. Although best described in terms of its wavelike characteristics in the wind field, it also consists of a weak trough of low pressure.

List of Acronyms

AWA: Applied Weather Associates

DA: Depth-Area

DAD: Depth-Area-Duration

dd: decimal degrees

DND: Drop number distribution

DSD: Drop size distribution

EPRI: *Electric Power Research Institute*

F: Fahrenheit

FERC: Federal Energy Regulatory Commission

GCS: Geographical coordinate system

GIS: Geographic Information System

GRASS: Geographic Resource Analysis Support System

GTF: Geographic Transposition Factor

HMR: Hydrometeorological Report

HRRR: High-Resolution Rapid Refresh Model

HYSPLIT: Hybrid Single Particle Lagrangian Integrated Trajectory Model

IDW: Inverse distance weighting

IPMF: In-place Maximization Factor

MADIS: NCEP Meteorological Assimilation Data Ingest System

mb: millibar

MTF: Moisture Transposition Factor

NCAR: National Center for Atmospheric Research

NCDC: National Climatic Data Center

NCEI: National Centers for Environmental Information

NCEP: National Centers for Environmental Prediction

NEXRAD: Next Generation Radar

NOAA: National Oceanic and Atmospheric Administration

NRC: Nuclear Regulatory Commission

NRCS: Natural Resources Conservation Service

NWS: National Weather Service

PMF: Probable Maximum Flood

PMP: Probable Maximum Precipitation

PRISM: Parameter-elevation Relationships on Independent Slopes

PW: Precipitable Water

SMC: Spatially Based Mass Curve

SPAS: Storm Precipitation and Analysis System

SPP: Significant Precipitation Period

SSM: Storm Separation Method

SST: Sea Surface Temperatures

TAF: Total Adjustment Factor

TAR: Total Adjusted Rainfall

USACE: US Army Corps of Engineers

USBR: Bureau of Reclamation

USGS: United States Geological Survey

WMO: World Meteorological Organization

1. Probable Maximum Precipitation Development Background

This study calculated Probable Maximum Precipitation (PMP) for the island of Puerto Rico which allows the probable Maximum Flood (PMF) to be calculated for any basin on the island (Figure 1.1). PMP depths are used in the computation of the PMF for the design of high-hazard structures. PMP depths provided in this study supersede the current PMP depths from Technical Paper 42 (TP 42) published by the US Weather Bureau (now the National Weather Service) in 1961. Since that time, significant advances in PMP development have occurred, especially related to quantifying the effects of topography, spatial and temporal distributions, and by adding more than 50 years of extreme rainfall data, including several tropical systems that have affected the island directly.

This study was initialized because of the need to reevaluate PMP depths and update the PMF for the Patillas Dam basin in southeastern Puerto Rico. However, because the processes and much of the data that would be utilized for that single basin are the same as would be utilized for the entire island, the island-wide study was completed. The Patillas Dam basin was of significant focus during this study and utilized in many of the testing and sensitivity processes.

PMP is a deterministic estimate of the theoretical maximum depth of precipitation that can occur over a specified area, at a given time of the year. Parameters to estimate PMP were developed using the storm based, deterministic approach as discussed in the HMRs and TP 42. This process for PMP development has subsequently been refined in the numerous site-specific, statewide, and regional PMP studies completed by Applied Weather Associates (AWA) since the early 1990's.

Methods used to derive PMP depths for this study included consideration of numerous extreme rainfall events that have been appropriately adjusted to each grid point and representing each PMP storm type in the region, tropical and general/easterly wave with convection (general) storms. Nearly 100 storms were initially considered occurring on the island of Puerto Rico and throughout the Caribbean in regions with similar meteorological and topographic characteristics.

For final PMP development 18 individual storm centers were utilized, including 14 tropical storms and four general storms. The large number of storm events provided an adequate database from which to derive the PMP depths and reduce uncertainty in the PMP depths. The process of combining maximized storm events by storm type into a hypothetical PMP design storm resulted in a reliable PMP estimation by combining the worst-case combination of meteorological factors in a physically possible manner.

As part of the storm adjustments and PMP calculation processes, air masses that provide moisture to both the historic observed storm and the possible PMP storm were assumed to be saturated through the entire depth of the atmosphere and contain the maximum moisture possible based on sea surface temperatures. This saturation process used moist pseudo-adiabatic temperature profiles for both the historic storm and the PMP storm. The method assumed that a sufficient period of record was available for adequate rainfall observations have identified a least a few storms of PMP-storm efficiency for use in PMP development. In essence, the identification and analysis of the largest storms on record over the large storm search domain is trading time for space to develop a dataset that can be assumed to represent PMP storms after storm adjustments are applied. The PMP development process assumes that if surplus atmospheric moisture had been available, an individual extreme storm would have maintained the same efficiency for converting atmospheric moisture to rainfall. Therefore, the ratio of the maximized rainfall amounts to the actual rainfall amounts would be the same as the ratio of the precipitable water observed versus the climatological maximum in the atmosphere associated with each storm.

Current understanding of meteorology does not support an explicit evaluation of storm efficiency for use in PMP evaluation. To compensate for this, the period of record was extended to include the entire historic record of rainfall data (nearly 150 years for this study), along with an extended geographic region from which to choose storms. Using the long period of record and the large geographic region, it is assumed that at least one storm with dynamics (storm efficiency) that approached the maximum efficiency for rainfall production used in the PMP development.

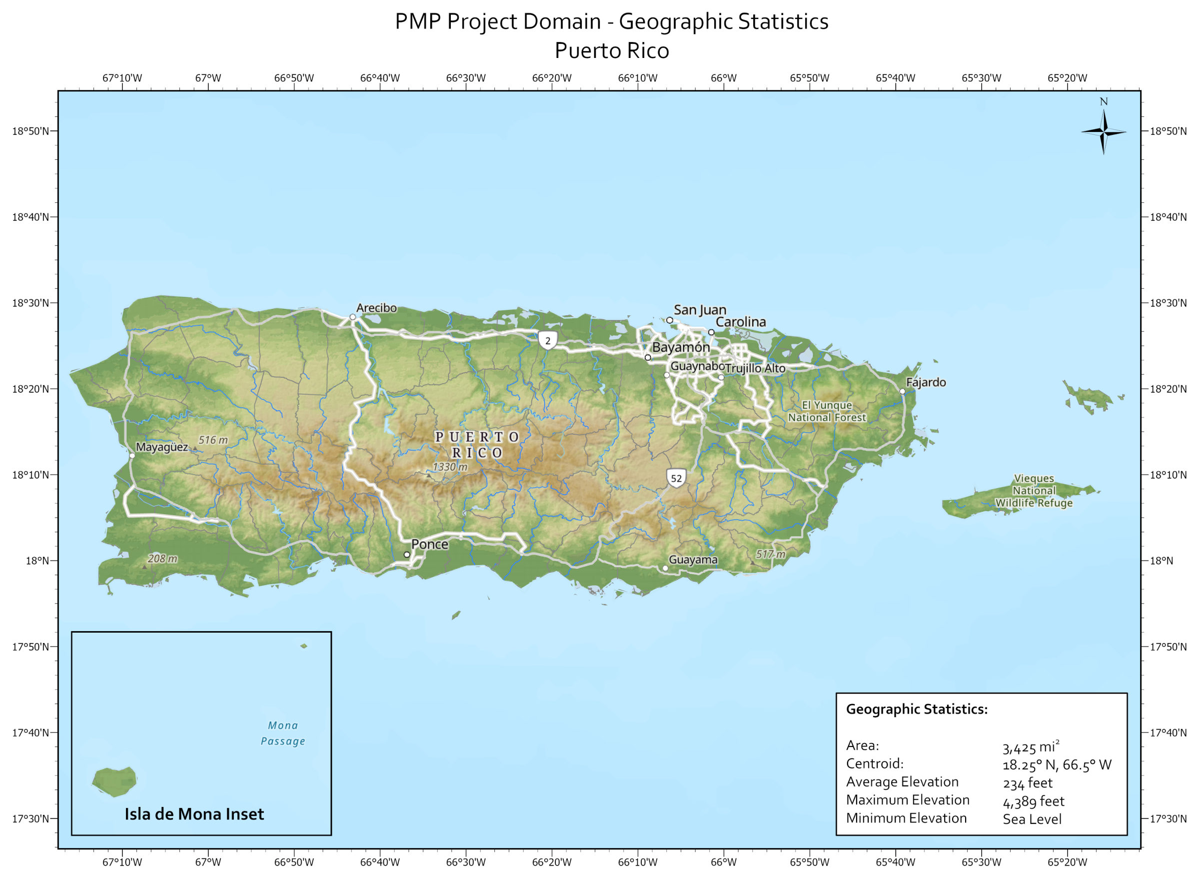


Figure 1.1: Probable Maximum Precipitation study domain

1.1 Previous PMP and Storm Analysis Background

Definitions of PMP are found in most of the HMRs issued by the National Weather Service (NWS). The definition used in the most recently published HMR is "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year" (HMR 59, p. 5) (Corrigan et al., 1999). Since the early 1940s, several government agencies have developed methods to calculate PMP for various regions of the United States. The NWS (formerly the U.S. Weather Bureau), the U.S. Army Corps of Engineers (USACE), and the U.S. Bureau of Reclamation (USBR) have been the primary Federal agencies involved in this activity. PMP depths presented in their reports are used to calculate the PMF, which in turn, is often used for the design of significant hydraulic structures. It is important to remember that the methods used to derive PMP and the hydrological procedures that use the PMP depths need to adhere to the requirement of being "physically possible." In other words, various levels of conservatism and/or extreme aspects of storms that could not physically occur in a PMP storm environment should not be used to produce combinations of storm characteristics that are not physically consistent in determining PMP depths or for the hydrologic applications of those depths.

The generalized PMP studies currently in use in the contiguous United States are shown in Figure 1.2. In addition to these HMRs, numerous Technical Papers and Reports deal with specific subjects concerning precipitation (e.g., Technical Paper 1, 1946; Technical Paper 16, 1952; NOAA Tech. Report NWS 25, 1980; and NOAA Tech. Memorandum NWS HYDRO 40, 1984). Topics in these papers include maximum observed rainfall amounts for various return periods and specific storm studies. Climatological atlases (e.g., Technical Paper No. 40, 1961; NOAA Atlas 2, 1973; and NOAA Atlas 14, 2004-2015) are available for use in determining precipitation return periods. Several site-specific, statewide, and regional studies (e.g., Tomlinson et al., 2002-2013; Kappel et al., 2012-2020) augment generalized PMP reports for specific regions included in the large areas addressed by the HMRs. Recent site-specific PMP projects completed have updated the storm database and many of the procedures used to estimate PMP depths in the HMRs. This study continued that process by applying the most current understanding of meteorology related to extreme rainfall events and updating the storm database through May of 2021. PMP results from this study provide values that replace those derived from TP 42 for Puerto Rico.

Although TP42 provides estimates of PMP depths for the island of Puerto Rico utilizing novel techniques and data for the time it was published. However, significant advances have occurred since the 1960's including several extreme rainfall events that have now been analyzed and included in this analysis. AWA has applied updated understanding specific to the island of Puerto Rico and incorporate more site-specific considerations utilizing storm-based adjustments and temporal patterns which provide improved PMP estimates. Additionally, by periodically reviewing storm data and advances in meteorological concepts, PMP analysts can identify relevant new data and approaches for use in making improved PMP estimates.

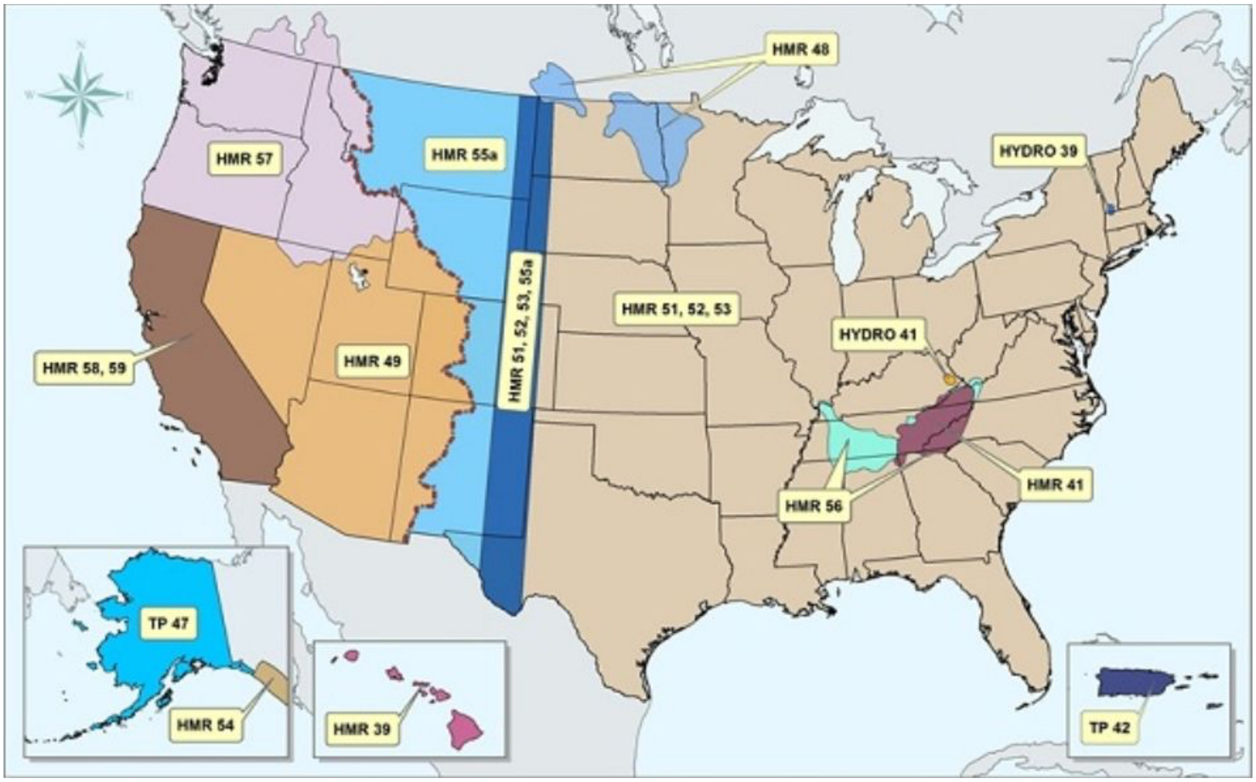


Figure 1.2: Hydrometeorological Report coverages

The climate in the region is influenced by the warm sea surface temperatures of the Caribbean and Atlantic Ocean tropical regions and on rare occasions diffuse frontal systems moving from the north. The location of the island within the tropical regions and at a latitude where tropical easterly waves affect the island, combine with the topography on the island to bring frequent rainfall. However, the topography of the island and the prevailing flow results in large amounts of spatial variability in accumulation magnitudes both from a mean annual and individual storm perspective. Figure 1.3 provides the mean annual precipitation across the island. This shows the influence of the easterly waves interacting with the topography on the eastern end of the island. Figure 1.4 displays the 100-year 24-hour precipitation frequency depths. When you compare the spatial patterns and gradients between these two datasets, the effects of the topography and interactions with more rare occurrences of tropical systems moving from east to west and south to north across the island are obvious. These are the most important characteristics for extreme rainfall and PMP-type storms.

Because of the distinctive climate regions and variance in topography, the development of PMP depths must account for the complexity of the meteorology and terrain throughout the island. Although the TP42 provided relevant data at the time it was published, the understanding of meteorology and effects of terrain on rainfall (orographic effects) have advanced significantly in the subsequent years. Limitations that can now be addressed include a limited number of analyzed storm events, no inclusion of storms that have occurred since the early 1960's, no process used to address orographic effects, inconsistent data and procedures used in TP42 versus HMRs, improved documentation allowing for reproducibility, and the outdated procedures used to derive PMP. This project incorporated the latest methods, technology, and data to address these complexities. Each of these were addressed and updated where data and current understanding of meteorology allowed.

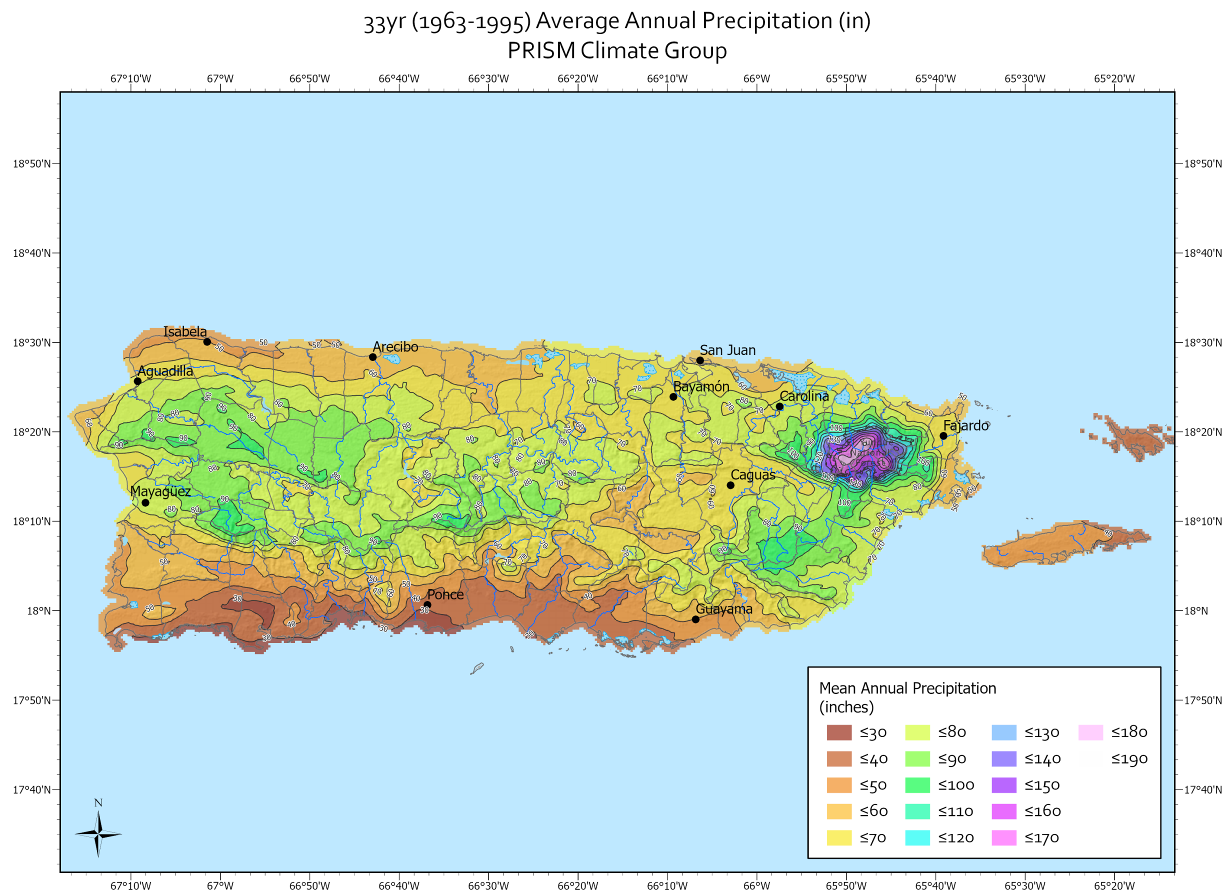


Figure 1.3: Mean annual precipitation over Puerto Rico based on PRISM analysis

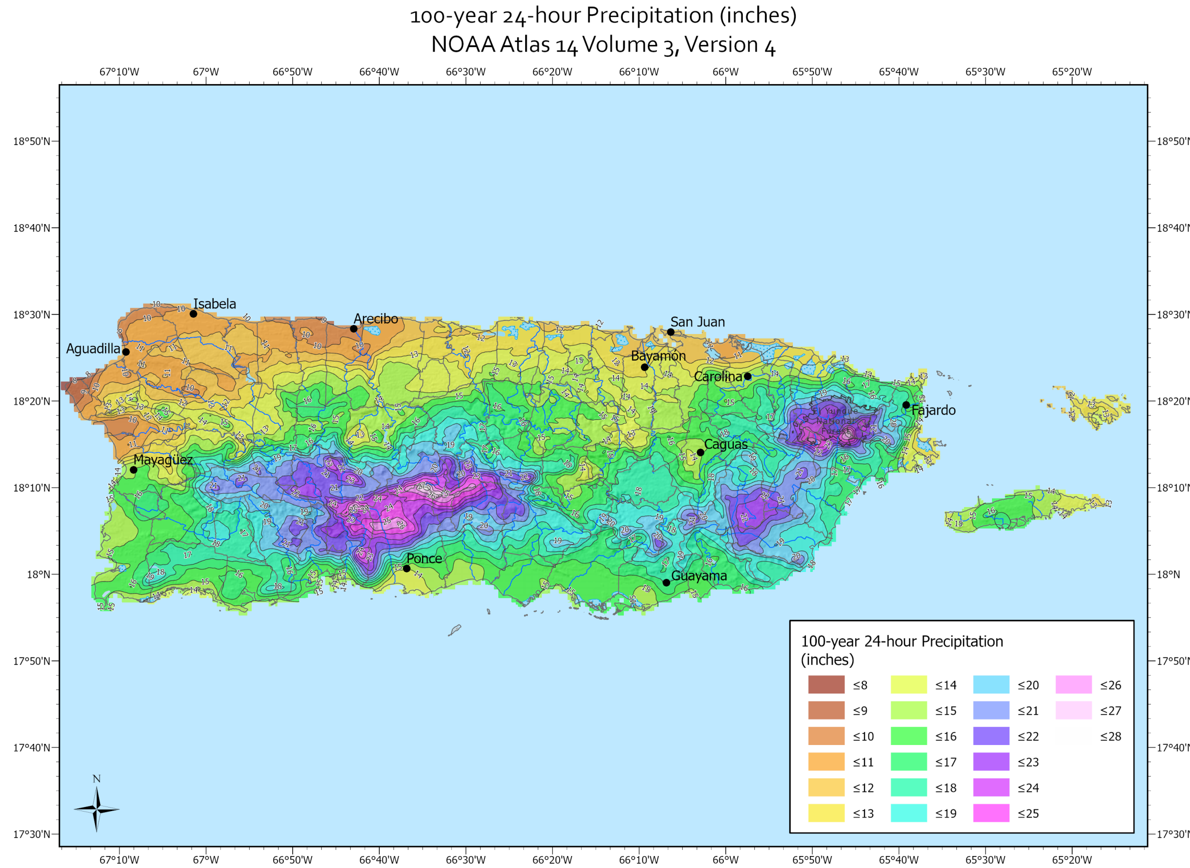


Figure 1.4: NOAA Atlas 14 100-year 24-hour precipitation frequency depths across Puerto Rico

Previous site-specific, statewide, and regional PMP projects completed by AWA provide examples of PMP studies that explicitly consider the unique climatology, seasonality, and topography of the area being studied and characteristics of historic extreme storms over meteorologically and topographically similar regions surrounding the area. The procedures incorporate the most up-to-date sets, techniques, and applications to derive PMP. All AWA PMP studies have received extensive review and the results have been used in computing the PMF for the high hazards dams and other relevant infrastructure. This study follows similar procedures employed in those studies while making improvements where advancements in computer-aided tools and transposition procedures have become available.

Several PMP studies have been completed by AWA within the regions of similar climatological and topographic interactions as found in this study region (Figure 1.5). Each of these studies provided PMP depths which updated those from relevant HMRs and previous studies. These are examples of PMP studies that explicitly consider the meteorology and topography of the study location along with characteristics of historic extreme storms over climatically similar regions. Information, experience, and data from these PMP studies in similar regions to this study were utilized. These included use of the Storm Precipitation Analysis System (SPAS) rainfall analyses (Hultstrand and Kappel, 2017) to analyze rainfall for PMP development, application of SST information for calculation of in-place storm maximization factors, and explicit understanding of the meteorology of the region.

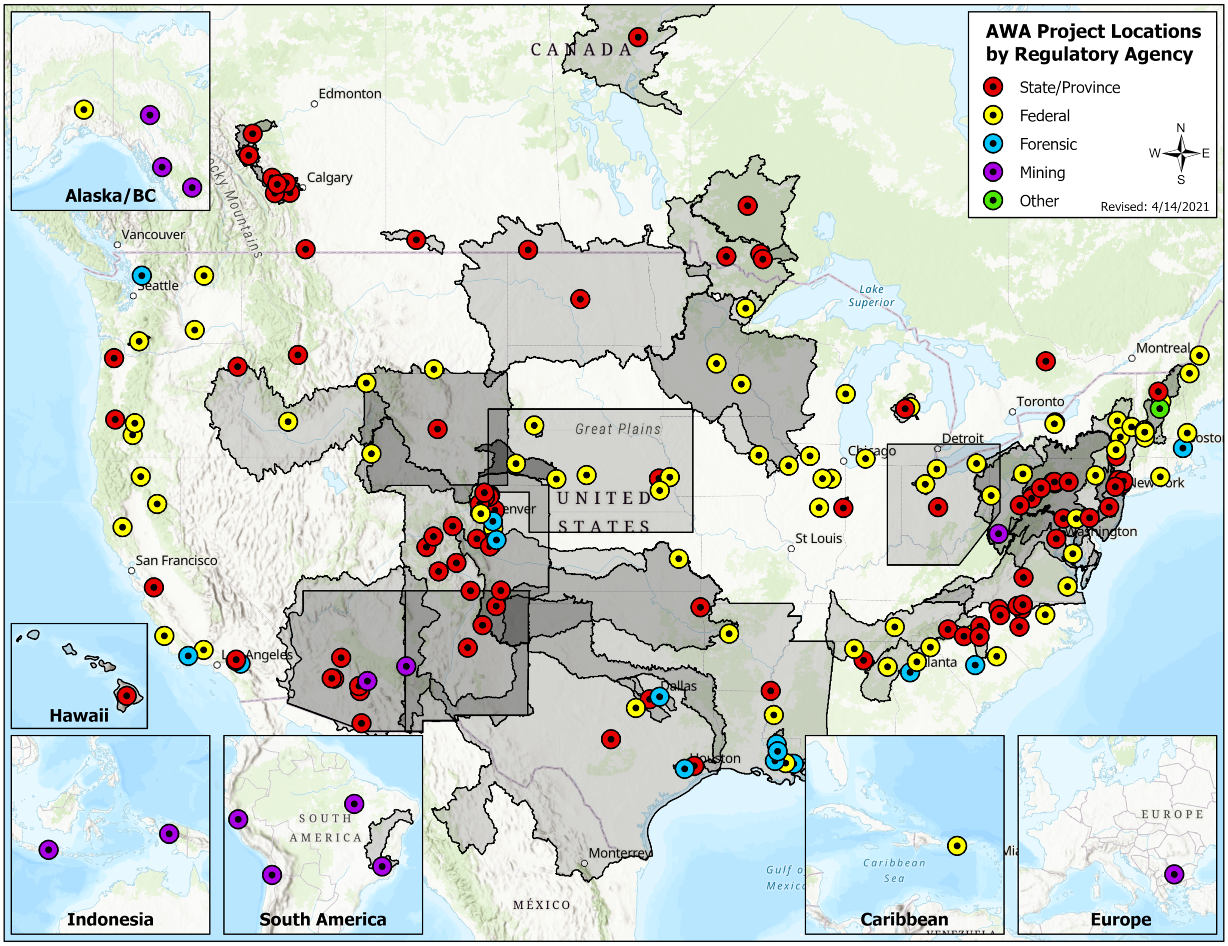


Figure 1.5: Locations of AWA PMP studies as of April 2021

1.2 Objective

This study determines reproducible estimates of PMP depths for use in computing the PMF for all basins within the overall project domain. The most reliable methods and data available were used and updates to methods and data used in TP42 were applied where appropriate.

1.3 PMP Analysis Grid Setup

A uniform grid covering the project domain provides a spatial framework for the analysis. The PMP grid resolution for this study was 0.00833 x 0.00833 decimal degrees (dd), or 30 arc-seconds, using the Geographic Coordinate System (GCS) spatial reference with the World Geodetic System of 1984 (WGS 84) datum. This resulted in 11,448 grid cells with centroids within the domain. Each grid cell represents an approximate area of 0.3-square miles. The grid network placement is essentially arbitrary. However, the placement was oriented in such a way that the grid cell centroids are centered over whole number coordinate pairs and then spaced evenly every 0.025 dd. For example, there is a grid cell centered over 18.0° N and 66.0° W. The PMP analysis grid is shown in Figure 1.6.

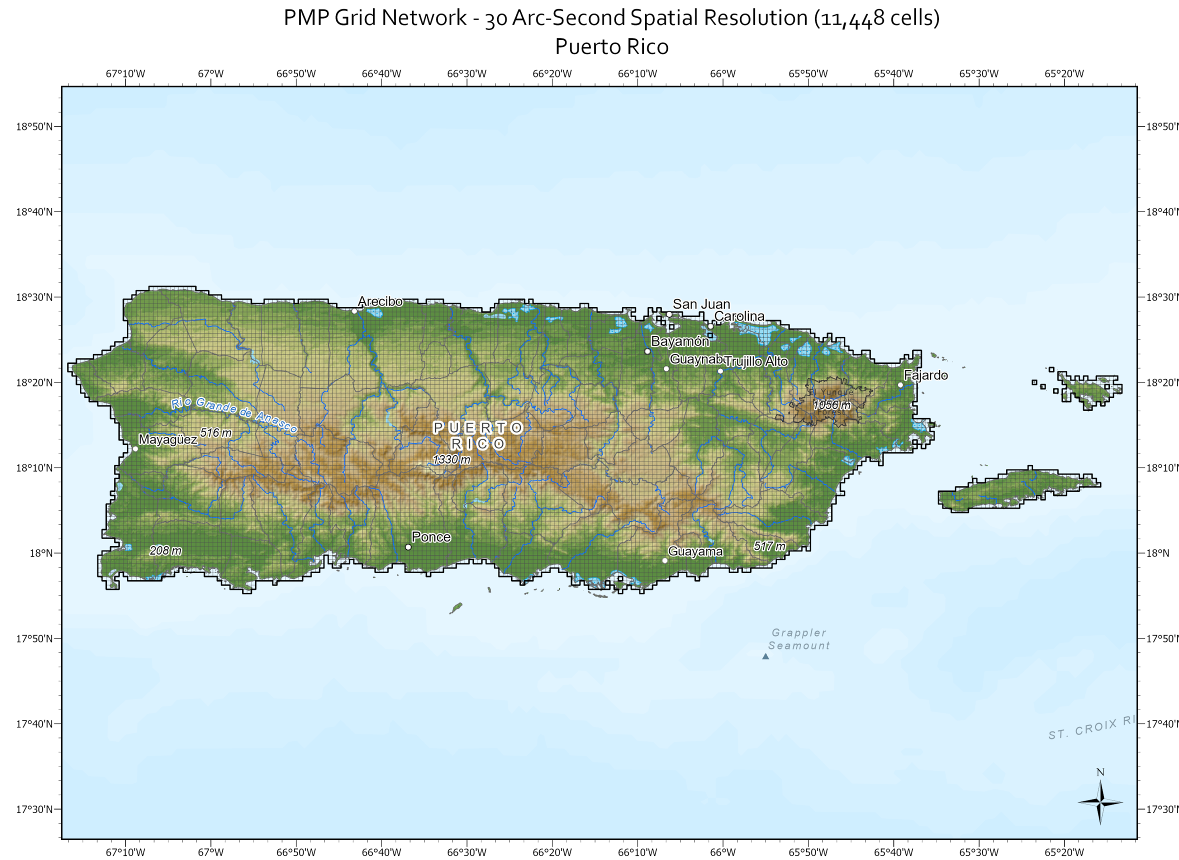


Figure 1.6: PMP analysis grid placement over the project domain

2. Methodology

The storm-based approach used in this study is consistent with many of the procedures that were used in the development of the HMRs and as described in the World Meteorological Organization PMP documents (WMO, 2009), with updated procedures implemented where appropriate. Methodologies reflecting the current standard of practice were applied in this study considering the unique meteorological and topographical interactions within the region as well as the updated scientific data and procedures available. Updated procedures are described in detail later in this report. Figure 2.1 provides the general steps used in deterministic PMP development utilizing the storm-based approach. Terrain characteristics are addressed as they specifically affect rainfall patterns spatially, temporally, and in magnitude.

This study identified major storms that occurred within the region where those storms were considered transpositionable within the study region. Each of the PMP storm types capable of producing PMP-level rainfall for both the tropical storms and general storms/easterly waves were identified and investigated. The "short list" of storms was extensively reviewed, quality controlled, and accepted as representative of all storms that could potentially effect PMP depths at any location or area size within the overall study domain. This short list of storms was utilized to derive the PMP depths for all locations.

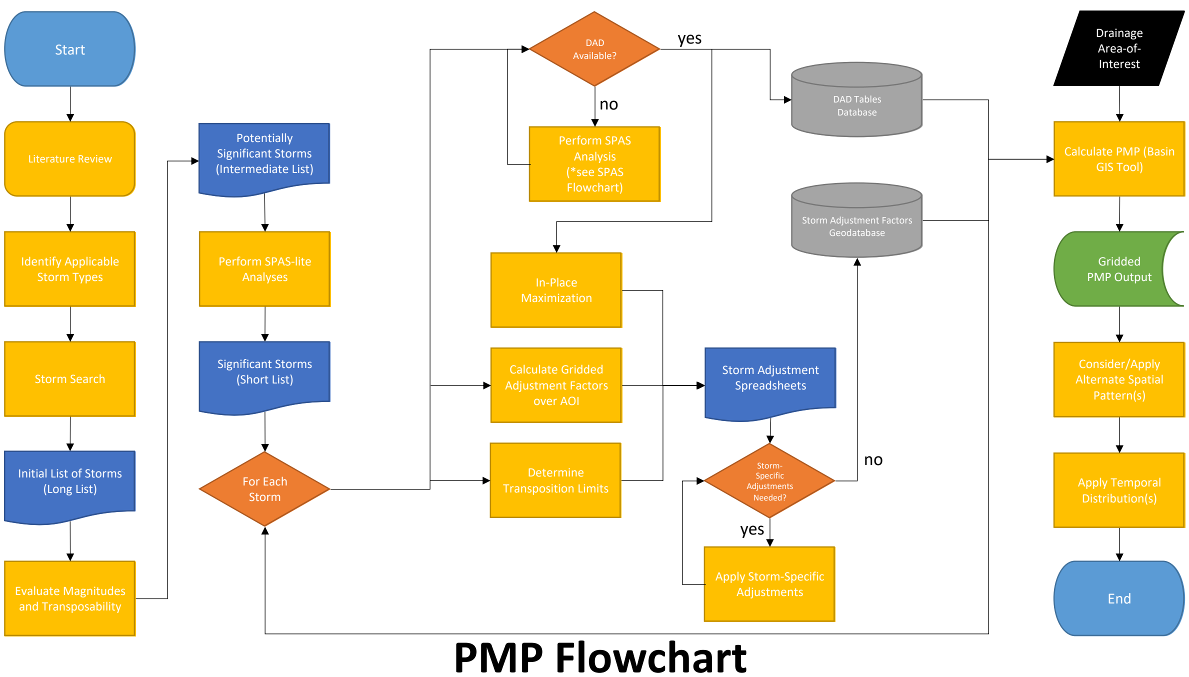


Figure 2.1: Probable Maximum Precipitation calculation steps

The moisture content of each of the short list storms was maximized to provide worst-case rainfall accumulation for each storm at the location where it occurred (in-place storm location). Storms were then transpositioned to each grid covering the island. Detailed evaluations of the storms of the short storm list were completed to confirm that the storm type and storm dynamics were similar to what could occur over the island and therefore could be utilized for final PMP development. This was most important for storms that occurred on other islands throughout the Caribbean, especially portions of the Lesser Antilles, Cuba, and Jamaica.

Storms transpositioned to the island were determined using meteorological judgment, comparison of adjustment factors, comparisons of PMP depths, comparison against previous transposition limits, discussions with study participants, and comparisons against precipitation frequency climatologies. Adjustments were applied to each storm as it was transpositioned to each grid point to calculate the amount of rainfall each storm would have produced at each grid point versus what it produced at the original location. These adjustments were combined to produce the total adjustment factor (TAF) for each storm for each grid point. The TAF is applied to the observed precipitation depths at the area size of interest to each storm.

SPAS is utilized to analyze the rainfall associated with each storm used for PMP development. SPAS has been used to analyze more than 800 rainfall events since 2002. SPAS analyses are used in PMP development as well as other meteorological applications. SPAS has been extensively peer reviewed and accepted as appropriate for use in analyzing precipitation accumulation by numerous independent review boards and as part of the Nuclear Regulatory Commission (NRC) software certification process. Several peer reviewed journal articles have utilized SPAS output and processes for various scientific investigations (e.g., Keim et al., 2018 and Brown et al., 2020). Appendix E provides a detailed description of the SPAS program. The TAF is a product of the In-Place Maximization Factor (IPMF) and the Geographic Transposition Factor (GTF).

The governing equation used for computation of the Total Adjusted Rainfall (TAR), for each storm for each grid cell for each duration, is given in Equation 1.

$$TAR_{xhr} = P_{xhr} \times IPMF \times GTF \qquad \text{(Equation 1)}$$

where:

TAR_{xhr} is the Total Adjusted Rainfall value at the x-hour (x-hr) duration for the specific grid cell at each duration at the target location;

P_{xhr} is the x-hour precipitation observed at the historic in-place storm location (source location) for the basin-area size;

In-Place Maximization Factor (*IPMF)* is the adjustment factor representing the maximum amount of atmospheric moisture that could have been available to the storm for rainfall production;

Geographic Transposition Factor (GTF) is the adjustment factor accounting for precipitation frequency relationships between two locations. This is used to quantify all processes that effect rainfall, including terrain, location, moisture, and seasonality.

Note, the largest of these values at each duration becomes PMP at each grid point. The data and calculations are run at the area size and duration(s) specified through user input. The PMP output depths are then provided for durations required for PMF analysis at a given location by storm type and provided as a basin average. These data have various spatial pattern and temporal pattern associated with them for hydrologic modeling implementation. The spatial and temporal patterns are based on climatological patterns and observed storm patterns and a synthesis of historic storm accumulation patterns used in this study. Various combinations of alternative spatial and temporal patterns are also possible at a given location. The user should consult with PREPA regulations, USBR, or AWA for guidance regarding the use of alternative spatial and/or temporal patterns is provided in the tool developed during this study.

3. Weather and Climate of the Region

The island of Puerto Rico is influenced by several factors that can potentially contribute to extreme rainfall and has a relatively active and varied weather pattern throughout the year. Consequently, rainfall events at both short and long durations are common. The island is surrounded by warm ocean waters and is in a preferred zone for tropical system development and frequency easterly waves. This allows high amounts of moisture to move directly into the island. Heavy rainfall is produced when lift is provided by easterly waves, diffuse fronts, connection, and/or tropical systems. The terrain of the island also plays a key role in rainfall magnitudes, with significant increases over windward locations and significant decreases over leeward locations (Figure 1.3).

The easterly trade winds transport moisture into the island from a generally east to west direction during normal synoptic conditions, bringing copious amounts of rain to the mountains around El Yunque National Forest and Sierra de Luquillo region. However, during times of disturbed weather when a frontal systems or tropical disturbance is moving through, these normal wind patterns can be significantly disrupted. This can result in heavy rainfall in other regions, most common over the central highlands (Cordillera Central).

Another mechanism, which creates lift in the region, is heating of the surface and lower atmosphere by the sun. This creates warmer air below cold air resulting in atmospheric instability and leads to rising motions or updrafts in the atmosphere. This will often result in ordinary afternoon and evening thunderstorms, especially when enhanced by onshore convergence associated with sea breeze mechanics. In unique circumstances, the instability and moisture levels in the atmosphere can reach very high levels and stay over the same region for an extended period of time and/or be enhanced by a shortwave or troughs moving through the region which cause additional lift and instability. This can lead to intense thunderstorms and very heavy rainfall. If these storms are focused over the same area for a long period, flooding rains can be produced. This type of storm produces some of the largest point rainfall recorded, but often does not affect larger areas with extreme rainfall amounts.

3.1 Regional Climatological Characteristics Affecting PMP Storm Types

Weather patterns in the region are characterized by two main storm types:

1. Areas of low pressure moving through the region from the west to northwest and torpcial easterly waves moving around the periphery of the Bermuda High Pressure from east to west following trade wind patterns (General storms);
    a. PMP-type General storms have a distinct seasonality with events most common from November through April
    b. These storm types include intense localized thunderstorms that will often form along a frontal system or in associated with topography as an enhanced tropical easterly wave progresses across the island
2. Tropical systems that form during the hurricane season from June through November
    a. Tropical depressions
    b. Tropical storms

c. Hurricanes

3.2 Descriptions of PMP Storm Types

PMP storm types investigated during the study were general storms and tropical systems. General storms are associated with frontal systems, tropical easterly waves, and associated isolated thunderstorms where main rainfall occurs over large areas sizes and longer durations often with embedded convection. Tropical systems produce high intensity rainfall over relatively large areas and can affect the entire island during one storm events. Storm type temporal patterns associated with each of these was explicitly investigated and utilized in this study. The development of these patterns and application for this study are described in Section 12.

The classification of storm types, and hence PMP development by storm type used in this study, is similar to descriptions provided in several HMRs and TP42. Storms were classified by rainfall accumulation characteristics, while trying to adhere to previously used classifications. Several discussions took place with study participants to ensure acceptance of the storm classifications.

Isolated thunderstorms were defined using the following guidance:

- The main rainfall accumulation period occurred over a 6-hour period or less
- Was previously classified as a thunderstorm in TP42
- Was not associated with overall synoptic patterns leading to rainfall across a large region
- Exhibited high intensity accumulations over small area sizes

Frontal systems/tropical easterly waves were defined using the following guidance:

- The main rainfall accumulation period lasted for 24 hours or longer
- Occurred with a synoptic environment associated with a low-pressure system, frontal interaction, and/or regional precipitation coverage
- Was previously classified as a general storm by TP42
- Frontal induced rainfall occurs November through April
- Easterly waves are most common from May to November (Difuentes, 2014 *in Hydrogeology of Puerto Rico and the Outlying Islands of Vieques, Culebra, and Mona*)

Tropical systems were defined using the following guidance:

- The rainfall was a direct result of a tropical system, either landfalling or directly offshore
- Was previously classified as a tropical storm by the, NWS, USACE, TP42, or in the HMRs
- Had a warm core close circulation
- Occurred during the hurricane season, with storms most frequent from August through October

3.2.1 Isolated Thunderstorms

Localized thunderstorms can produce extreme amounts of precipitation over short durations and over small area sizes, generally 6 hours or less over area sizes of 500 square miles or less. During any given hour, the heaviest rainfall only covers very small areas, generally less than 100 square miles.

Because this storm type is associated with an isolated environment conducive to convective development, these storms go through a distinct life cycle and general do not last more than a few hours. This is related to the moisture feed into the storm and the stabilizing effects of the rainfall in the surrounding environment. However, on rare occasion a focusing mechanism can help regenerate storm over the same area with repeated cycles of heavy rainfall. This can be associated with a front or diffuse boundary, topographic interactions, sustained low-level winds advecting moisture into the areal, or a combination of these factors. Thunderstorms and tropical downpours are common throughout Puerto Rico, but they usually don't have a favorable set of these factors together in one spot and therefore start and end quickly at any given location. However, within this short timeframe, extremely heavy, but localized rainfall can accumulate.

3.2.2 Frontal Systems

This storm type occurs in association with frontal systems and along boundaries between contrasting air masses. In Puerto Rico, these fronts are usually hard to distinguish because the contrast between air masses is small after having traveled a long distance from their original source and interaction with the modifying effects of the warm ocean water. However, even the modified frontal system can produce significant rainfall when it is moving slowly or stalled over the same region. This is enhanced by the effects of topography as well.

These are most prevalent on the north side of the island and into the central highlands. Fronts that produce extreme rainfall in Puerto Rico have a distinct seasonality from November through April. Precipitation associated with frontal systems is enhanced when the movement of weather patterns slow or stagnates, allowing moisture and instability to affect the same general region for several days. In addition, when there is a larger than normal thermal contrast between air masses in combination with high levels of moisture, PMP-level precipitation can occur. The January 1992 "Three Kings Day" (el dia de Reyes) storm is an excellent example of this type of storm event over the island (https://www.weather.gov/safety/flood-states-pr.)

Another example of this storm type in the region is the world record rainfall that occurred over eastern Jamaica near Silver Hill Planation. In this region an amazing 135 inches of rainfall accumulated from November 4th through the 11th (Jamaica Weather Report, November 1909, https://library.noaa.gov/Collections/Digital-Docs/Foreign-Climate-Data/Jamaica-Climate-Data).

Although detailed synoptic and upper-level observations were lacking, AWA along with the USBR were able to recreate the synoptic patterns that resulted in this rainfall and evaluate model reanalysis output from the time. The evaluations confirmed that this event was the results of an extraordinarily strong cold front moving through the region along with enhanced gap flow winds between the islands of Cuba and Hispaniola impacting the eastern portion of Jamaica for several days. This allowed the front system to interact with high levels of moisture picked up from the warm Caribbean waters and be enhanced by the topography over several days. The pattern lasted for several days after the front passed the island where is stalled off the coast of Costa Rica and Panama. It then became a seeding mechanism for a late season hurricane that returned north passing just east of Jamaica between the 11th and 12th of November (Figure 3.1).

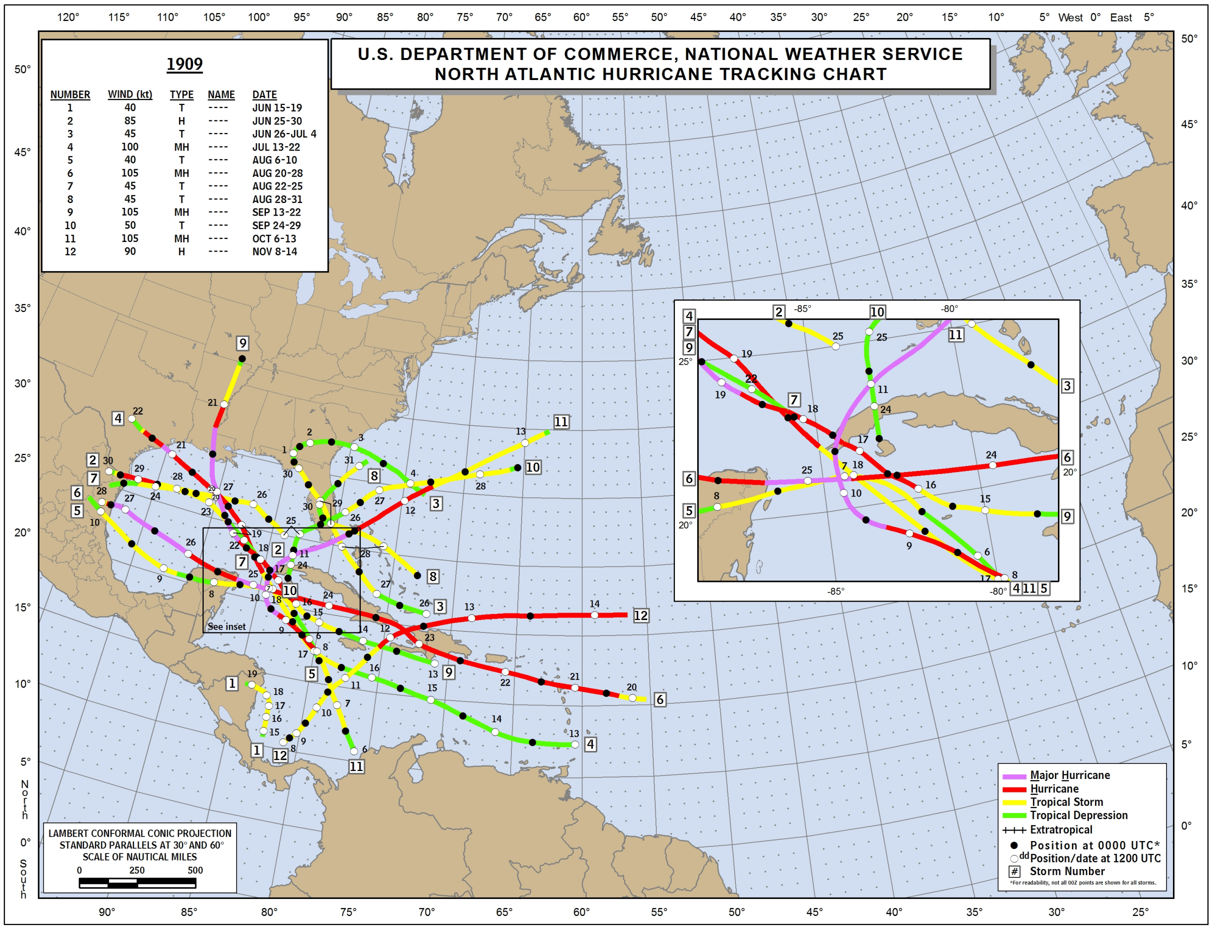


Figure 3.1: Hurricane tracks from 1909, from https://www.nhc.noaa.gov/data/tracks/tracks-at-1909.png

Interestingly, it was not the hurricane that cause the heavy rainfall over Jamaica, but instead the frontal interactions, excessive moisture picked up from the Caribbean water surface, and the continued northerly flow impinging on the island and the topography for several days. Because this storm produces such immense amounts of rainfall, it is controlling of PMP depths when transpositioned to Puerto Rico. Therefore, extensive investigations took place to confirm its transpositionability for this study.

The investigations investigated whether a similar synoptic pattern could affect Puerto Rico and if so, would it produce the same outcome. Given that the island of Jamaica is in a somewhat more favorable location for frontal activity and the unique gap flow that can occur between the opening on the eastern end of Cuba and the western end of Hispaniola it was decided the full effect of this setup could not occur in the same way as over Puerto Rico. However, mainly of the same features do occur over Puerto Rico, including interactions with fronts moving from the north/northwest, northerly flow impinging on topography over the island, and strong moisture advection from the warm tropical water in the region. Therefore, it was decided to utilize this storm for general storm PMP development but reduce its adjustment factors that account for the less favorable environment that would occur over Puerto Rico. Utilizing a 100-year 24-hour precipitation depth of 36.91" for the GTF calculation produced a maximum gridded GTF value of 0.75 over Puerto Rico (i.e., 75% of the rainfall depths analyzed in-place in Jamaica). A GTF of 0.75 provides a reasonable, yet conservative, adjustment for transposing the storm to Puerto Rico. Refer to Section 9.5 for a description on the general methods used to calculate the GTF.

3.2.3 Tropical Easterly Waves

Tropical easterly waves which do not turn into tropical systems affect the island frequently from April through November. These are disturbances which move through the lower and mid levels of the atmosphere producing lift. This lift will often result in disturbed weather patterns where showers and thunderstorms develop ahead of and along with the easterly waves. When the interact with topography, rainfall can be greatly enhanced. The following is a discussion from theweatherpredction.com, https://www.theweatherprediction.com/weatherpapers/032/index.html specific to easterly waves and rainfall over the island "Puerto Rico has a conditionally unstable atmosphere and abundance of low-level moisture and with heat combined with forcing mechanism, such as sea breeze, fronts and mountain uplift. Diurnal convective and sea breeze rainfall events are most prevalent during summer months, African easterly waves create an unstable environment. Easterly trade winds prevail almost the entire year, this wind regime is characterized by two principal factors: diurnal land and sea breezes."

Most of these easterly waves move through quickly bringing showers and thunderstorms over several hours and will often repeat over several days. Because these follows the general steering currents or trade winds in the region at the latitude of Puerto Rico, they move from east to west across the island. This allows them to preferably interact with the elevated terrain on the eastern end of the island, south of San Juan into the El Yunque National Forest and the Sierra de Luquillo region Gomez-Gomez et al., 2014).

Although rainfall from easterly waves is relatively common in Puerto Rico, on rare occasions the lift, instability, and moisture associated with a given easterly wave can be result in extreme rainfall. This can be enhanced by the topography in the region and result in severe flooding.

3.2.4 Tropical Systems

Tropical systems directly impact the island of Puerto Rico on a relatively infrequent basis considering its location in the path of so many storms during the Atlantic hurricane season. This is mostly related to the small size of the island versus any specific meteorological reason. Many tropical systems bring rainfall to the island, but often move by fast enough that overall effects are minimal. On rare occasions, a hurricane will take a preferred path directly over the island, either from east to west or southeast to northwest, and result in massive devastation. The most recent example was Hurricane Maria September 2017. This followed a preferred path for heavy rainfall and significant wind damage moving onshore at the southeastern section of the island and exiting along the north section near Arecibo. This as very similar to the infamous San Felipe Hurricane of September 1928 (https://www.aoml.noaa.gov/hrd/data_sub/perez_1_10.pdf), which resulted in similar devastation across the island (Figure 3.2).

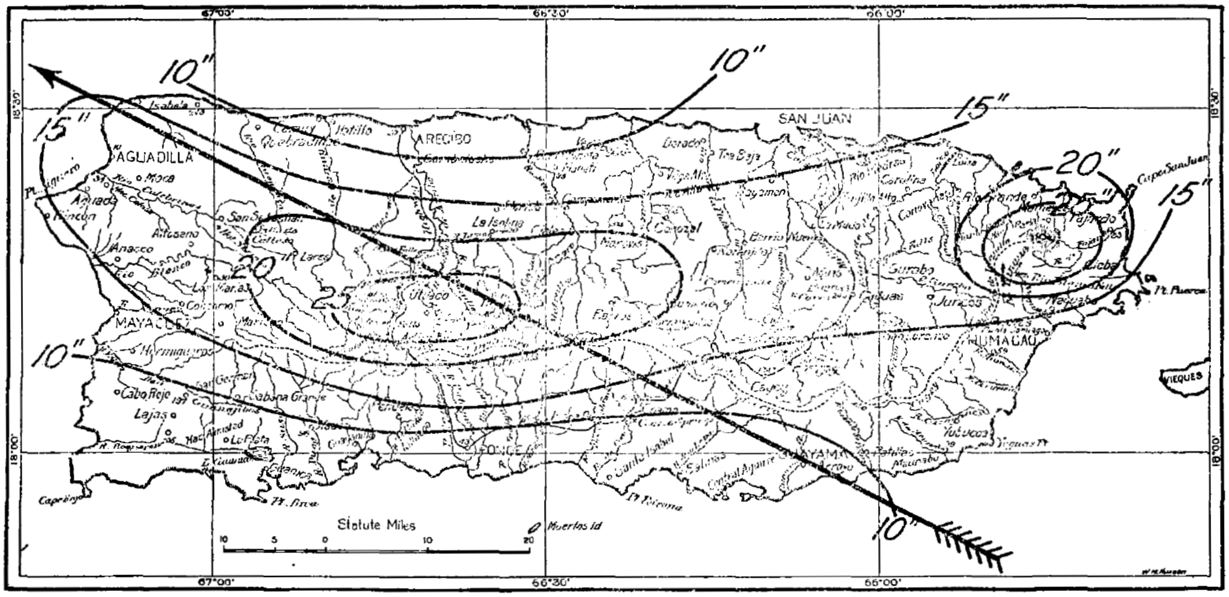


FIG. 3.—Rainfall distribution in Porto Rico hurricane, September 13, 1928

Figure 3.2: San Felipe Hurricane of September 1928 track across Puerto Rico (from Fassig, 1928)

Tropical systems have produced some of the largest rainfall observed in Puerto Rico, especially when they travers the island in the preferred paths. This allows them to interact with the topography so that rainfall amounts are enhanced while they are still able to draw moisture and energy from the warm tropical waters.

However, because this storm type requires a specific combination of warm water temperatures and proper atmospheric conditions to be present, they only form during June through October, with August and September being the most common period (Keim and Muller, 2009 and TP 42). As mentioned in Section 3.23 tropical easterly waves are often the seed for tropical systems as they move east to west across the Atlantic and Caribbean. These can enhance thunderstorm activity and increase rain rates significantly (Leppert et al., 2013).

4. Topographic Effects on Precipitation

Differences in elevation can play a significant role in precipitation development and accumulation patterns and magnitude. Terrain within the region both enhances and depresses precipitation depending on whether the terrain is forcing the air to rise (upslope effect) or descend (downslope) and whether the terrain limits moisture availability to a given location. In Puerto Rico, these two factors are constantly working against each other. This occurs as air and moisture are forced to rise as they move inland an encounter higher terrain moving east to west and north to south through the region. In general, the highest annual rainfall and PMP depths are located in regions closest along the central highlands (Cordillera Central) and in the eastern end of the island in El Yunque National Forest/ Sierra de Luquillo region.

To account for the effect of precipitation by terrain features and how this related to PMP development, explicit evaluations were performed using precipitation frequency climatologies and investigations into past storm spatial patterns and individual storm accumulation patterns across the region. NOAA Atlas 14 precipitation frequency climatologies (Bonnin et al., 2008) were used in this analysis.

These climatologies were used to derive GTF ratios and develop the spatial distribution of the PMP. This approach is similar to the use of the NOAA Atlas 2 100-year 24-hour precipitation frequency climatologies used in HMR 55A (Section 6.3 and 6.4, Hansen et al., 1988), HMR 57 (Section 8.1, Hansen et al., 1994), and HMR 59 (Section 6.61. and 6.6.2, Corrigan et al., 1999) as part of the Storm Separation Method (SSM) to quantify orographic effects in topographically significant regions. The GTF process address many of the discussions used to model hurricane rainfall discussed in Sections 2.4 and 2.5 in TP42.

The terrain within the region exhibits sharp rises often over short distances of areas inland from the immediate coastline (Figure 4.1). Elevations vary from sea level feet to over 4,000 feet in the central highlands (Cordillera Central). When elevated terrain features are upwind of a drainage basin, depletion of low-level atmospheric moisture available to storms over the basin can occur. Conversely, when incoming air is forced to rise as it encounters elevated terrain, release of conditional instability can occur more effectively and enhance the conversion of moisture in the air to precipitation. These interactions must be considered in the PMP determination procedures and explicitly in the storm adjustment process and PMP depths.

Quantification of terrain effects are inherently captured in the GTF process by evaluating rainfall depths at the 100-year recurrence interval using the 6-hour duration for local storms and the 24-hour duration for general and tropical storms at both the source (storm center) and target (grid point) location. This comparison produced a ratio that quantified the differences of precipitation processes, including topography, between the two locations. The assumption is that the precipitation frequency data represent all aspects that have produced precipitation at a given location over time, including the effect of terrain both upwind and in-place. Therefore, if two locations are compared within regions of similar meteorological and topographical characteristics, the resulting difference of the precipitation frequency climatology should reflect the difference of all precipitation producing processes between the two locations, including topography.

This relationship between precipitation frequency climatology and terrain is also recognized in the WMO PMP Manual (WMO, 1986 pg. 54 and by the Australian Bureau of Meteorology (Section 3.1.2.3 of Minty et al., 1996). Although the orographic effect at a particular location may vary from storm to storm, the overall effect of the topographic influence (or lack thereof) is inherently included in the climatology of precipitation that occurred at that location, assuming that the climatology is based on storms of the same type. In WMO 2009 Section 3.1.4 it is stated "since precipitation-frequency values represent equal probability, they can also be used as an indicator of the effects of topography over limited regions. If storm frequency, moisture availability, and other precipitation-producing factors do not vary, or vary only slightly, over an orographic region, differences in precipitation-frequency values should be directly related to variations in orographic effects." Therefore, by applying appropriate transposition limits, analyzing by storm type, and utilizing durations representative of each storm type, it is assumed the storms being compared using the precipitation frequency data are of similar moisture availability and other precipitation-producing factors.

Use of the GTF calculation to represent differences in all precipitation processes between two locations was explicitly evaluated and determined during this study through various sensitivities and discussions with the others involved in this study. Recent AWA PMP studies have included similar sensitivities and evaluations to confirm the use of precipitation frequency climatologies calculate difference in precipitation producing processes, including topography between two locations (e.g., Tennessee Valley Authority Regional PMP, 2015; Colorado-New Mexico Regional Extreme Precipitation Study 2018; Pennsylvania statewide PMP, 2019; Oklahoma-Arkansas-Louisiana-Mississippi, 2019).

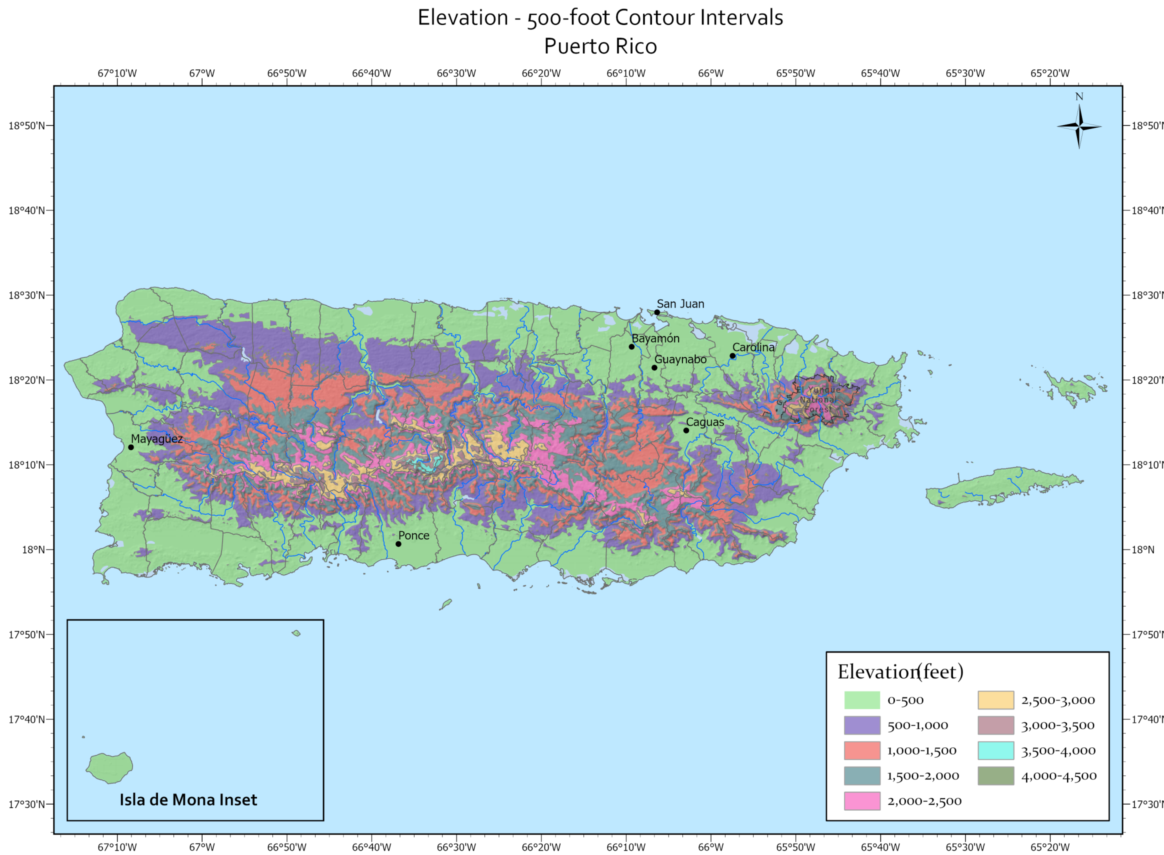


Figure 4.1: Elevation variation in 500-foot contour intervals

5. Data Description and Sources

An extensive storm search was conducted as part of this study to derive the list of storms to use for PMP development. This included investigating the storms that occurred throughout the island and the greater Caribbean region in general. The updated storm search completed utilized data from the sources below:

1. Discussions with the study participants and PREPA
2. San Juan National Weather Service personnel and other data published by NWS offices (e.g., https://www.wpc.ncep.noaa.gov/tropical/rain/tcpr.html; https://www.weather.gov/safety/flood-states-pr; https://library.noaa.gov/Collections/Digital-Docs/Foreign-Climate-Data/Jamaica-Climate-Data#o02126905)
3. Data from various governmental weather agencies in Jamaica and other locations throughout the Caribbean
4. Technical Paper 42 available from the Hydrometeorological Design Studies Center website at https://www.weather.gov/owp/hdsc_pmp
5. Cooperative Summary of the Day / TD3200 through 2020. These data are published by the National Center for Environmental Information (NCEI), previously the National Climatic Data Center (NCDC). These are stored on AWA's database server and can be obtained directly from the NCEI.
6. Hourly Weather Observations published by NCEI, U.S. Environmental Protection Agency, and Forecast Systems Laboratory (now National Severe Storms Laboratory). These are stored on AWA's database server and obtained directly from the NCEI.
7. NCEI Recovery Disk. These are stored on AWA's database server and can be obtained directly from the NCEI.
8. U.S. Corps of Engineers Storm Studies (USACE, 1973)
9. United States Geological Society (USGS) Flood Reports
10. Data from supplemental sources, such as Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS), Weather Underground, Forecast Systems Laboratories, RAWS, and various Google searches
11. Peer reviewed journals

5.1 Use of Sea Surface Temperatures for Storm Maximization

HMR and WMO procedures for storm maximization use a representative storm dew point as the parameter to represent available moisture to a given storm. The exception is for locations where the moisture supplying the storms originates over an ocean source (e.g., HMR 57 and HMR 59). This is the case for all the storms evaluated in this study. Dew point observations are not generally available over ocean regions. When the source region of atmospheric moisture resulting in a rainfall event originates from over the ocean, a substitute for dew points observations is required. The NWS adopted a procedure for using SSTs as surrogates for dew point data (U.S. Navy Marine Climate Atlas, 1981). The value used as the maximum SST in the PMP calculations is determined using the SSTs two standard deviations warmer (+2-sigma) than the mean SST (Worley et al., 2005; Kent et al., 2007; and Reynolds et al., 2007). This provides a value for the maximum SST that has a probability of occurrence of about 0.025 (i.e., about the 40-year recurrence interval value).

HYSPLIT model output provides detailed analyses for determining the upwind trajectories of atmospheric moisture that was advected into the storm systems. Using these trajectories as general guidance, the moisture source locations can be investigated. This is especially helpful over ocean regions where surface data are lacking to help with guidance in determining the moisture source region for a given storm. The procedures followed are similar to the approach used in HMR 59. However, by utilizing the HYSPLIT model trajectories, much of the subjectivity is eliminated. Further, details of each evaluation can be explicitly provided, and the results are reproducible. SSTs for in-place maximization and storm transpositioning follow a similar procedure to that used with land-based surface dew points. Use of the HYSPLIT model provides a significant improvement in determining the inflow wind vectors compared to older methods of extrapolating coastal wind observations and estimating moisture advection from synoptic features over the ocean. This more objective procedure is especially useful for situations where a long distance is involved to the moisture source regions.

Timing is not as critical for inflow wind vectors extending over the oceans since SSTs change very slowly with time compared to dew point values over land. What is important is the changing wind direction, especially for situations where there is curvature in the wind fields. Any changes in wind curvature and variations in timing are inherently captured in the HYSPLIT model re-analysis fields, thereby eliminating another subjective parameter. Timing of rainfall is determined using the rainfall mass curves from the region of maximum rainfall associated with a given storm event. The location of the storm representative SST was determined by identifying the location where the SSTs are generally changing less than 1°F in an approximate 1° x 1° latitude and/or longitude distance following the inflow vector upwind. This is used to identify the homogeneous (or near homogeneous) region of SSTs associated with the atmospheric moisture source for the storm being analyzed. The value from the SST daily analysis for that location is used for the storm representative SST. The storm representative SST becomes a surrogate for the storm representative dew point in the maximization procedure.

The value for the maximum SST was determined using the mean +2-sigma (two standard deviations warmer than the mean) SST for that location. SSTs were substituted for dew points in this study for several storms where the inflow vector originated over the Caribbean and Atlantic Ocean. The data presented in Appendix F shows the moisture source region for each storm and whether dew points or SSTs were used in the maximization calculations.

For storm maximization, the value for the maximum SST is determined using the mean +2-sigma SST for that location for a date two weeks before or after the storm date (which ever represents the climatologically warmer SST period). Storm representative SSTs and the mean +2-sigma SSTs are used in the same manner as storm representative dew points and maximum dew point climatology values in the maximization and transpositioning procedure. Storm representative SSTs and the mean +2 sigma SSTs are used in the same manner as storm representative dew points and maximum dew point climatology in the maximization and transpositioning procedure.

6. Data Quality Control and Quality Assurance

During the development of the deterministic PMP depths, quality control (QC) and quality assurance (QA) measures were in-place to ensure data used were free from errors and processes followed acceptable scientific procedures. AWA QC/QA procedures were in-place internally while the independent reviewer and other study participants provided detailed additional review.

The built in QA/QC checks that are part of the SPAS algorithms were utilized. These include gauge quality control, gauge mass curve checks, statistical checks, gauge location checks, co-located gauge checks, rainfall intensity checks, observed versus modeled rainfall checks, ZR relationship checks (if radar data are available). These data QA/QC measures help ensure accurate precipitation reports, ensure proper data analysis and compilation of values by duration and area size, and consistent output of SPAS results. For additional information on SPAS, the data inputs, modeled outputs, and QA/QC measures, see Appendix E. For the storm adjustment process, internal QA/QC included validation that all IPMF were 1.00 or greater, that upper (1.50) and lower (0.50) limits of the GTF were applied, and that any unique GTF limits were applied as appropriate.

Maps of gridded GTF values were produced to cover the PMP analysis domain (Appendix B). These maps serve as a tool to spatially visualize and evaluate adjustment factors. Spot checks were performed at various positions across the domain and hand calculations were done to verify adjustment factor calculations are consistent. Internal consistency checks were applied to compare the storm data used for PMP development against previous PMP depths spatially, against TP42 PMP depths, against world record rainfall depths, and NOAA Atlas 14 precipitation depths.

Maps of each version (see Appendix D for the Version Log notes) of PMP depths were plotted at various area sizes and durations to ensure proper spatial continuity of PMP depths. Updates were applied to ensure reasonable gradients and depths based on overall meteorological and topographical interactions. Comparisons were completed against TP42 and precipitation frequency climatologies. The PMP tool utilized to calculate PMP for this study employs very few calculations, however the script utilizes Python’s ‘try’ and ‘except’ statements to address input that may be unsuitable or incorrect.

The independent reviewer and other study participants completed external QA/QC on several important aspects of the PMP development. Storms used for PMP development were evaluated, the transposition limits of important storms were discussed in detail, the storm adjustment values for each storm were reviewed, and the PMP depths across the region reviewed, discussed, and tested. The results of these tests were crucial in setting limitations and guidelines for appropriate application. In addition, study participants provided review and comment on the temporal accumulation pattern development, the GIS tool output, and report documentation.

7. Storm Selection

7.1 Storm Search Process

The initial search began with identifying storms that had been used in TP42, were noted in various hurricane and extreme rainfall documentation from the NWS, peer reviewed journals, and other government agencies in the region covered by the storm search domain (Figure 7.1).

These storm lists were combined to produce a long list of storms for this study. Each storm was individually evaluated to identify all information that could be utilized to determine important information about each storm that could be utilized to decide of whether to keep or discard the storm. Each storm was analyzed to determine whether it was used in TP42, whether it produced extreme rainfall, whether information was available to evaluate the storm in detail, and/or whether it produced an extreme flood event.

Each storm was then classified by storm type (e.g., local, tropical, or general). Storm types were discussed during various review calls to ensure concurrence and cross-referenced with previous storm typing to ensure consistency. The storms were then grouped by storm type, storm location, and duration for further analysis to define the final short list of storms used for PMP development. These storms were plotted and mapped using GIS to better evaluate the spatial coverage of the events throughout the region by storm type to ensure adequate coverage for PMP development.

The recommended storm list was presented to the study participants for discussion and evaluation. The recommended short list of storms was based on the above evaluations and experience with past studies and relevance for this project. The recommended short storm list was reviewed and discussed in detail during review meetings and subsequently through the end of the project as various iterations of the PMP were developed. Iterations of how each storm was used can be found in the PMP Version log provided in Appendix D.

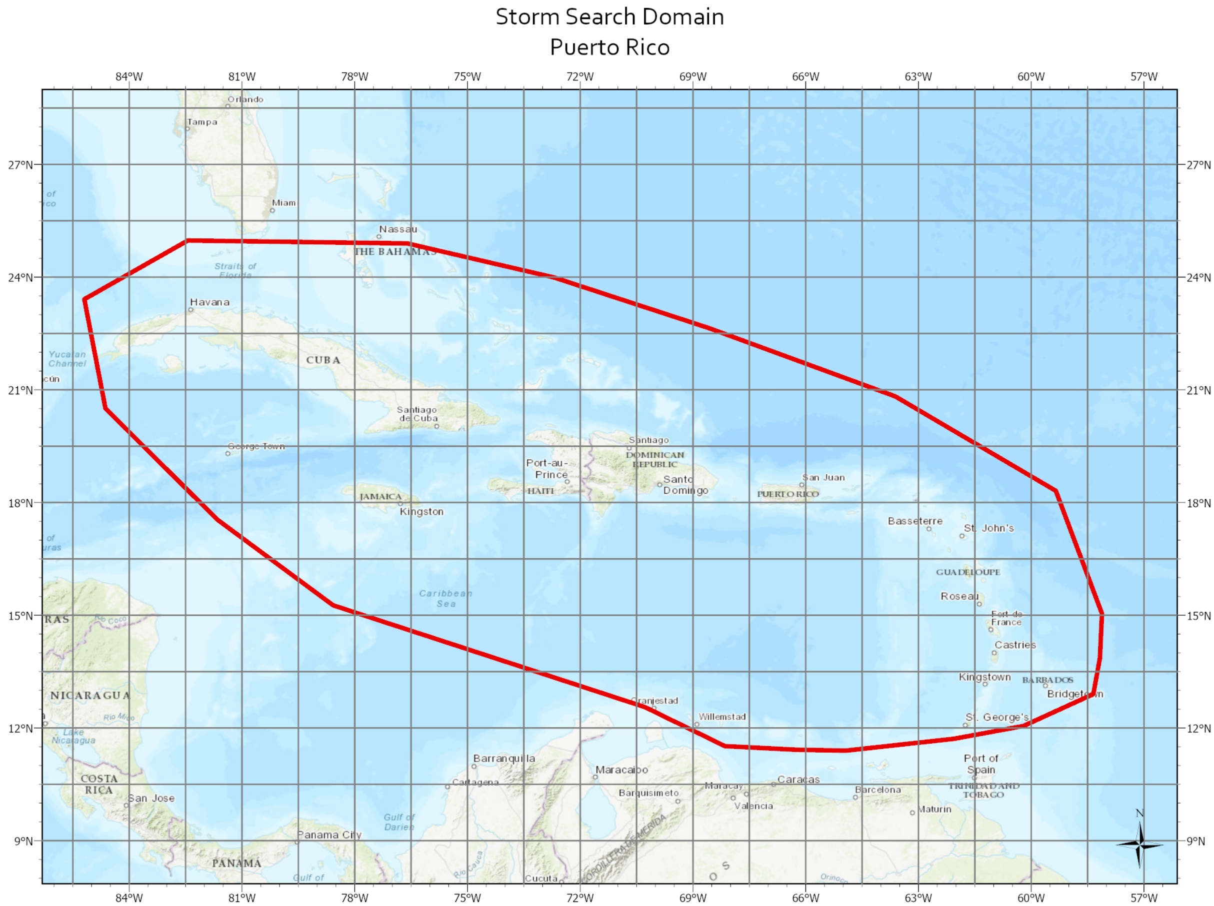


Figure 7.1: Overall storm search domain used to identify potential storm events

7.2 Short Storm List Development

From the initial storm list, the storms to be used for PMP development were identified and moved to the final short storm list. Each storm was investigated using both published and unpublished references described above and application of AWA's knowledge related to PMP studies to determine its significance in the rainfall and flood history. Detailed discussions about each important storm took place with the study participants. These included evaluations and comparisons of the storms, discussions of each storm's effects in the location of occurrence, discussion of storms in regions that were underrepresented, discussion of storms importance for PMF development in previous design analyses, and other meteorological and hydrological relevant topics.

Consideration was given to each storm's transpositionability within the overall domain and each storm's relative magnitude compared to other similar storms on the list and whether another storm of similar storm type was significantly larger. In this case, what is considered is whether after all adjustments are applied a given storm would still be smaller than other storms used. To determine this, several evaluations were completed. These included use of the storm in previous PMP studies, comparison of the precipitation values at various area sizes, and comparison of precipitation values after applying a 50% maximization to the observed values.

7.3 Final PMP Storm List Development

The final short storm list used to derive PMP depths for this study considered each of the discussions in the previous sections in detail to develop the final short storm list. Each storm on the final short storm list exhibited characteristics that were determined to be possible over island of Puerto Rico. The storms that made it through these final evaluations were placed on the short storm list (Tables 7.1). Figures 7.2 displays the location of each short list storms. The callouts also provide the storm name and date that can be cross-referenced with the information provided in Table 7.1.

The short storm list contains 18 storms, far more storms than were ultimately controlling of the PMP depths. Each of these storms were fully analyzed as part of this study using the SPAS process (Appendix E). Ultimately, only a subset of the storms on the short list control PMP depths at a given location for a given duration, with most providing support for the PMP depths. This is one of the steps that helps to ensure no storms were omitted which could have affected PMP depths after all adjustment factors were applied.

The conservative development of the short storm list is completed because the final magnitude of the rainfall accumulation associated with a given storm is not known until all the total adjustment factors have been calculated and applied. In other words, a storm with large point rainfall values may have a relatively small total adjustment factor, while a storm with a relatively smaller but significant rainfall value may end up with a large total adjustment factor. The combination of these calculations may provide a TAR value for the smaller rainfall event that is greater than the larger rainfall event after all adjustments are applied.

Table 7.1: Final short storm list used for PMP development

SPAS ID	Storm Name	Location	Lat.	Lon.	Year	Month	Day	Total Rainfall (in.)	Storm Center Elevation (ft.)	Storm Type	Storm Rep. SST	Climatological Maximum SST	In-place Maximization Factor	Temporal Transposition Date	Storm Rep. Lat.	Storm Rep. Lon.	Moisture Inflow Vector
SPAS_1747_1	SILVER HILL PLANTATION	JA	18.096	-76.738	1909	11	5	105.19	3,990	GENERAL/EW	81.5	85.5	1.21	24-Oct	20.00	-74.00	NE @ 220
SPAS_1751_1	TORO NEGRO	PR	18.171	-66.496	1992	1	5	22.41	2,976	GENERAL/EW	79.5	83.0	1.19	20-Dec	16.00	-66.00	SSE @ 155
SPAS_1751_2	EL JUNQUE NP	PR	18.271	-65.754	1992	1	5	13.17	2,879	GENERAL/EW	79.5	83.0	1.19	20-Dec	16.00	-66.00	S @ 157
SPAS_1752_1	SAN JUAN	PR	18.441	-66.015	2013	7	18	9.60	10	GENERAL/EW	82.5	84.5	1.09	15-Jul	18.00	-64.00	ESE @ 135
SPAS_1748_1	ADJUNTAS	PR	18.171	-66.588	1928	9	13	33.65	3,645	TROPICAL	84.0	86.0	1.09	26-Sep	15.00	-61.00	SE @ 430
SPAS_1749_1	SABANA	PR	18.279	-65.763	1960	9	4	19.15	2,861	TROPICAL	84.0	85.5	1.07	15-Sep	21.00	-62.00	NE @ 305
SPAS_1750_1	JAYUYA 1SE	PR	18.179	-66.579	1970	10	2	42.37	3,576	TROPICAL	84.0	86.0	1.09	23-Sep	15.00	-65.00	SSE @ 245
SPAS_1753_1	CAGUAS	PR	18.131	-66.045	2017	9	19	38.09	1,725	TROPICAL	84.0	85.0	1.04	15-Sep	20.00	-60.00	ENE @ 415
SPAS_1760_1	DOS BOCAS	PR	18.329	-66.688	1975	9	14	34.17	1,108	TROPICAL	83.5	85.5	1.09	15-Sep	21.00	-64.00	NE @ 255
SPAS_1762_1	TORO NEGRO FOREST	PR	18.165	-66.505	1985	10	4	32.07	2,724	TROPICAL	82.0	85.5	1.17	21-Sep	17.00	-63.00	ESE @ 245
SPAS_1763_1	JAYUYA	PR	18.201	-66.595	1998	9	22	30.52	1,963	TROPICAL	84.0	85.0	1.04	15-Sep	20.00	-58.00	ENE @ 575
SPAS_1764_1	GENDARMARIE	St. Martin	18.079	-63.071	1999	11	18	34.15	100	TROPICAL	84.0	85.5	1.07	4-Nov	14.00	-64.50	SSW @ 295
SPAS_1765_1	COMFORT CASTLE	JA	18.038	-76.404	2001	10	29	38.85	925	TROPICAL	84.0	85.0	1.04	15-Oct	20.00	-65.00	ENE @ 760
SPAS_1766_1	ANGELINA	DR	19.096	-70.221	2007	10	28	36.67	164	TROPICAL	83.5	86.0	1.11	13-Oct	16.00	-64.00	ESE @ 460
SPAS_1767_1	PATILLAS	PR	18.013	-66.029	2008	9	24	30.94	130	TROPICAL	84.0	86.0	1.09	15-Sep	15.00	-61.00	SSE @ 390
SPAS_1768_1	BELLEISLE	JA	18.279	-78.179	2010	9	28	38.54	20	TROPICAL	84.5	86.0	1.06	15-Sep	17.00	-81.50	SSW @ 235
SPAS_1769_1	DESRACHES	St. Lucia	13.771	-60.621	2010	10	30	33.48	0	TROPICAL	83.5	85.5	1.09	15-Oct	13.00	-58.00	ESE @ 185

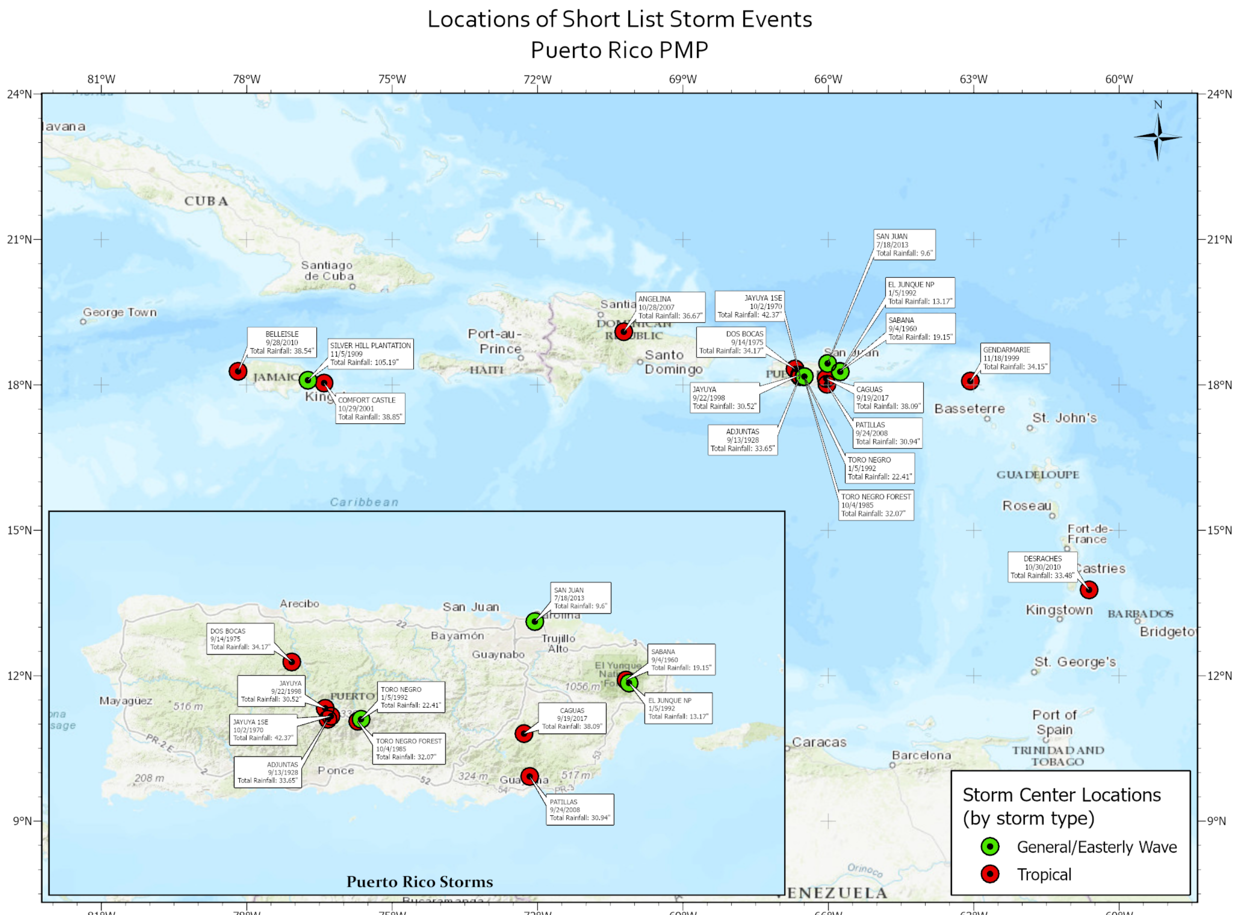


Figure 7.2: Final short storm list locations, all storms

8. SPAS Analysis Results

For all storms identified as part of this study, Depth-Area-Duration (DAD) and hourly gridded rainfall data were needed. Hourly gridded rainfall information was required for all storms for the GTF calculations to be completed and to calculate PMP depths. SPAS was used to compute DADs and hourly gridded rainfall data for all the storms. Results of all SPAS analyses used in the study are provided in Appendix F. This includes the standard output files associates with each SPAS analysis, including the following:

- SPAS analysis notes and description
- Total storm isohyetal
- DAD table and graph
- Storm center mass curve (hourly and incremental accumulation)

There are two main steps in the SPAS DAD analysis: 1) The creation of high-resolution hourly rainfall grids and 2) the computation of Depth-Area (DA) rainfall amounts for various durations, i.e., how the depth of the analyzed rainfall varies with area sizes being analyzed. The reliability of the results from step 2) depends on the accuracy of step 1). Historically the process has been very labor intensive. SPAS utilizes GIS concepts to create spatially oriented and highly accurate results in an efficient manner (step 1). Furthermore, the availability of NEXRAD (NEXt generation RADar) data allows SPAS to better account for the spatial and temporal variability of storm precipitation between rain gage locations.

Prior to NEXRAD, the NWS developed and used a method based on Weather Bureau Technical Paper No. 1 (1946). Because this process has been the standard for many years and holds merit, the DAD analysis process developed for this study attempts to follow the NWS procedure as much as possible. By adopting this approach, some level of consistency between the newly analyzed storms and the hundreds of storms already analyzed by the USACE, USBR, and/or NWS can be achieved. Appendix E provides a detailed description of the SPAS program with the following sections providing a high-level overview of the main SPAS processes.

8.1 SPAS Data Collection

The areal extent of a storm's rainfall is evaluated using existing maps and documents along with plots of total storm rainfall. Based on the storm's spatial domain (longitude-latitude box), hourly and daily rain gauge data are extracted from the database for the specified area, dates, and times. To account for the temporal variability in observation times at daily stations, the extracted hourly data must capture the entire observational period of all extracted daily stations. For example, if a station takes daily observations at 8:00 AM local time, then the hourly data needs to be complete from 8:00 AM local time the day prior. If the hourly data are sufficient to capture all the daily station observations, the hourly variability in the daily observations can be properly addressed.

The daily database is comprised of data from NCDC TD-3206 (pre-1948) and TD-3200 (generally 1948 through present). The hourly database is comprised of data from NCDC TD-3240 and NOAA's Meteorological Assimilation Data Ingest System (MADIS). The daily supplemental database is largely comprised of data from "bucket surveys," local rain gauge networks (e.g., USGS, CoCoRaHS, etc.) and daily gauges with accumulated data.

8.2 SPAS Mass Curve Development

The most complete rainfall observational dataset available is compiled for each storm. To obtain temporal resolution to the nearest hour in the final DAD results, it is necessary to distribute the daily precipitation observations (at daily stations) into hourly bins. In the past, the NWS had accomplished this process by anchoring each of the daily stations to a single hourly station for timing. However, this may introduce biases and may not correctly represent hourly precipitation at locations between hourly observation stations. A preferred approach is to anchor the daily station to some set of nearest hourly stations. This is accomplished using a spatially based approach called the spatially based mass curve (SMC) process.

8.3 Hourly and Sub-Hourly Precipitation Maps

At this point, SPAS can either operate in its standard basemap mode or in NEXRAD-mode to create high resolution hourly or sub-hourly (for NEXRAD storms) grids. In practice, both modes are run when NEXRAD data are available so that a comparison can be made between the methods. Regardless of the mode, the resulting grids serve as the basis for the DAD computations.

8.4 Standard SPAS Mode Using a Basemap Only

The standard SPAS mode requires a full listing of all the observed hourly rainfall values, as well as the newly created estimated hourly data from daily and daily supplemental stations. This is done by creating an hourly file that contains the newly created hourly mass curve precipitation data (from the daily and supplemental stations) and the "true" hourly mass curve precipitation. If not using a base map, the individual hourly precipitation values are simply plotted and interpolated to a raster with an inverse distance weighting (IDW) interpolation routine in a GIS.

8.5 SPAS-NEXRAD Mode

In general, most current radar-derived rainfall techniques rely on an assumed relationship between radar reflectivity and rainfall rate. This relationship is described by the Equation 2 below:

$$Z = aR^b \qquad \text{Equation 2}$$

where Z is the radar reflectivity, measured in units of dBZ, R is the rainfall rate, a is the "multiplicative coefficient" and b is the "power coefficient". Both a and b are related to the drop size distribution (DSD) and the drop number distribution (DND) within a cloud (Martner et al., 2005).

The NWS uses this relationship to estimate rainfall using their network of Doppler radars (NEXRAD) located across the United States. A standard default Z-R algorithm of $Z = 300R^{1.4}$ has been the primary algorithm used throughout the country and has proven to produce highly variable results. The variability in the results of Z vs. R is a direct result of differing DSD and DND, and differing air mass characteristics across the United States (Dickens, 2003). The DSD and DND are determined by a complex interaction of microphysical processes in a cloud. They fluctuate hourly, daily, seasonally, regionally, and even within the same cloud (see Appendix E for a more detailed description). Using the technique described above, NEXRAD rainfall depths and temporal distribution estimates are determined for the area in question.

8.6 Depth-Area-Duration Program

The DAD extension of SPAS runs from within a Geographic Resource Analysis Support System (GRASS) GIS environment and utilizes many of the built-in functions for calculation of area sizes and average rainfall depths. The following is the general outline of the procedure:

1. Given a duration (e.g., x-hours) and cumulative precipitation, sum up the appropriate hourly or sub-hourly precipitation grids to obtain an x-hour total precipitation grid starting with the first x-hour moving window.
2. Determine x-hour precipitation total and its associated areal coverage. Store these values. Repeat for various lower rainfall thresholds. Store the average rainfall depths and area sizes.
3. The result is a table of depth of precipitation and associated area sizes for each x-hour window location. Summarize the results by moving through each of the area sizes and choosing the maximum precipitation amount. A log-linear plot of these values provides the depth-area curve for the x-hour duration.
4. Based on the log-linear plot of the rainfall depth-area curve for the x-hour duration, determine rainfall amounts for the standard area sizes for the final DAD table. Store these values as the rainfall amounts for the standard sizes for the x-duration period. Determine if the x-hour duration period is the longest duration period being analyzed. If it is not, analyze the next longest duration period and return to step 1.
5. Construct the final DAD table with the stored rainfall values for each standard area for each duration period.

8.7 Comparison of SPAS DAD Output Versus Previous DAD Results

The SPAS process and algorithms have been thoroughly reviewed as part of many AWA PMP studies. In addition, the SPAS program was reviewed as part of the NRC software verification and validation program to ensure that its use in developing data for use in NRC regulated studies was acceptable (Hultstrand and Kappel, 2017). The result of the NRC review showed that the SPAS program performed exactly as described and produced expected results.

9. Storm Adjustments

Storm maximization (also called moisture maximization in HMR 59) is the process of increasing rainfall associated with an observed extreme storm under the potential condition that additional moisture could have been available to the storm and resulted in more rainfall. In this study, storm maximization was accomplished by comparing the observed SSTs against the climatological maximum SSTs and calculating the IPMF.

The observed rainfall for a given storm was then multiplied by the IPMF, representing the enhanced rainfall amounts that could potentially have been produced had those climatological maximum amounts of moisture been available when the storm occurred. An additional consideration is usually applied that selected the climatological maximum SST for a date two weeks towards the time of the year when more moisture is available versus the date that the storm actually occurred. This procedure assumed that the storm could have occurred two weeks earlier or later in the year when SSTs are higher.

9.1 In-Place Maximization Process

Maximization was accomplished by comparing SST which represented the observed storm's moisture source to a climatological maximum and calculating the enhanced rainfall amounts that could potentially be produced if the climatological maximum moisture had been available during the observed storm period. As noted, the climatological maximum SST for a date two weeks towards the warm season is selected with higher amounts of moisture from the date that the storm occurred. This procedure assumes that the storm could have occurred with the same storm dynamics two weeks towards the time in the year when higher maximum SSTs (and hence more moisture) could occur. This assumption follows HMR guidance and is consistent with procedures used to develop PMP values in all the current HMR documents (e.g., HMR 51 Section 2.3), the WMO Manual for PMP (WMO, 2009), as well as in all prior AWA PMP studies. AWA utilized general guidelines outlined in HMR 57 Section 4.3 and HMR 59 Section 4.2 to determine the storm representative SST location but with updated tools and information. These included using the synoptic weather patterns associated with a given event to gain an understanding of the general moisture source regions

The storm data appendix, Appendix F provides the individual analysis maps used to determine each storm representative SST value and storm adjustment investigations including the HYSPLIT model output, the SST observations, the storm center location, the storm representative location, and the IPMF for each storm.

Each storm used for PMP development has been thoroughly reviewed in previous studies and was evaluated by the independent reviewer and study participants to confirm the reasonableness of the storm representative value and location used. As part of this process, AWA provided and discussed all the information used to derive the storm representative value for review, including the following:

- Daily SST observations
- HYSPLIT model output
- Storm adjustment spreadsheets

- Storm adjustments maps with data plotted

These data allowed for an independent review of each storm. Results of this analysis demonstrated that the values AWA utilized to adjust each storm was reasonable for PMP development.

For storm maximization, daily SST values are used to determine the storm representative value for all storms used in this study. This value is then maximized using the appropriate climatological value representing the +2 sigma value at the same location moved two weeks towards the season of higher climatological maximum values.

HYSPLIT model output (Draxler and Rolph, 2013; Stein et al., 2015; and Rolph et al., 2017) provides detailed and reproducible analyses for assisting in the determination of the upwind trajectories of atmospheric moisture that was advected into the storm systems. Using these model trajectories, along with an analysis of the general synoptic weather patterns and available surface data, the moisture source region for candidate storms is determined. This procedure is similar to the approach used in the HMRs. However, by utilizing the HYSPLIT model, much of the subjectivity found in the HMR analysis process was corrected. Further, details of each evaluation can be explicitly provided, and the HYSPLIT trajectory results based on the input parameters defined are reproducible. Available HYSPLIT model results are provided as part of Appendix F.

The comparison of the storm representative SST values against the climatological maximum values results in a ratio of observed moisture versus climatological maximum moisture. Therefore, this value is always 1 or greater. In addition, the intent of the process is to produce a hypothetical storm event that represents the upper limit of rainfall that a given storm could have produced with the ideal combination of moisture and maximum storm efficiency (atmospheric processes that convert moisture to precipitation) associated with that storm. This assumes that the storm efficiency processes remain constant as more moisture is added to the storm environment. Therefore, an upper limit of 1.50 (50%) is applied to the IPMF with the assumption that increases beyond this amount would change the storm efficiency processes and the storm would no longer be the same storm as observed from an efficiency perspective.

This upper limit is a standard application applied in the HMRs (e.g., HMR 51 Section 3.2.2). Note, this upper limit was investigated further during the Colorado-New Mexico REPS study using the Dynamical Modeling Task and the HRRR model interface (Alexander et al., 2015). This explicitly demonstrated that storm efficiency changes as more moisture is added, well before the 50% moisture increase level for the storms investigated (Mahoney, 2016). Therefore, the use of 1.50 as an upper limit is a conservative application.

9.2 Storm Representative Sea Surface Temperature Determination Process

For storm maximization, daily SST values for the time frame most consistent with the actual rainfall accumulation period for an individual storm were used to determine the storm representative value. To determine which time frame was most appropriate, the total rainfall amount was analyzed. The duration closest to when approximately 90% of the rainfall had accumulated was used to determine the duration used, i.e., 6-hour, 12-hour, or 24-hour.

Once the general upwind location was determined by investigating HYSPLIT, surface weather patterns, and topical system movement, the daily SST observations were analyzed for all available stations within the vicinity of the inflow vector. From these data, the appropriate value was averaged for several stations within the moisture source region covering the appropriate time and space for moisture advection into the observed event. These values were used to derive the storm representative SST, with the location noted for use in transposition calculations. The line connecting this point with the storm center location (point of maximum rainfall accumulation) is termed the moisture inflow vector. The information used and values derived for each storm's moisture inflow vector are included in Appendix F.

HYSPLIT was used during the analysis of each of the rainfall events included on the short storm list when available (1948-present). Use of a trajectory model provides increased confidence in determining moisture inflow vectors and storm representative dew points. The HYSPLIT trajectories have been used to analyze moisture inflow vectors in other PMP studies completed by AWA since 2006. During these analyses, the model trajectory results were verified, and the utility explicitly evaluated (e.g., Tomlinson et al., 2006-2012; Kappel et al., 2013-2021).

In determining the moisture inflow trajectories, HYSPLIT was used to compute the trajectory of the atmospheric moisture inflow associated with the storm's rainfall production, both location and altitude, for various levels in the atmosphere. The HYSPLIT model was run for trajectories at several levels of the lower atmosphere to capture the moisture source for each storm event. These included 700mb (approximately 10,000 feet), 850mb (approximately 5,000 feet), and storm center location surface elevation.

For most of the analyses, a combination of all three levels was determined to be most appropriate for use in evaluation of the upwind moisture source location. It is important to note that the resulting HYSPLIT trajectories are only used as a general guide to evaluate the moisture source for storms in both space and time. The final determination of the storm representative SST and its location was determined following the standard procedures used by AWA in previous PMP studies (e.g., Tomlinson, 1993; Tomlinson et al., 2006-2012; Kappel et al., 2012-2021) and as outlined in the HMRs (e.g., HMR 57 Section 4.3).

The process involves deriving the daily SST values at all locations in a large region along the HYSPLIT inflow vectors. Values representing the daily SST are analyzed in Excel spreadsheets. This evaluation includes an analysis of the timing of the observed SST values to ensure they occurred in a source region where they would be advected into the storm environment at the time of the rainfall period. Several locations are investigated to find values that are of generally similar magnitude (within a degree or two Fahrenheit). Once these representative locations are identified, an average of the values to the nearest half degree is determined and a location in the center of the stations is identified. This becomes the storm representative value, and the location provides the inflow vector (direction and distance) connecting that location to the storm center location. This follows the approach used in HMR 51 Section 2, HMR 55A Section 5, and HMR 57 Section 4, with improvements provided using

HYSPLIT and updated maximum dew point climatologies. Appendix F of this report contains each of the HYSPLIT trajectories analyzed as part of this study for each storm (when used).

9.2.1 Storm Representative SST Determination Example

The storm representative SST was determined using the mean +2-sigma (two standard deviations warmer than the mean) SST for that location. SSTs were substituted for dew points in this study for storms because moisture source region and inflow vector originated over the Atlantic Ocean. Data presented in Appendix F show the moisture source region for each storm and the SSTs used in the maximization calculations. For storm maximization, the value for the maximum SST was determined using the mean +2-sigma SST for that location for a date two weeks before or after the storm date (which ever represents the climatologically warmer SST period). Storm representative SSTs and the mean +2-sigma SSTs were used in the same manner as storm representative dew points and maximum dew point climatology representing the 15th of the month values in the maximization and transpositioning procedure. Figure 9.1provides the HYPLIT trajectories used to investigate the moisture source region in time and space, while Figure 9.2 provides the daily SST data used to determine the storm representative SST for Hurricane Maria September 2017 storm (SPAS 1753).

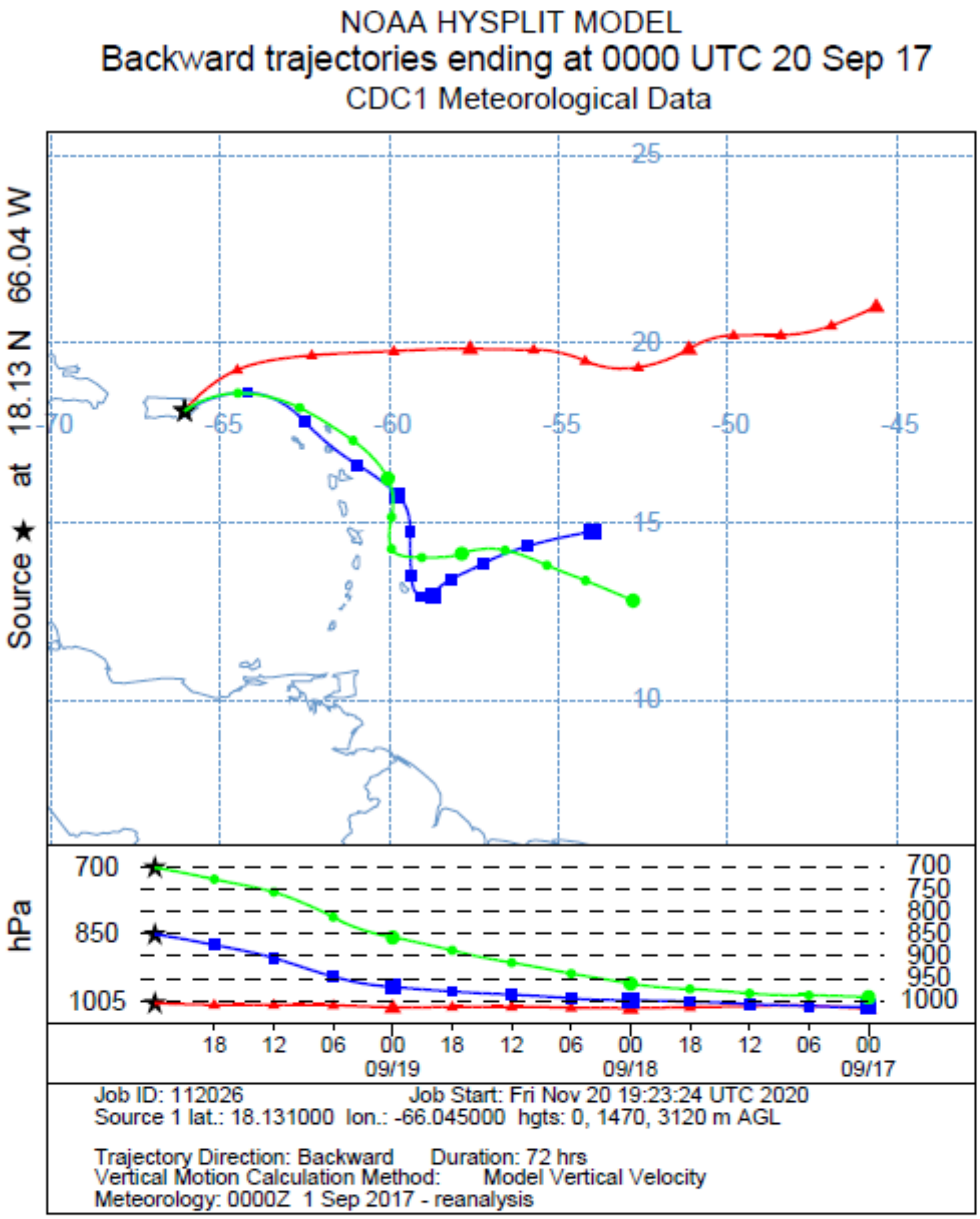


Figure 9.1: HYSPLIT trajectory model results for Hurricane Maria September 2017 (SPAS 1753)

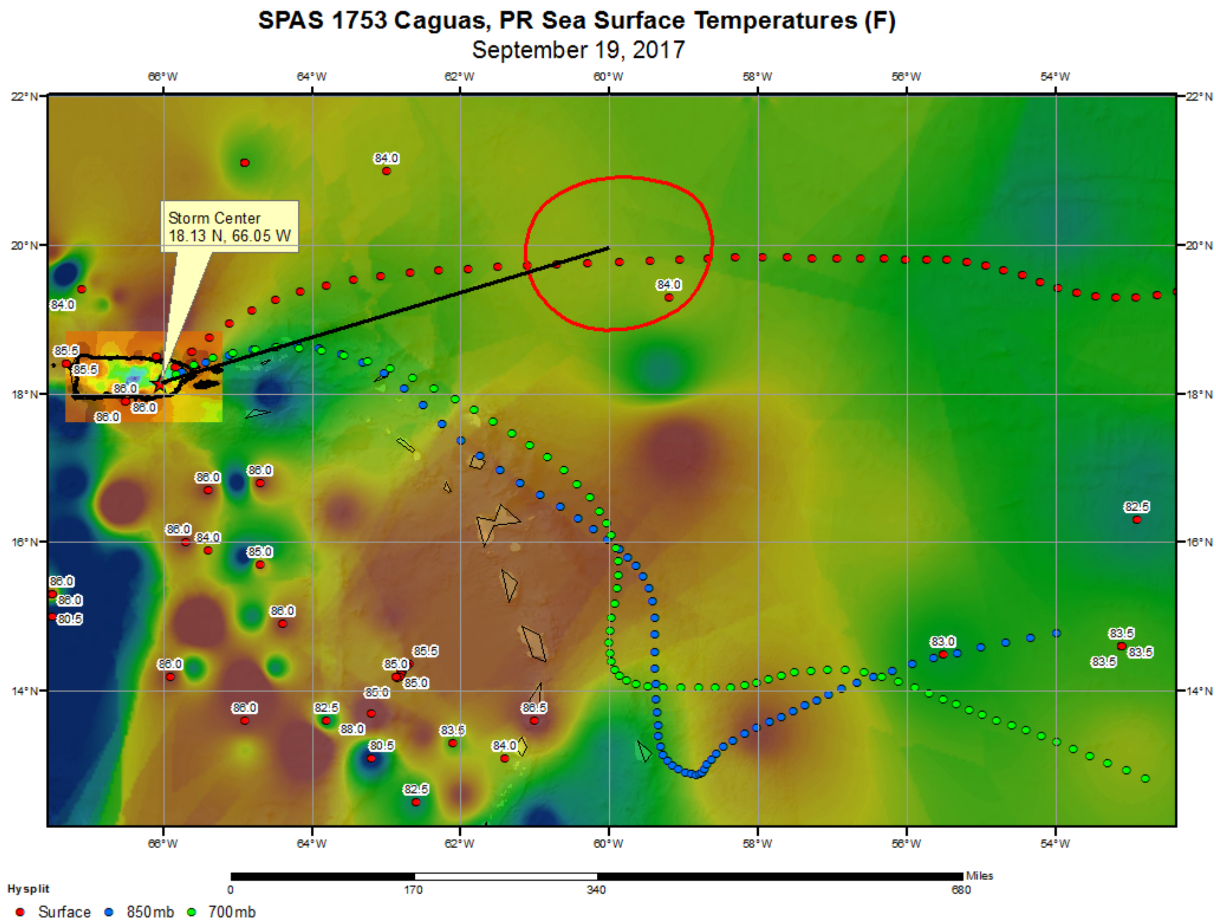


Figure 9.2: Daily SST and moisture source region, along with HYSPLIT trajectory model results for Hurricane Maria September 2017 (SPAS 1753)

In this example, the first decision was whether adequate SST observations were available in regions where moisture could have originated from and been entrained into the Hurricane to produce rainfall over Puerto Rico. SSTs were investigated to determine regions of homogenous temperatures in a region that was appropriate in time and space according to the HYSPLIT trajectories. Several regions were possibilities in this case. Next, the track of the Hurricane and its relation to moisture advection into the storm center was considered. This better matched the surface (red dots) HYSPLIT trajectory. Finally, sensitivity calculations were performed using several couplets of storm representative SST values versus the +2-sigma climatological maximum values to ensure the range of maximizations was within a reasonable range (i.e., greater than 1.00). After the investigations were completed, the storm representative location of 20.0°N and 60.0°W was chosen.

All storms have maximization factors that are greater than 1.00, with an average of around 1.10 in this study (Table 7.1). Lower IPMF generally results when sufficient observational data have captured the moisture source region and when a storm is as close to PMP as can reasonably be expected. In these cases, the values reflect observed SST values in the moisture source region which were near the climatological maximum that could be expected to occur along with maximum storm efficiency. Note that every degree change of the storm representative SST values results in approximately 4-5% change in the maximization factor.

9.3 In-Place Maximization Factor (IPMF) Calculation

Storm maximization is quantified by the IPMF using Equation 3.

$$IPMF = \frac{W_{p,max}}{W_{p,rep}} \qquad \text{Equation 3}$$

where,

$W_{p,max}$	=	precipitable water for maximum dew point (in.)
$W_{p,rep}$	=	precipitable water for representative dew point (in.)

The available precipitable water, Wp, is calculated by determining the precipitable water depth present in the atmospheric column (from sea level to 30,000 feet) and subtracting the precipitable water depth that would not be present in the atmospheric column between sea-level and the surface elevation at the storm location using Equation 4.

$$W_p = W_{p,30,000'} - W_{p,elev} \qquad \text{Equation 4}$$

where,

W_p	=	precipitable water above the storm location (in.)
$W_{p,30,000'}$	=	precipitable water, sea level to 30,000′ elevation (in.)
$W_{p,elev}$	=	precipitable water, sea level to storm surface elevation (in.)

9.4 Transposition Considerations

PMP-type storm events in regions of similar meteorological and topographic settings surrounding a location are a very important part of the historical evidence on which a PMP estimate is based. Since most locations have a limited period of record for rainfall data, the number of extreme storms that have been observed over a location is limited. Historic storms that have been observed within similar meteorological and topographic regions are analyzed and adjusted to provide information describing the storm rainfall as if that storm had occurred over the location being studied.

Transfer of a storm from where it occurred to a location that is meteorologically and topographically similar is called transposition. The underlying assumption is that storms transposed to the location could have occurred under similar meteorological and topographical conditions. To properly relocate such storms, it is necessary to address issues of similarity as they relate to meteorological conditions, moisture availability, and topography. In this study, adjustment factors used in transpositioning of a storm are quantified by using the GTF.

All storms on the final short storm list were moved to all grids covering the island. This was a conservative application but is considered meteorologically accurate given the storm type and synoptic patterns are the same throughout the island. There are of course significant variations in rainfall occurrence, magnitude, and spatial patterns, but these are captured and quantified through the application of the GTF process.

The transposition process is one of the most important aspects of PMP development. This step also contains significant subjectivity as the processes utilized to define transposition limits are difficult to quantify. General guidelines are provided in the HMRs (e.g., HMR 51 Section 2.4.1 and HMR 55A Section 8.2) and previous AWA PMP studies. AWA utilized these guidelines as well as updated procedures including the following:

- Experience and understanding of extreme rainfall processes in the study region and how those factors vary by location, storm type, and season
- Understanding of topographical interactions and how those effect storms by location, storm type, and season
- Use of GTF values as sensitivity
- Spatial continuity of PMP depths
- Comparisons against NOAA Atlas 14 precipitation frequency climatology
- Discussions with others involved in the study

An important aspect of this study was the involvement of the PREPA, USBR, and AECOM in evaluating and reviewing individual storm transposition limits and development of the final short storm list. AWA received input in helping to define the overall transposition limits used in the study. Once an individual storm was determined to be transpositionable to the island, the resulting GTF values were reviewed during the review meetings.

Although somewhat subjective, decisions to adjust the transposition limits for a storm were based on the understanding of the meteorology which resulted in the storm event, similarity of topography between the two locations, access to moisture source, seasonality of occurrence by storm type, and comparison to other similar storm events. The PMP Version Log provided in Appendix D provides the numerous iterations of PMP development and the various transposition limit adjustments that were applied to storms during the PMP development process.

For all storms, the IPMF does not change during this process. The GTF changes as a storm is moved from its original location to a new location. The spatial variations in the GTF were useful in making decisions on transposition limits for many storms. As described previously, values larger than 1.50 for a storm's maximization factor exceed limits that would no longer produce the same storm as the originally observed event. In these situations, changing a storm by this amount is likely also changing the original storm characteristics so that it can no longer be considered the same storm at the new location. The same concept applies to the GTF. GTF values greater than 1.50 indicate that transposition limits have most likely been exceeded. In addition, a lower limit of 0.50 was applied for the same reason, but this inherently affects a much more limited set of storms and regions. Therefore, storms were re-evaluated for transpositionability in regions which results in a GTF greater than 1.50.

9.5 Geographic Transposition Factor (GTF) Calculation

The GTF is calculated by taking the ratio of transposed 100-year rainfall to the in-place 100-year rainfall.

$$GTF = \frac{R_t}{R_s} \qquad \text{Equation 6}$$

where,

R_t = climatological 100-year rainfall depth at the target location

R_s = climatological 100-year rainfall depth at the source storm center

The in-place climatological precipitation (R_s) was determined for the SPAS-analyzed total storm maximum rainfall center location. The corresponding transposed climatological precipitation (R_t) was taken at each target grid point in the basin. The 100-year precipitation was used for each transposed location and also for the in-place location for storm centers. The 24-hour precipitation frequency climatologies are used for both the General/Easterly-wave and Tropical storm types. NOAA Atlas 14 volume 3 (Bonnin et al., 2008) provided the source of the 100-year precipitation depths for all target grid points and storm centers over Puerto Rico. For the storm centers outside Puerto Rico (Jamaica, Dominican Republic, St. Martin, and St. Lucia), site-specific 100-year precipitation estimates were calculated following the same methodologies utilized to derive NOAA Atlas 14 precipitation frequency depths.

9.6 Total Adjustment Factor (TAF)

The TAF is a combination of the total moisture and terrain differences on the SPAS analyzed rainfall after being maximized in-place and then transpositioned to the target grid point.

$$TAF_{xhr} = P_{xhr} \times IPMF \times GTF \qquad \text{(from Equation 1)}$$

The TAF, along with the other storm adjustment factors, is exported and stored within the storm's adjustment factor feature class to be accessed by the GIS PMP tool as described in the following section.

10. Development of PMP Values

10.1 PMP Calculation Process

To calculate PMP, the TAF for each storm must be applied to the storm's SPAS analyzed DAD value for the area size and duration of interest to yield a total adjusted rainfall value. The storm's total adjusted rainfall value is then compared with the adjusted rainfall values of every storm in the database transposable to the target grid point. The largest adjusted rainfall depth becomes the PMP for that point at a given duration. This process must be repeated for each of the grid cells intersecting the input basin for each applicable duration and storm type. The gridded PMP is averaged over the basin of interest to derive a basin average and the accumulated PMP depths are temporally and spatially distributed.

A GIS-based PMP calculation tool was developed to automate the PMP calculation process. The PMP tool is a Python scripted tool that runs from a Toolbox in the ArcGIS desktop environment. The tool accepts a basin polygon feature or features as input and provides gridded, basin average, and temporally distributed PMP depths as output. These PMP output elements can be used with hydrologic runoff modeling simulations for PMF calculations. Full documentation of the PMP tool usage and structure is found in Appendix G. The PMP tool provides depths at an areal-average for a given basin area size. This area can be overwritten with a specific user-defined area-size within the tool dialogue. The PMP tool can be used to calculate PMP depths for the 1-, 2-, 3-, 4-, 5-, 6-, 12-, 24-, 48-, 72-, 96-, and 120-hour durations.

10.1.1 Spatial Application Considerations

It is important to remember that the initial gridded PMP depths are spatially distributed closely following the precipitation frequency patterns. This represents one possible spatial scenario and is generally considered a conservative application. However, other spatial patterns are possible that may result in a more severe flood response. For smaller basins, generally less than 50-square miles, the choice of spatial pattern should make little difference. However, for larger basins, this may have a significant impact. Because the number of possible spatial patterns for all of the basins covered in the study is almost unlimited, it is not feasible to test all possible spatial patterns as part of the GIS tool output. Instead, if alternative spatial patterns are needed, it is suggested that observed storm patterns be utilized.

It is recommended that other spatial patterns be tested for larger basins where the location of the storm center and associated accumulation patterns could produce an outcome that is significantly different than the default spatial pattern. In all cases, it is important that the spatial pattern adhere to the caveat of producing a "physically possible" representation of the PMP design storm. This can be done by redistributing the basin average PMP depths for a given basin to follow the observed storm patterns.

10.1.2 Sample Calculations

The following sections provide sample calculations for the storm adjustment factors for the Hurricane Eloise center of Dos Bocas, Puerto Rico of September 1975 (SPAS 1760) tropical storm event when transposed to 18.0583°N, 66.0333°W (grid point ID #3,282). The target location is about 50 miles west-southwest of the storm center, inside the Patillas Dam basin (Figure 10.1). Table 10.1 highlights the adjustment factors in the Storm Adjustment Factor feature class table for the storm at this target grid point location.

Table 10.1 – Dos Bocas, Puerto Rico September 1975 Adjustment Factors for Sample Target Location

ID	STORM	LON	LAT	ELEV	IPMF	GTF	TAF
3282	1760_1	-66.0333	18.0583	485.6	1.09	1.17	1.27

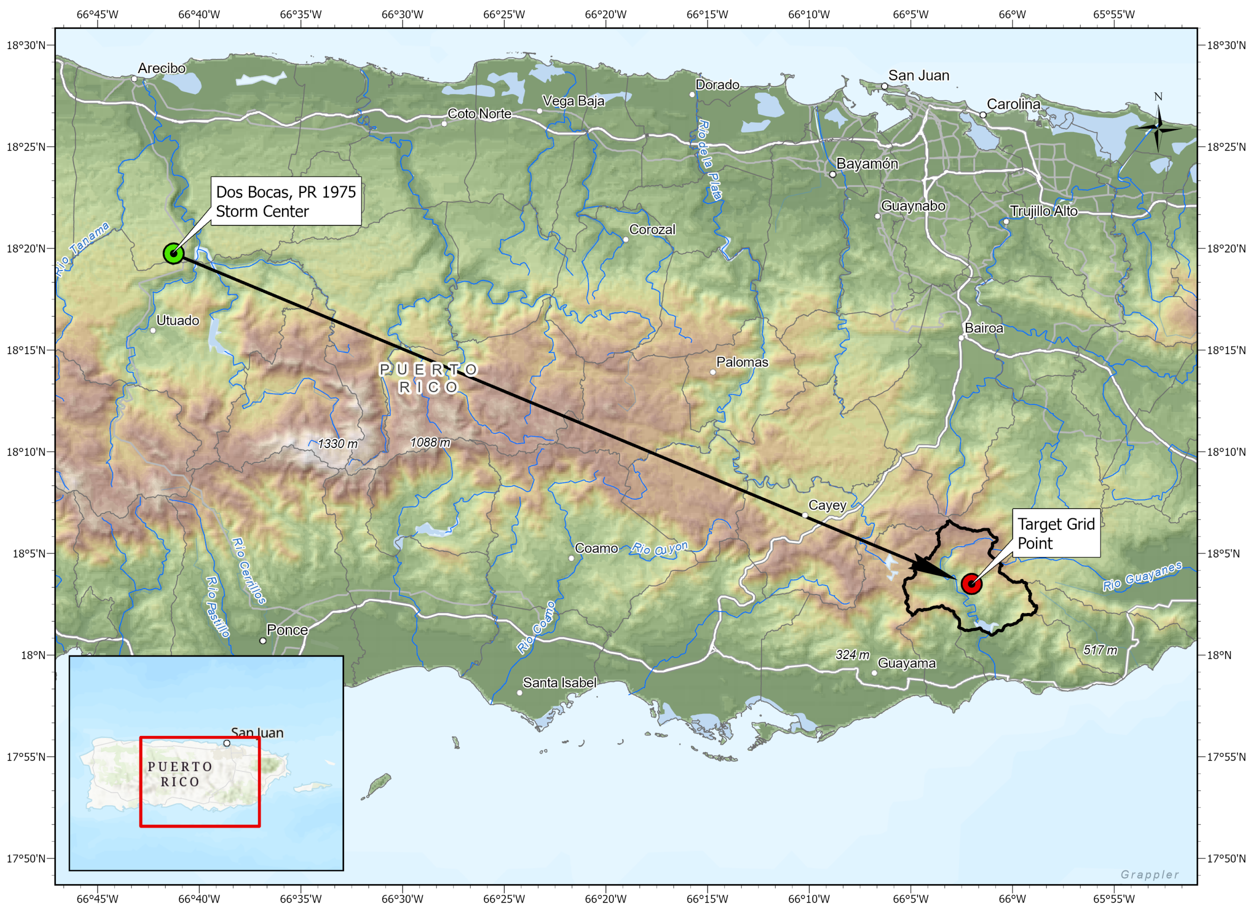


Figure 10.1: Sample transposition of Dos Bocas, PR, 1975 (SPAS 1760) to grid point #3,282

10.1.3 Sample Precipitable Water Calculation

Using the storm representative dew point temperature and storm center elevation as input, the precipitable water lookup table returns the depth, in inches, used in Equation 4. The storm representative +2σ SST is 83.5°F at the storm representative location 255 miles northeast of the storm center (see Appendix F for the detailed storm maximization and analysis information). The storm center elevation is approximated at 1,108 feet at the storm center location of 18.329°N, 66.688°W. The storm representative available moisture ($W_{p,\ rep}$) is calculated using Equation 4:

$$W_{p,rep} = W(@83.5°)_{p,30,000'} - W(@83.5°)_{p,1,100'}$$

or,

$$W_{p,rep} = 4.21" - 0.35"$$

$$W_{p,rep} = 3.86"$$

The mid-September storm was assigned a temporal transposition date of September 15th. The September climatological 100-year maximum 24-hour average +2σ SST at the storm representative SST location is 85.46°F. The monthly temperature is rounded to the nearest ½ degree Fahrenheit to a climatological maximum +2σ SST of 85.5°. The in-place climatological maximum available moisture ($W_{p,\ max}$) is calculated.

$$W_{p,max} = W(@85.5°)_{p,30,000'} - W(@85.5°)_{p,1,100'}$$

$$W_{p,max} = 4.58" - 0.39"$$

$$W_{p,max} = 4.19"$$

10.1.4 Sample IPMF Calculation

In-place storm maximization is applied for each storm event using the methodology described in Section 9.1. Storm maximization is quantified by the IPMF using Equation 4:

$$IPMF = \frac{W_{p,max}}{W_{p,rep}}$$

$$IPMF = \frac{4.19"}{3.86"}$$

$$IPMF = 1.085$$

10.1.5 Sample GTF Calculation

The ratio of the 100-year 24-hour climatological precipitation depth at the target grid point #3,282 location to the storm center was evaluated to determine the storm's GTF at the target location. The 24-hour rainfall depth (R_t) of 17.19" was extracted at the grid point #3,282 location from the 100-year 24-hour NOAA Atlas 14 precipitation frequency climatology.

$$R_t = 17.19"$$

Similarly, the 24-hour rainfall depth (R_s) of 14.70" was extracted at the storm center location from the 100-year 24-hour NOAA Atlas 14 precipitation frequency climatology.

$$R_s = 14.70"$$

Equation 6 provides the climatological precipitation ratio to determine the GTF.

$$GTF = \frac{R_t}{R_s}$$

$$GTF = \frac{17.19"}{14.70"}$$

$$GTF = 1.17"$$

The GTF at grid #3,282 is 1.17, or a 17% rainfall increase from the storm center location due to the geographic effects captured within the precipitation climatology. The GTF is then considered to be a temporal constant for the spatial transposition between that specific source/target grid point pair, for that storm only, and can be applied to the other durations for that storm.

10.1.6 Sample TAF Calculation

$$TAF = IPMF \times GTF \qquad \text{(from Equation 1)}$$

$$TAF = 1.085 \times 1.17$$

$$TAF = 1.27$$

The TAF for the Dos Bocas, 1975 event when moved to the grid point at 35.0°N, 92.0°W, representing storm maximization and transposition, is 1.27. This is an overall increase of 27% from the original SPAS analyzed in-place rainfall. The TAF can then be applied to the storm's rainfall depth taken from the SPAS depth-area-duration table, at the basin area-size, to calculate the total adjusted rainfall. If the total adjusted rainfall is greater than the depth for all other transposable storms, it becomes the PMP depth at that grid point for that duration.

11. PMP Results

The PMP tool provides basin-specific PMP based on the area-size of the basin. For each storm type analyzed, the tool provides output in ESRI file geodatabase format. The output also includes a basin average PMP table. If the sub-basin average option was checked, the tool provides averages for each sub-basin. The depths are calculated for the area-size of the basin, so no further areal reduction should be applied. The tool also provides a point feature class containing PMP depths and controlling storms listed by SPAS ID and storm name, date, and location, in addition to gridded raster PMP depth files. There are also temporally distributed accumulated rainfall tables for each temporal pattern applied to the basin described in Section 12. A basin average PMP depth-duration chart in the .png image format is also included in the output folder. An example depth-duration chart is shown in Figure 11.1. All output tables are exported to a 'csv' folder in comma delimited text format. Detailed output information is included in the PMP tool documentation in Appendix G.

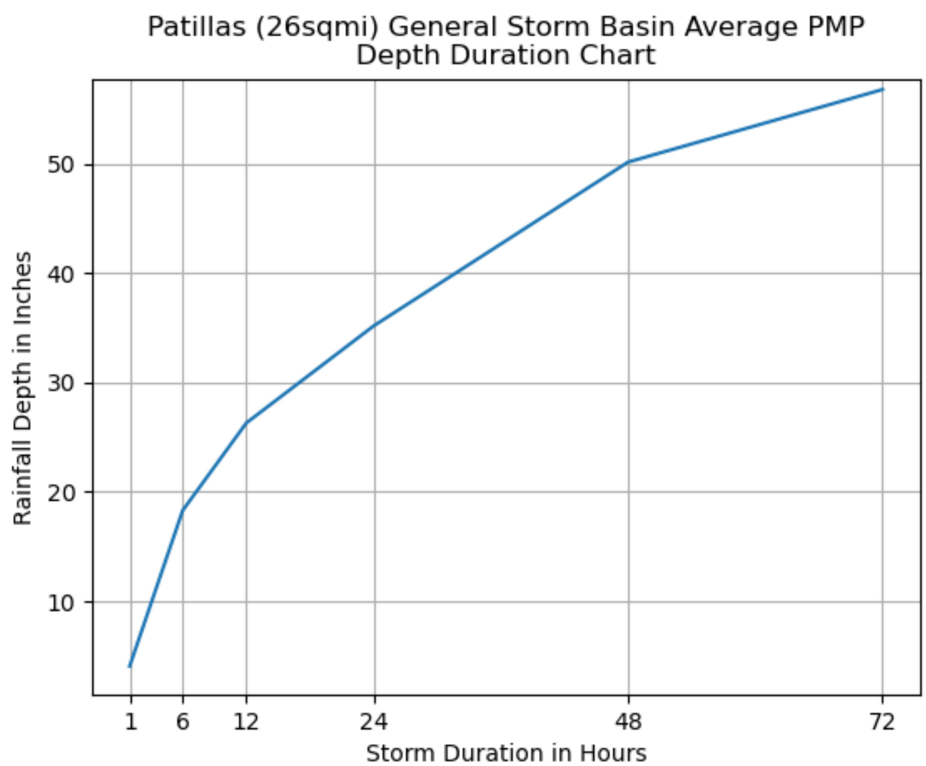


Figure 11.1: Sample PMP depth-duration chart for Patillas Dam provided in output folder

Gridded PMP depths were calculated for the entire study region at various index area-sizes for several durations as a visualization aid. The maps in Appendix A illustrate the depths for 1-, 25-, and 100-square mile area sizes for local storm PMP at 1-, 6-, 24-, 72-, and 120-hour durations for general/easterly wave and tropical storm PMP. Figure 11.2-11.7 provide example PMP maps across the island for 1-, 24- and 72-hour durations for the general storm/easterly wave and tropical storm types.

Figures 11.8-11.13 provide the depth-duration charts for 1-, 25-, and 100-sqare miles for two example location, Patillas Dam on the southeast portion of the island and Guajataca Dam on the northwestern portion of the island. These show how all the storms used in the study compared to each other at various areas sizes after all adjustments were applied (refer to Table 7.1 for the storm type). This is important for PMP development and ensuring the depths are reasonable and appropriately envelope the largest adjusted depths from several storms.

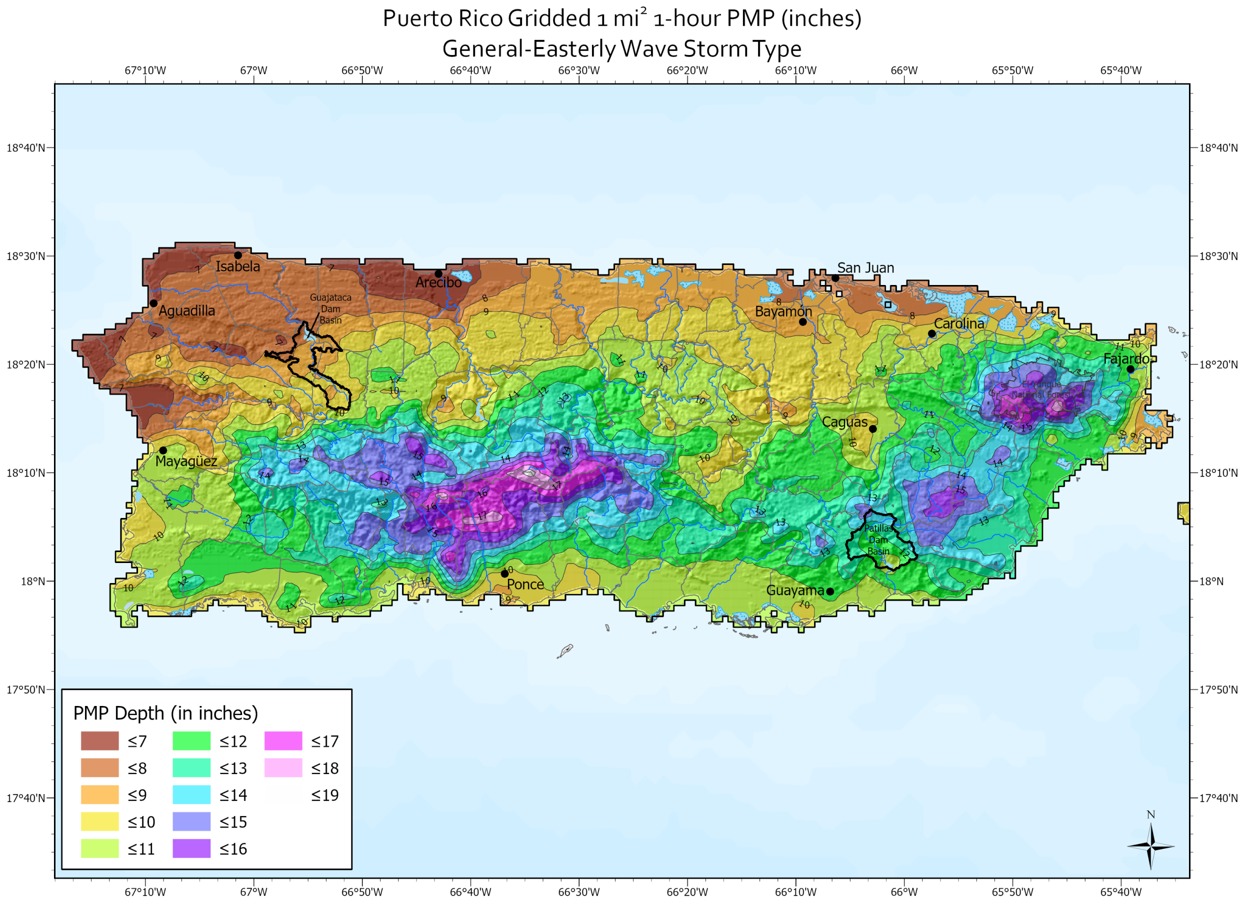


Figure 11.2: PMP depths for the general storm/easterly wave storm type at 1-square mile 1-hour across Puerto Rico

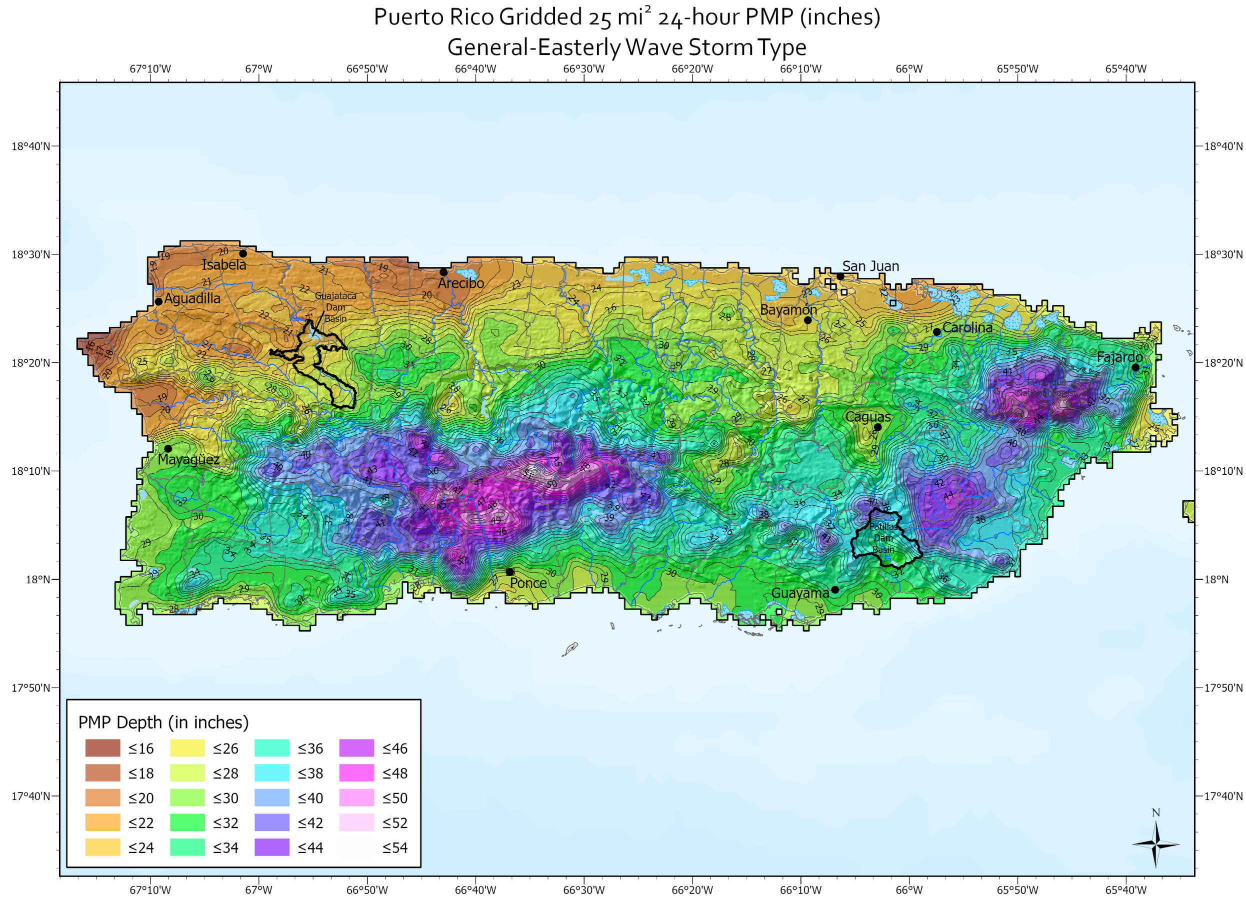


Figure 11.3: PMP depths for the general storm/easterly wave storm type at 25-square miles 24-hours across Puerto Rico

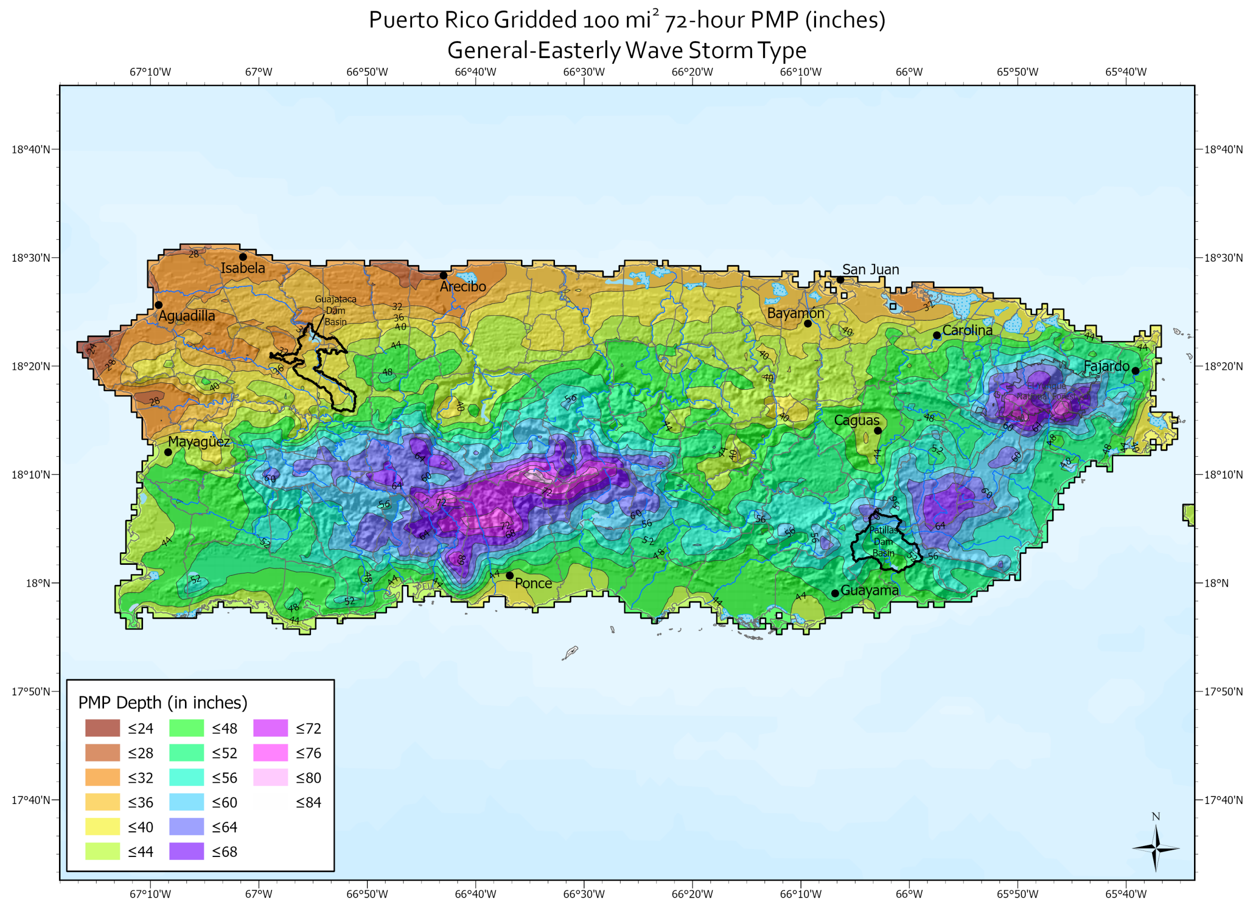


Figure 11.4: PMP depths for the general storm/easterly wave storm type at 100-square miles 72-hours across Puerto Rico

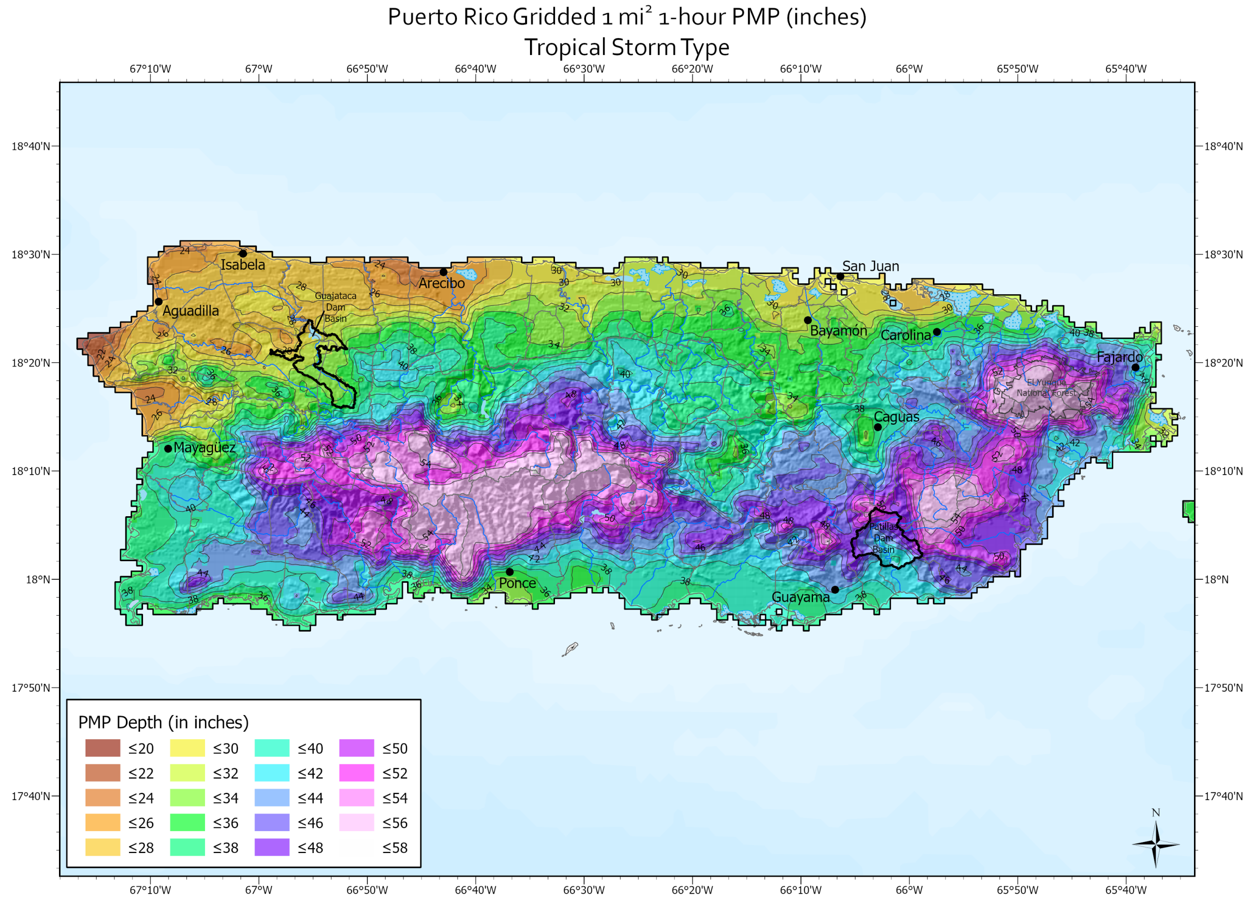


Figure 11.5: PMP depths for the tropical storm type at 1-square mile 1-hour across Puerto Rico

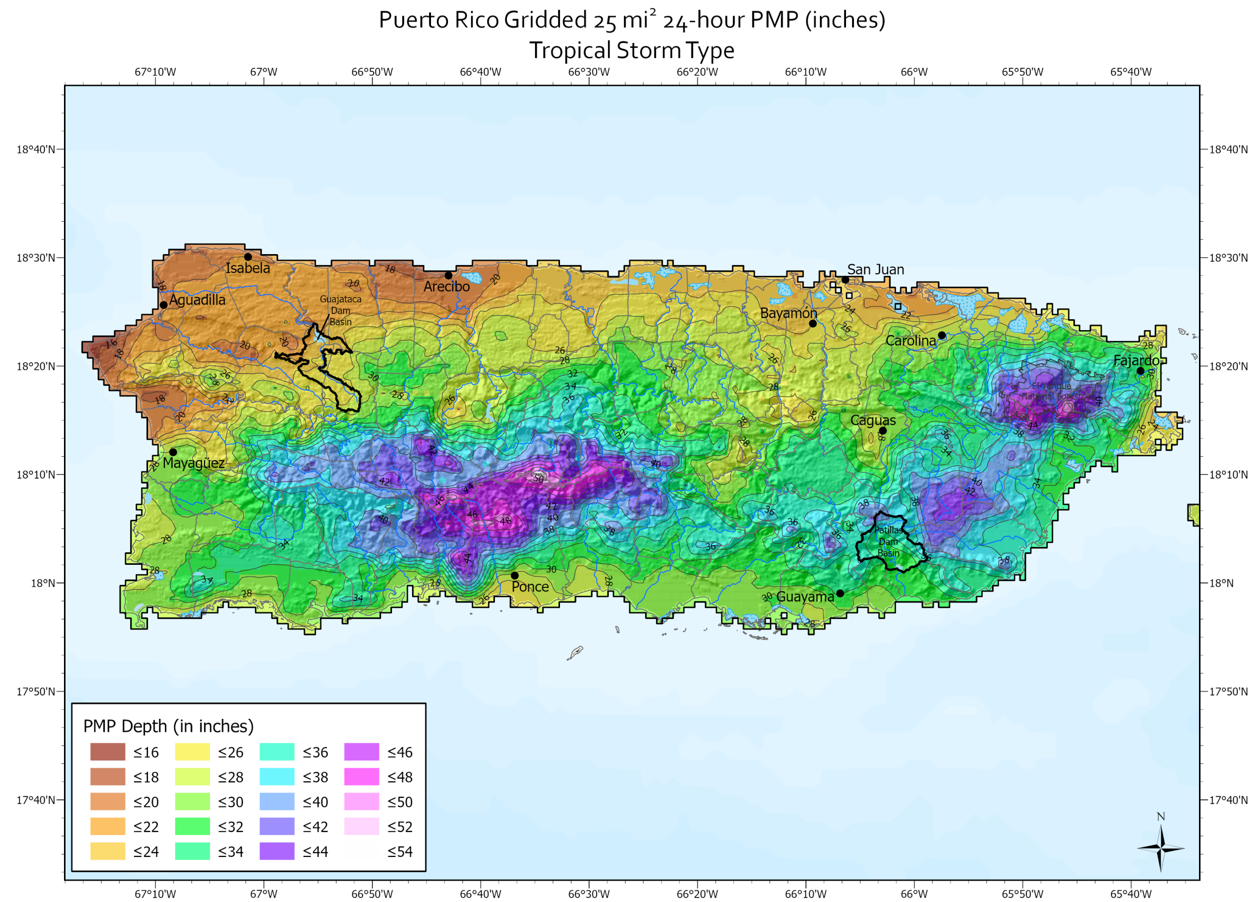


Figure 11.6: PMP depths for the tropical storm type at 25-square miles 24-hours across Puerto Rico

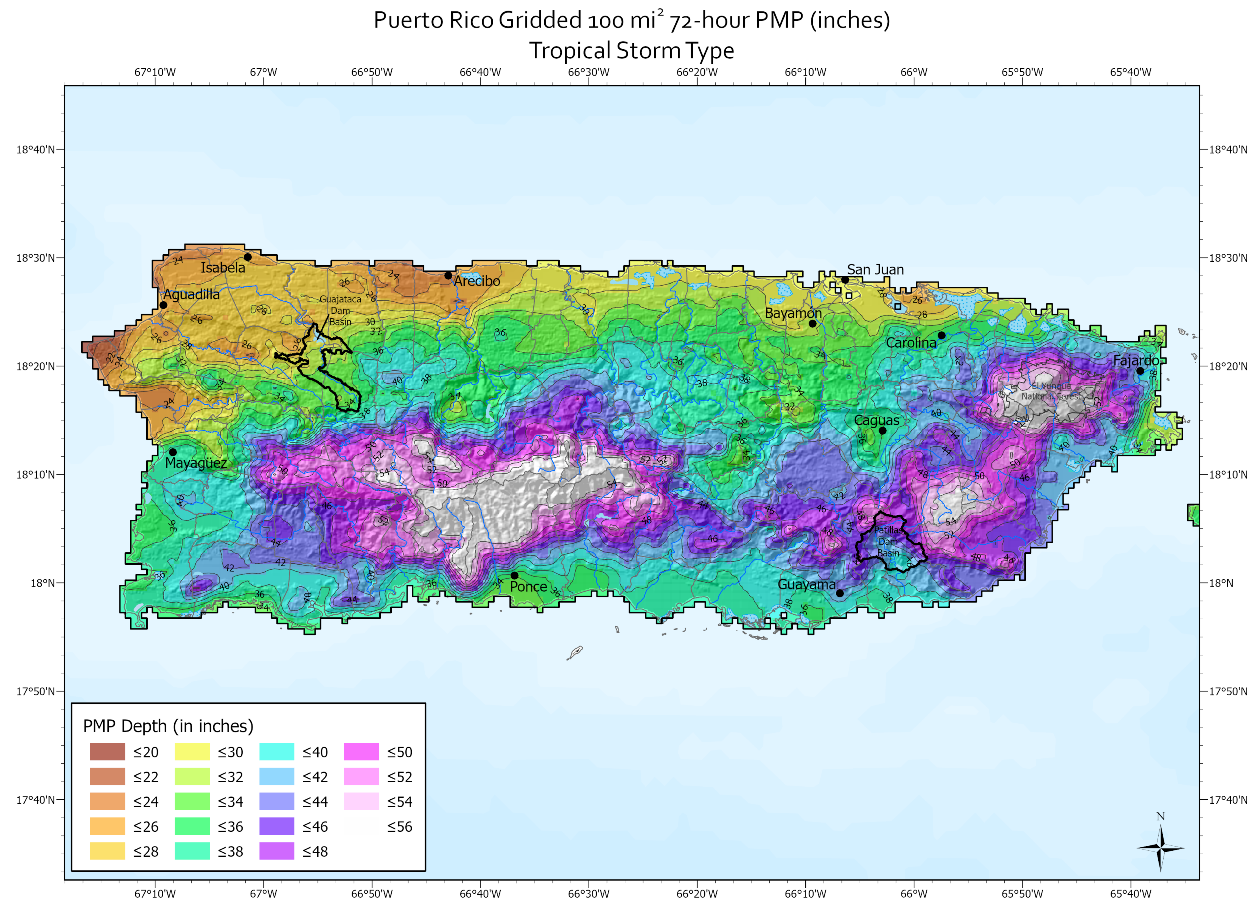


Figure 11.7: PMP depths for the tropical storm type at 100-square miles 72-hours across Puerto Rico

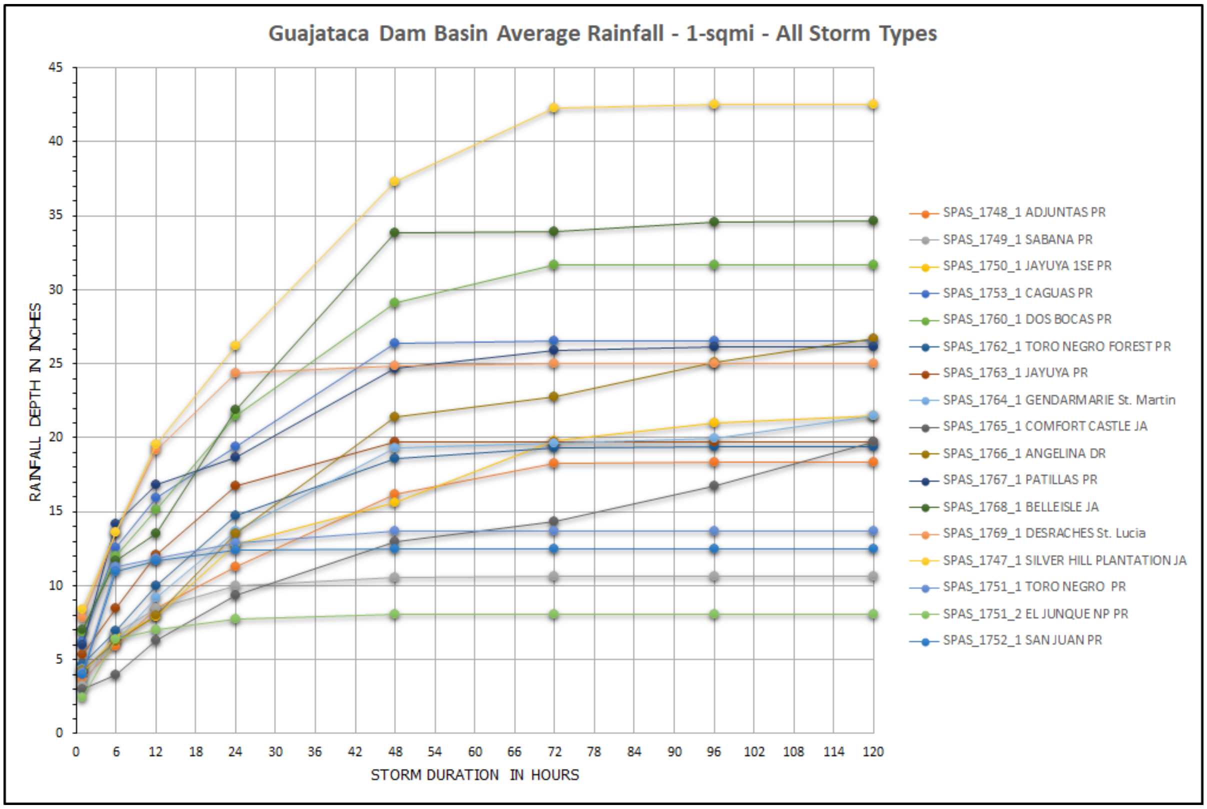


Figure 11.8: PMP depth-duration chart for 1-square mile using the Guajataca Dam location

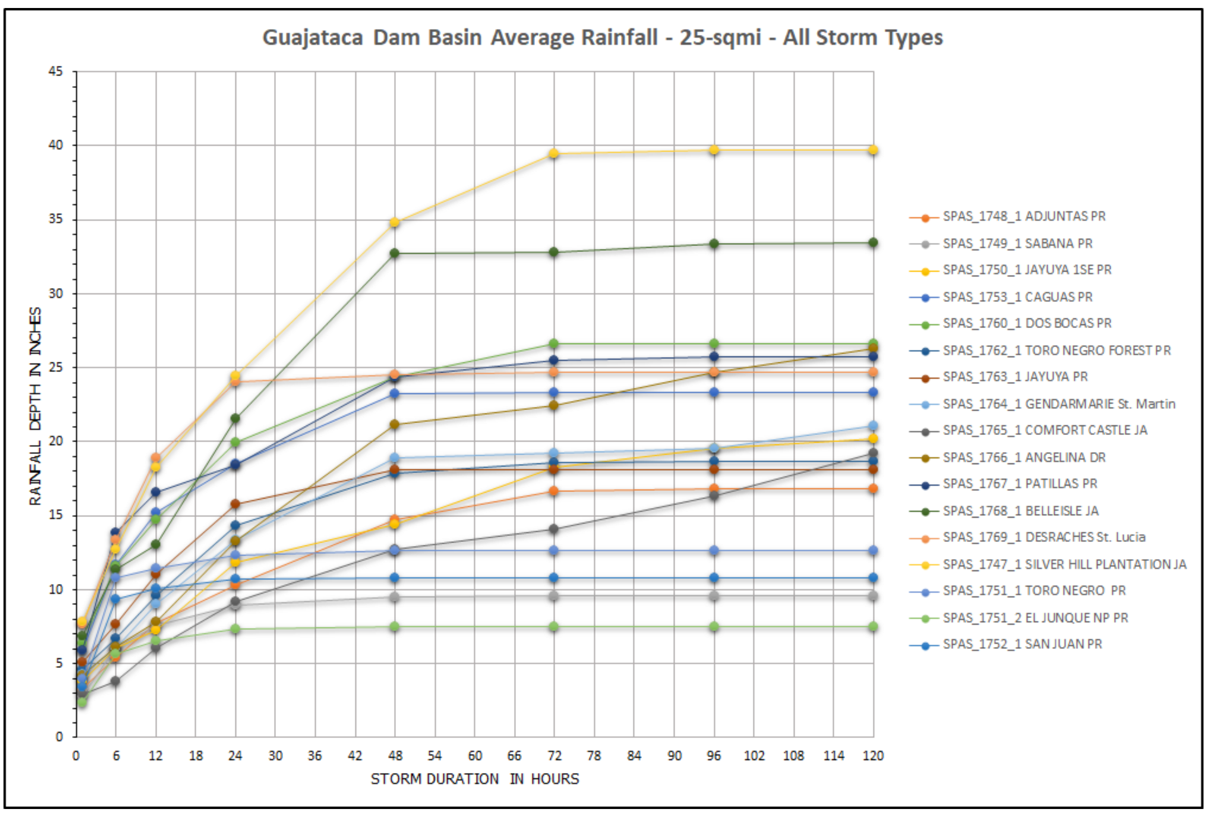


Figure 11.9: PMP depth-duration chart for 25-square mile using the Guajataca Dam location

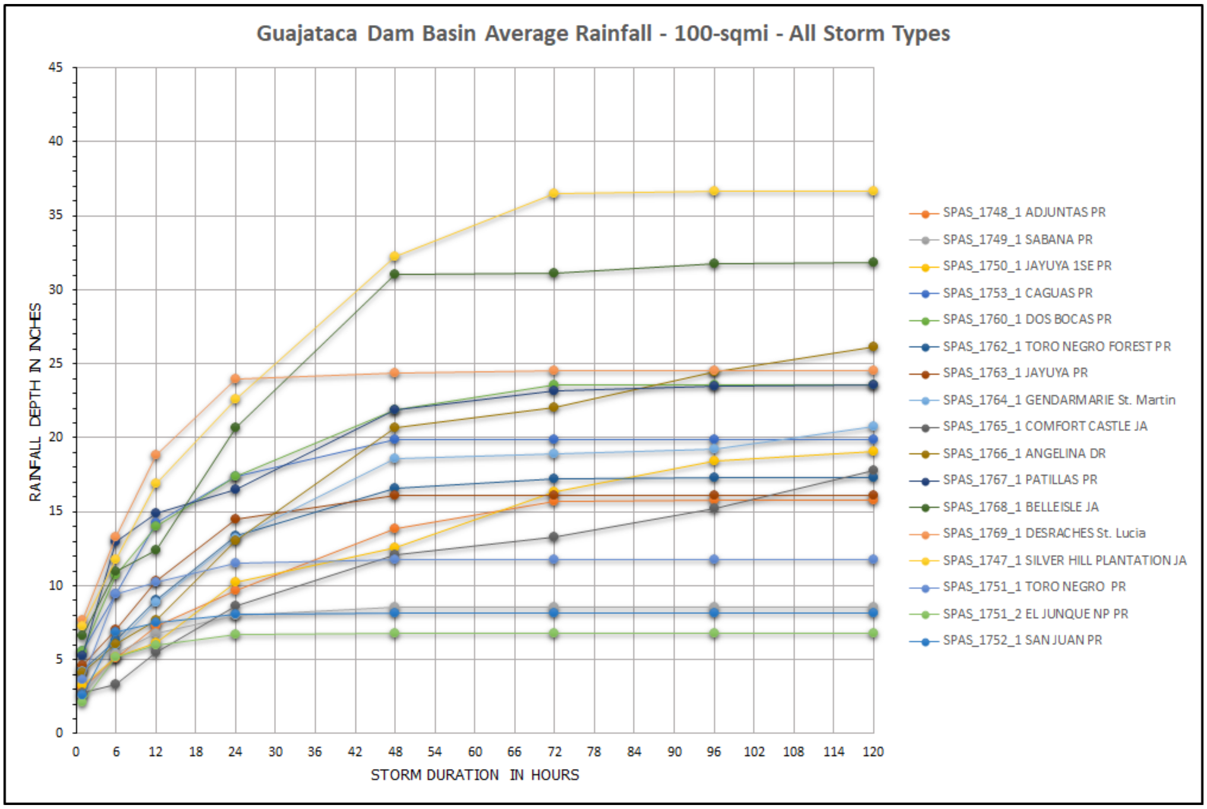


Figure 11.10: PMP depth-duration chart for 100-square mile using the Guajataca Dam location

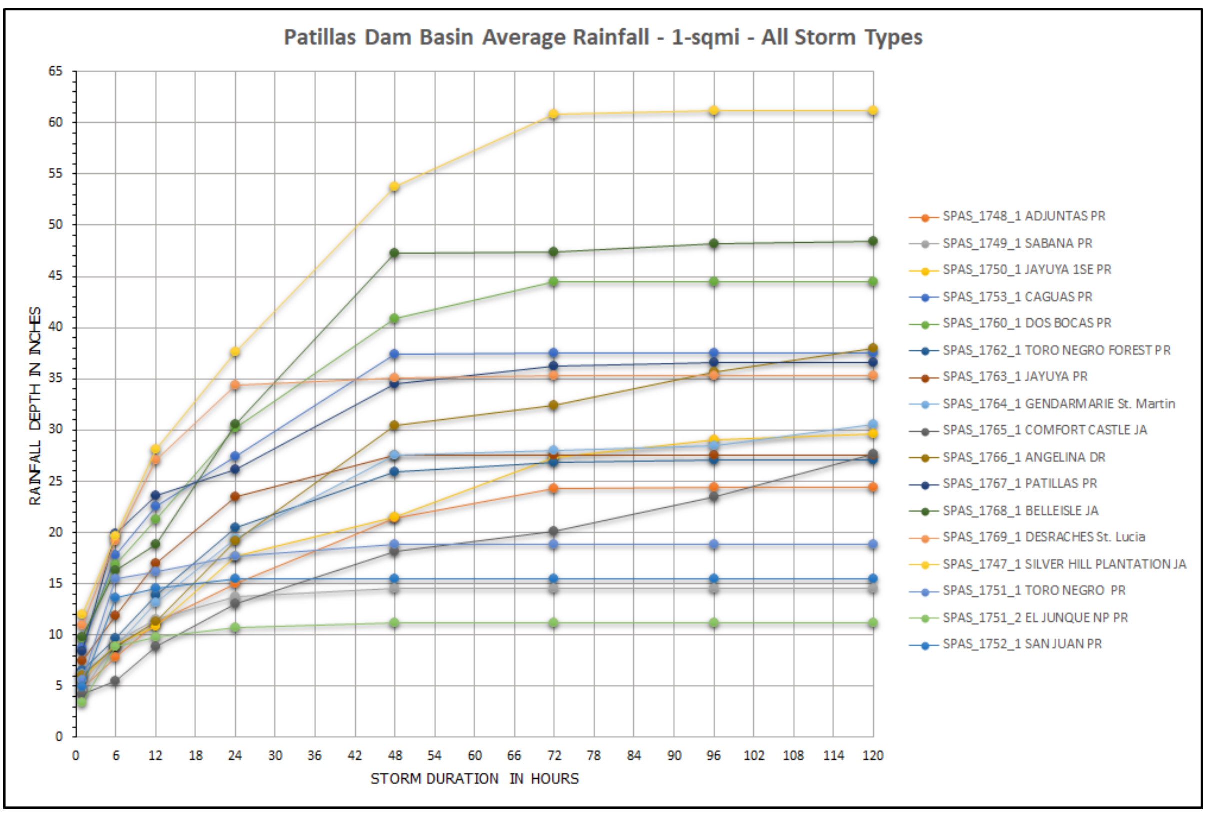


Figure 11.11: PMP depth-duration chart for 1-square mile using the Patillas Dam location

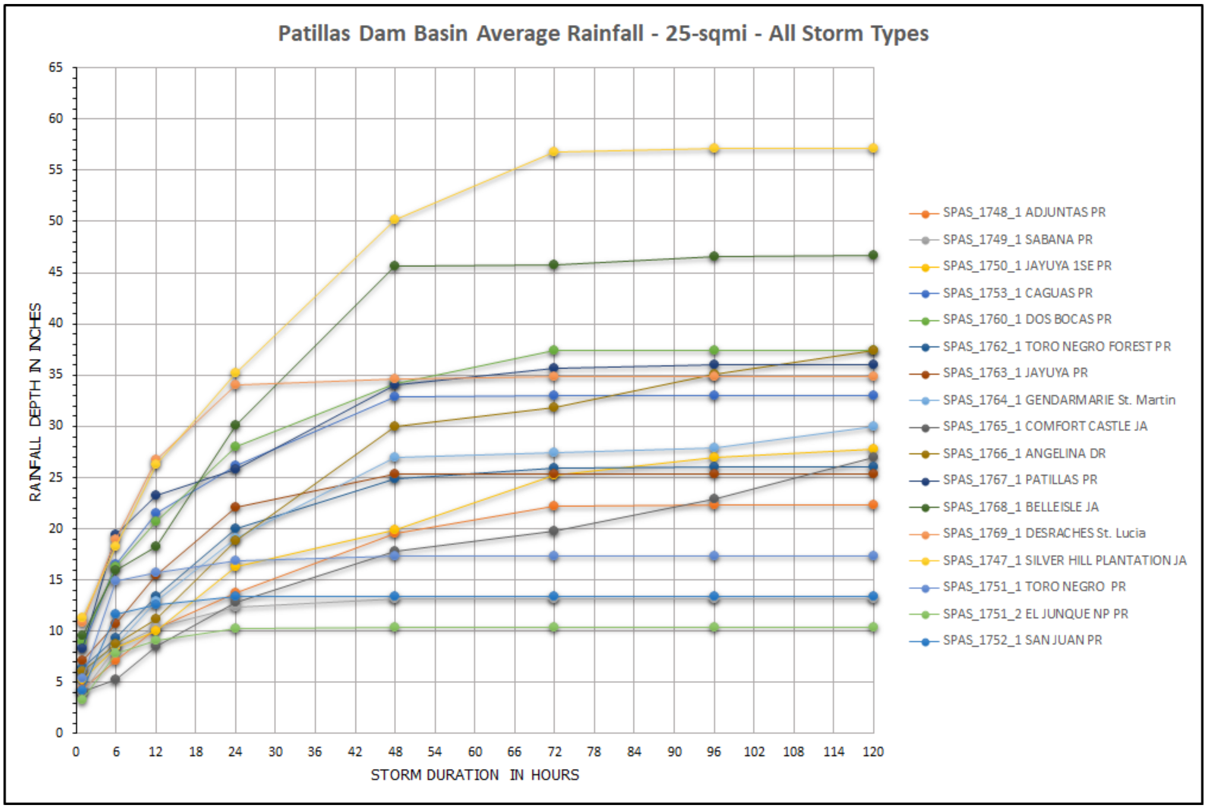


Figure 11.12: PMP depth-duration chart for 25-square mile using the Patillas Dam location

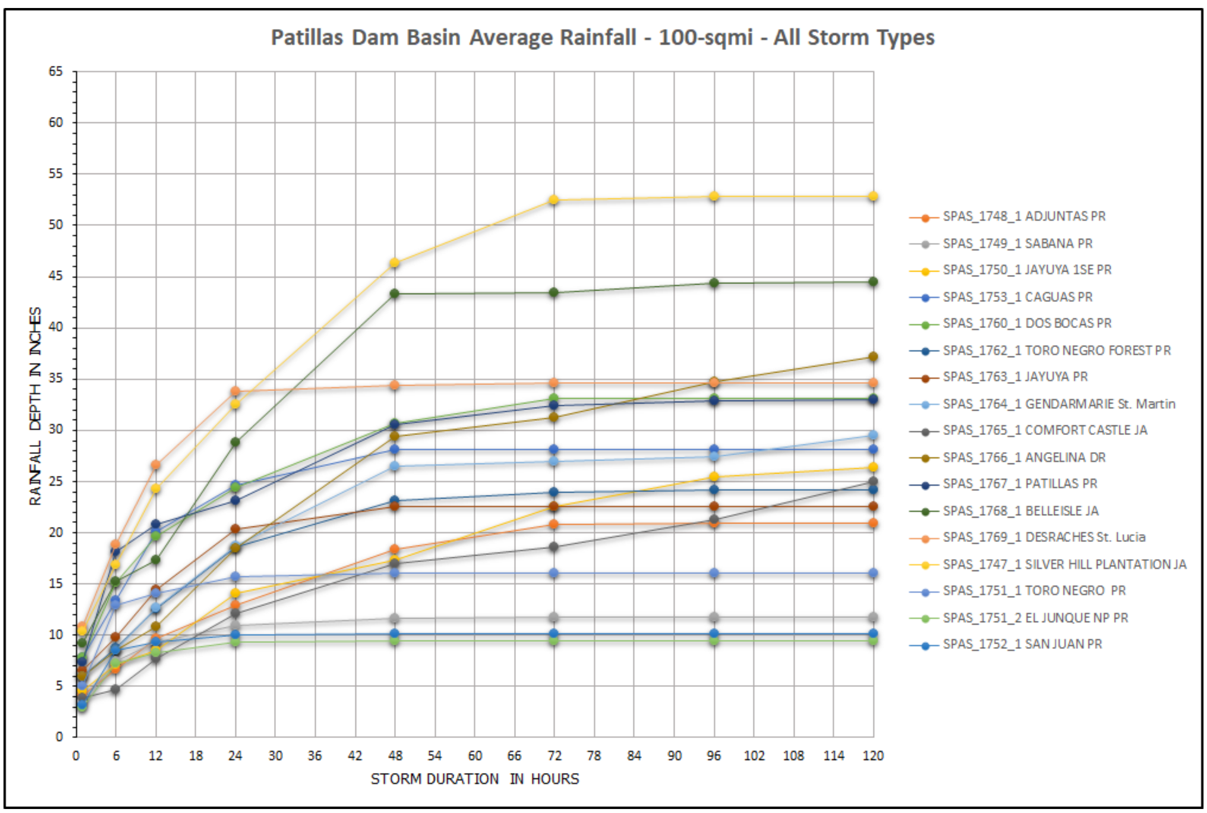


Figure 11.13: PMP depth-duration chart for 100-square mile using the Patillas Dam location

12. Development of Temporal Distribution for Use in Runoff Modeling

Temporal patterns to be utilized with the PMP depths were taken from the tropical and general storms patterns developed from relevant storms that were part of the Oklahoma-Arkansas-Louisiana-Mississippi Regional PMP study (Kappel et al., 2019). A detailed description of the temporal pattern development process and data are provided in Section 12 of that study for reference[1]. The temporal patterns developed in that study are similar to those that occur in Puerto Rico. Therefore, those same patterns were applied here. In addition to those temporal patterns, the actual accumulation patterns associated with each controlling storm from this study are included in the PMP tool. This allows for numerous meteorically possible temporal patterns to be applied for a given basin. The goal of applying various temporal patterns is to ensure that the worst-case, yet physically possible PMF is modeled for any basin.

12.1 Alternating Block (Critically Stacked) Pattern

Based on HMR 52 (Hansen et al., 1982) procedures and the USBR Flood Hydrology Manual (Cudworth, 1989) a "critically stacked" temporal distribution was developed. The critically stacked temporal pattern yields a significantly different distribution than actual distributions associated with the storms used for PMP development in this study and in similar analysis of adjacent PMP studies (e.g., Louisiana and Mississippi). The critically stacked pattern imbeds PMP depths by duration within one another, i.e., the one-hour PMP is imbedded within the 3-hour, which is imbedded within the 6-hour, which is in turn imbedded in the 24-hour PMP. Figure 12.1 provides a graphical illustration of a critically stacked pattern. The critically stacked procedure has often been chosen in the past for runoff modeling because it represents a worst-case design scenario and ensures PMP depths are equaled at all durations.

[1] Documentation can be found at each of the four state's dam safety web sites, this link is from the Oklahoma Water Resources Board dam safety web site, https://www.owrb.ok.gov/damsafety/pdf/2019RegionalPMPStudy.pdf

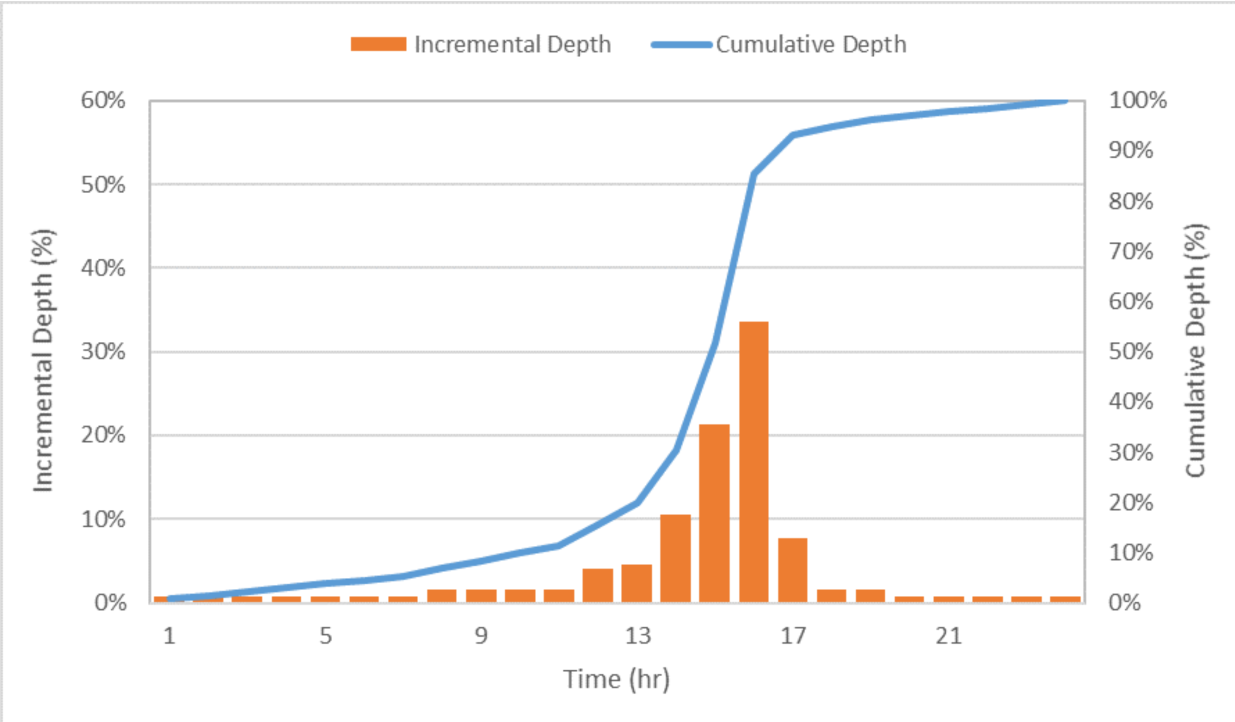


Figure 12.1: Graphical representation of the critically stacked temporal pattern

12.2 PMP Tool Temporal Distributions

The PMP tool optionally applies the various available temporal patterns to the basin average PMP for potential use in runoff modeling for dam safety analysis. The available distributions include 10th and 90th percentile Huff Curves, Synthetic Curve, Critically Stacked pattern, and the individual controlling storm-based accumulation patterns. The tool provides tabular PMP depth accumulations in geodatabase table format as well as comma separated text format tables.

The Huff Curves and Synthetic Curve are distributed to 15-minute time steps over a 72-hour duration. For the Huff and Synthetic Curves, the first 24-hour period is the second largest 24-hour PMP evenly distributed. The second 24-hour period are distributed according to the Huff and Synthetic patterns described above. The final 24-hour period is the third largest 24-hour PMP evenly distributed. For each storm type, there will be an output table containing three temporal distribution columns: 72-hour 10th Percentile, 72-hour 90th Percentile, and 72-hour Synthetic.

The Critically Stacked patten is also distributed to 15-minute time steps over a 72-hour duration. For each storm type, there will be an output table containing the PMP distributed to the Critically Stacked temporal pattern.

The controlling storm-based temporal patterns are distributed to 60-minute time steps over both 6-hour and 24-hour durations. The user is reminded to consult the appropriate dam safety regulator on the accepted application of these distributions for runoff modeling. For each storm type, and for both the 6-hour and 24-hour durations, there will be an output table containing a temporal distribution column for each controlling storm at that duration. Due to the nature of the gridded analysis, there may be more than one controlling storm, and resulting temporal pattern, for a given duration. The user is reminded to consult the appropriate dam safety regulator on the accepted application of these distributions for runoff modeling.

13. Sensitivities and Comparisons

In the process of deriving PMP values, various assumptions and meteorological judgments were made within the framework of state-of-the-practice processes. These parameters and derived values are standard to the PMP development process; however, it is of interest to assess the sensitivity of PMP values to assumptions that were made and to the variability of input parameter values.

PMP depths and intermediate data produced for this study were rigorously evaluated throughout the process. ArcGIS was used as a visual and numerical evaluation tool to assess gridded values to ensure they fell within acceptable ranges and met test criteria. Several iterations of maps were produced as visual aids to help identify potential issues with calculations, transposition limits, DAD values, or storm adjustment values. The maps also helped to define storm characteristics and transposition limits, as discussed previously. Over the entire PMP analysis domain, different storms control PMP depths at different locations for a given duration and area size.

In some instances, a discontinuity of PMP depths between adjacent grid point locations resulted. In Puerto Rico, this occurs because of the highly variable topography and precipitation frequency climatologies. Therefore, different storms are affecting adjacent grid points and may result in a shift in values over a short distance. It is important to note that these discontinuities make little difference in the overall basin average PMP depths as applied for hydrologic analysis purposes for most basins. The discontinuities are only seen when analyzing data at the highest resolution (e.g., individual grid points). Any significant discontinuities would potentially have the most significant effect for small basins where there are a small number of grid points representing the drainage. In those instances, each grid point value would have an exaggerated effect on the basin average PMP.

13.1 Comparison of PMP Depths to TP42

This study employs a variety of improved methods when compared to previous HMR studies. These methods include:

- A far more robust storm analysis system with a higher temporal and spatial resolution
- Improved SST and precipitation climatologies that provide an increased ability to maximize and transpose storms
- Gridded PMP calculations which result in higher spatial and temporal resolutions
- Explicit evaluation of topographic effects
- A greatly expanded storm record

AWA digitized the PMP depths from figures provided in TP 42 to allow for PMP comparisons with TP 42 on a gridded basis. A gridded percent change was calculated for the area-sizes and durations common with the TP42 index PMP maps. The maximum PMP depth from this study were used for comparisons to account for differences in storm typing between the PMP from this study and TP42. Figures 13.1-13.2 provide the average percent change (negative is a reduction) from TP42 across each of the transposition regions analyzed. Note there is a significant range of variation, with some locations producing higher PMP depths (generally in the areas of significant topography) and other locations showing significant reductions (lower coastal regions that were hatched in TP42 applied a lower limit everywhere because of lack of data and other information).

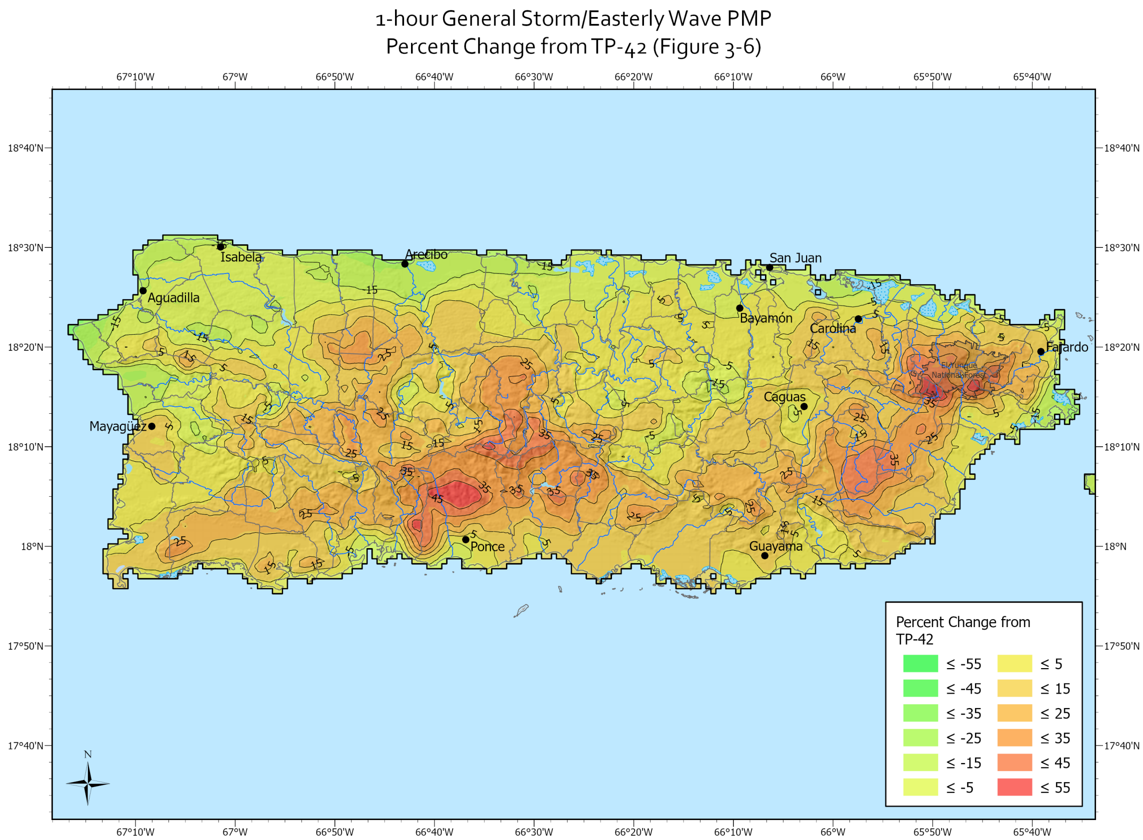


Figure 13.1: Percent difference from TP42 1-hour PMP against Puerto Rico 1-hour PMP

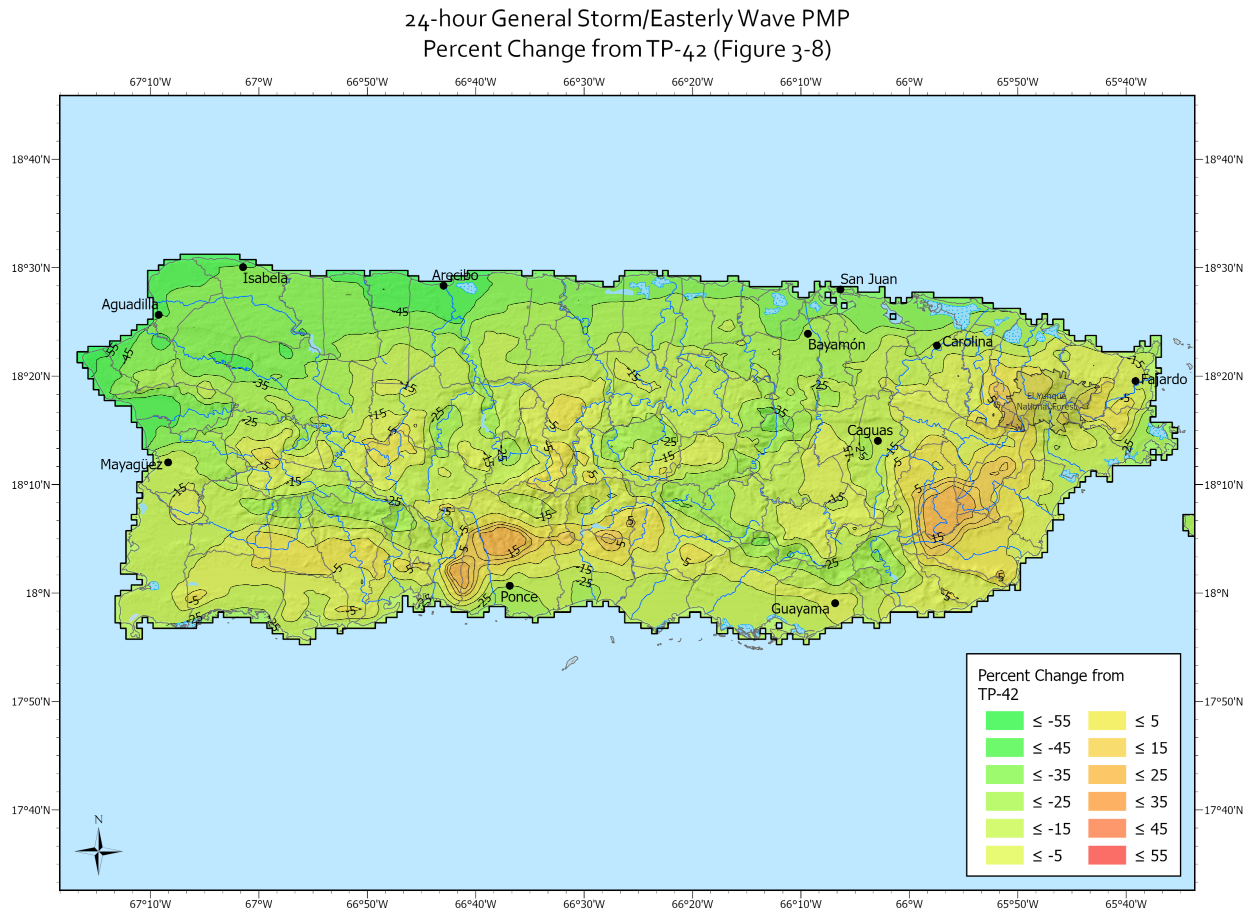


Figure 13.2: Percent change from TP 42 24-hour PMP to Puerto Rico 24-hour PMP

13.2 Comparison of PMP Values with Precipitation Frequency

The ratio of the PMP to 100-year return period precipitation amounts is generally expected to range between two and four, with values as low as 1.7 and as high as 5.5 for regions east of 117°W found in HMR 57 and HMR 59 (Hansen et al., 1994; Corrigan et al., 1999). Further, as stated in HMR 59 "…*the comparison indicates that larger ratios are in lower elevations where short-duration, convective precipitation dominates, and smaller ratios in higher elevations where general storm, long duration precipitation is prevalent*" (Corrigan et al., 1999, p. 207).

For this study, the maximum 24-hour 1-square mile PMP was compared directly to the 100-year 24-hour rainfall-only values on a grid-by-grid basis for the entire analysis domain using a GIS. The comparison was presented as a ratio of PMP to 100-year rainfall, and it was determined for each grid point. Figures 13.3-13.4 illustrate the PMP to 100-year rainfall ratios for 24-hour general storm and 24-hour tropical storm PMP respectively. The PMP to 100-year return period rainfall ratios vary from 2.0 to 2.5, after combining storm types. The values are in reasonable proportion expected for the study area and demonstrate the PMP values are at appropriately rare levels.

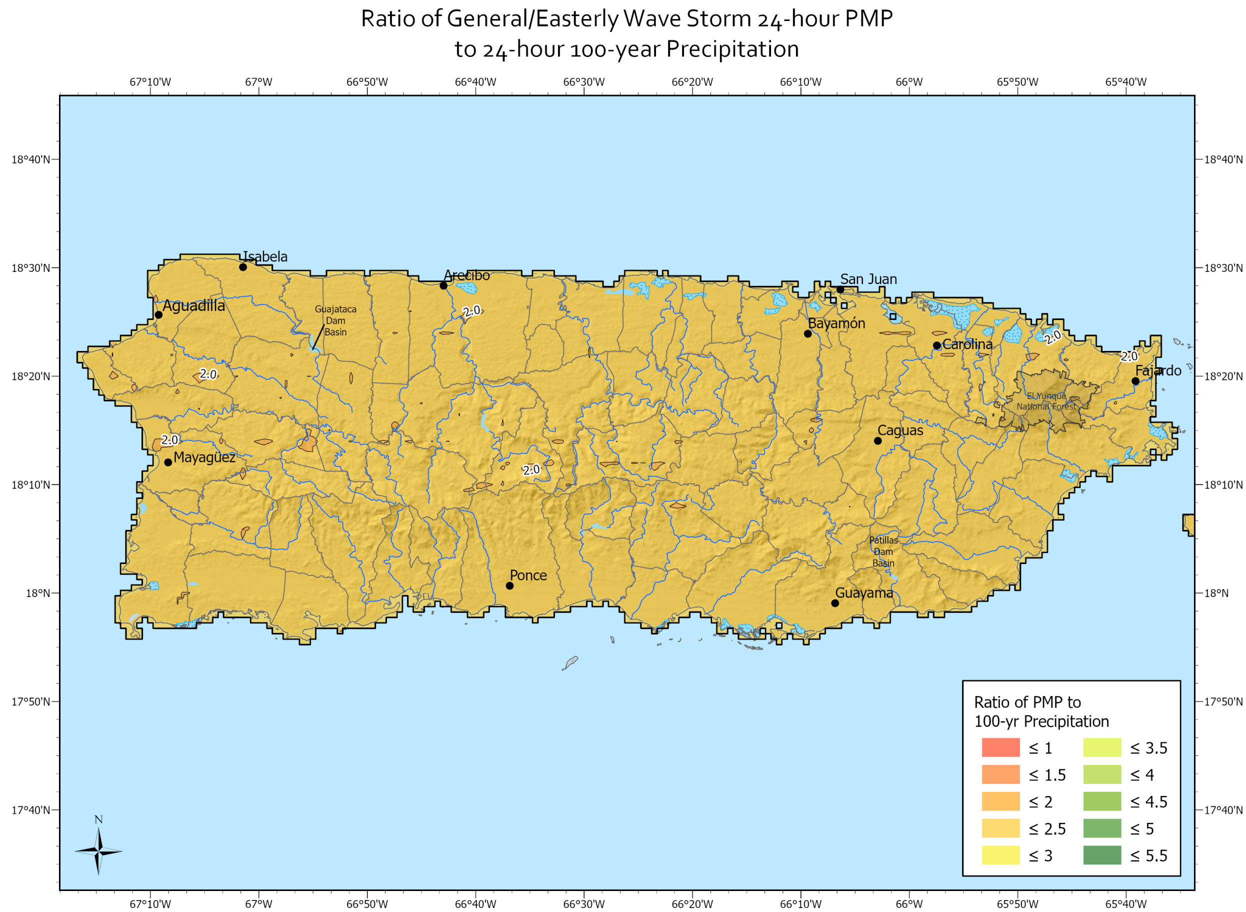


Figure 13.3: Ratio of 24-hour 1-square mile general storm PMP to 100-year precipitation

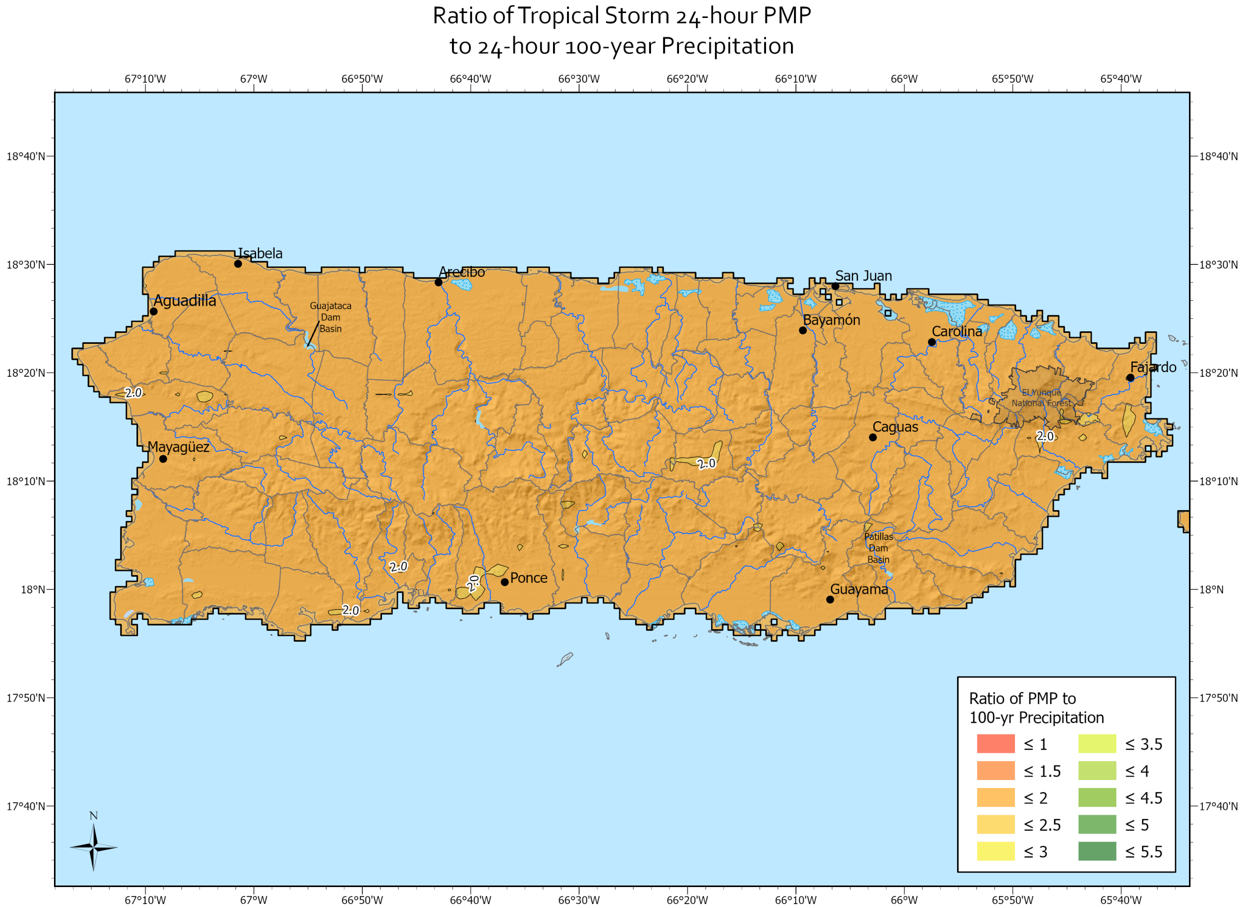


Figure 13.4: Ratio of 24-hour 1-square mile tropical storm PMP to 100-year precipitation

14. Uncertainty and Limitations

14.1 Sensitivity of Parameters

In the process of deriving PMP depths, various assumptions and meteorological judgments were made. Additionally, various parameters and derived values were used in the calculations, which are standard to the PMP development process. It is of interest to assess the sensitivity of PMP depths to assumptions that were made and to the variability of parameter values.

14.2 Saturated Storm Atmosphere

The PMP development process assumes that the atmosphere is saturated from the ground through the top of the atmosphere (30,000 feet or 300mb) for both the observed storm events and the hypothetical PMP storms. Applying this assumption, a moist pseudo-adiabatic temperature profiles is applied to both the historic storms and the hypothetical PMP storm to quantify the amount of atmospheric moisture available to the observed storm and the maximized (PMP storm). Initial evaluations of this assumption in the EPRI Michigan/Wisconsin PMP study (Tomlinson, 1993) and the Blenheim Gilboa study (Tomlinson et al., 2008) indicated that historic storm atmospheric profiles were generally not entirely saturated and contained somewhat less precipitable water than was assumed in the PMP procedure. This was also shown by Chen and Bradley (2006). More detailed evaluations were completed by Alaya et al., (2018) utilizing an uncertainty analysis and modeling framework. This again demonstrated that the assumption of a fully saturated atmosphere in conjunction with maximum storm efficiency may not be possible. However, recent work on a PMP storm, Hurricane Harvey utilized high resolution atmospheric profiles and showed that the atmosphere was fully saturated (Fernandez-Caban et al., 2019). This demonstrates that this assumption is possible when associated with a PMP-type storm event.

What is used in the storm maximization process during PMP development is the ratio of precipitable water associated with each storm. If the precipitable water values for each storm were both slightly overestimated, the ratio of these values would be essentially unchanged.

For example, consider the case where instead of a historic storm with a storm representative dew point of 70°F degrees having 2.25 inches of precipitable water assuming a saturated atmosphere, it had 90% of that value or about 2.02 inches. The PMP procedure assumed the same type of storm with similar atmospheric characteristics for the maximized storm but with a higher dew point, say 76°F degrees. The maximized storm, having similar atmospheric conditions, would have about 2.69 inches of precipitable water instead of the 2.99 inches associated with a saturated atmosphere with a dew point of 76°F degrees. The maximization factor computed using the assumed saturated atmospheric values would be 2.99″/2.25″ = 1.33. If both storms were about 90% saturated instead, the maximization factor would be 2.69″/2.02″ = 1.33. Therefore, potential inaccuracy of assuming saturated atmospheres (whereas the atmospheres may be somewhat less than saturated) should have a minimal impact on storm maximization and subsequent PMP calculations.

14.3 Maximum Storm Efficiency

The assumption is made that if a sufficient period of record is available for rainfall observations, at least a few storms would have been observed that attained or came close to attaining the maximum efficiency possible in nature for converting atmospheric moisture to rainfall for regions with similar climates and topography. The further assumption is made that if additional atmospheric moisture had been available, the storm would have maintained the same efficiency for converting atmospheric moisture to rainfall. The ratio of the maximized rainfall amounts to actual rainfall amounts would be the same as the ratio of precipitable water in the atmosphere associated with each storm.

There are two issues to be considered. First relates to the assumption that a storm has a rainfall efficiency close to the maximum possible. Unfortunately, state-of-the-science in meteorology does not support a theoretical evaluation of storm efficiency. However, if the period of record is considered (generally over 100 years), along with the extended geographic region with transpositionable storms, it is accepted that there should have been at least one storm with dynamics that approached the maximum efficiency for rainfall production.

The other issue pertains to the assumption that storm efficiency does not change if additional atmospheric moisture is available. Storm dynamics could potentially become more efficient or possibly less efficient depending on the interaction of cloud microphysical processes with the storm dynamics. Offsetting effects could indeed lead to the storm efficiency remaining essentially unchanged. For the present, the assumption of no change in storm efficiency seems acceptable.

14.4 Storm Representative SST and Maximum SST

The maximization factor depends on the determination of storm representative SST values, along with maximum historical SST values. In the case for Puerto Rico, SST were used as a surrogate for dew points in all maximization factor calculations. The magnitude of the maximization factor varies depending on the values used for the storm representative SST and the maximum SST. Holding all other variables constant, the maximization factor is smaller for higher storm representative SSTs as well as for lower maximum SST values. Likewise, larger maximization factors result from the use of lower storm representative SSTs and/or higher maximum SSTs. The magnitude of the change in the maximization factor varies depending on the SST values. For the range of SST values used in most PMP studies, the maximization factor for a particular storm will change about 5% for every 1°F difference between the storm representative and maximum SST values. The same sensitivity applies to the transposition factor, with about a 5% change for every 1°F change in either the in-place maximum SST or the transposition maximum SST.

14.5 Judgment and Effect on PMP

During the process of PMP development several decisions were based on meteorological judgment. These include the following:

- Storms used for PMP development
- Storm representative dew point value and location

- Storm transposition limits
- Use of precipitation frequency climatologies to represent differences in precipitation processes (including orographic effects) between two locations

Each of these processes were discussed and evaluated during the PMP development process internally within AWA and with the Steering Committee and others involved in the project. The resulting PMP depths derived as part of the PMP development reflect the most defensible judgments based on the data available and current scientific understanding. The PMP results represent reproducible, reasonable, and appropriately conservative estimates for use in the development of the PMF for high hazard and critical infrastructure.

14.6 Limitation of Applying the PMP Depths

This study focused on the development of PMP depths from 1-hour through 120-hours at areas sizes from 1-square mile through the entire island that would be applied to a single basin and its sub basins. In addition, no detailed analysis was completed regarding antecedent or subsequent precipitation or hydrologic conditions, and these should be investigated separately and on an individual basin level.

Finally, PMP depths from this study are to be applied to a single basin or region assuming that PMP occurs in a worst-case, yet meteorologically possible scenario over a given location. Therefore, if concurrent precipitation depths are needed over adjoining or nearby locations, PMP should not be applied concurrently. Instead, other methods should be utilized to derive the concurrent rainfall. Examples would include running the PMP tool again at the overall larger area size and subtracting out the PMP volume over the basin of interest, utilizing precipitation frequency climatologies and appropriate areal reduction factors to distribute concurrent rainfall outside of the PMP region, or utilizing observed rainfall patterns to inform the spatial extent of a giving synoptic weather pattern. In all cases, care should be taken to not violate the requirement of the PMP design storm being “physically possible”.

14.7 Climate Change and PMP

The effect of climate change on the number and intensity of extreme rainfall events is unknown as of the date of this report. With a warming of the atmosphere, there can potentially be an increase in the available atmospheric moisture for storms to convert to rainfall (e.g., Kunkel et al., 2013). However, storm dynamics play a significant role in that conversion process and the result of a warming climate on storm dynamics is not well understood. A warmer climate may lead to a change in the frequency of storms and/or a change in the intensity of storms, but there is no definitive evidence to indicate the trend or the magnitude of potential changes regarding PMP level rainfall (Herath et al., 2018). Significant research has been completed on hurricane climatology and intensity, with no definitive conclusions for the Atlantic basin (e.g., Wallace et al., 2021; Emanuel 2021; Lin et al., 2020; Knutson et al., 2020; Knutson et al., 2019; Emanuel 2021; Walsh et al., 2015). AWA has completed several detailed analyses of climate change projections on PMP (Kappel et al., 2020). These results are inconclusive and often show no significant change, even under the most aggressive future emission scenarios. Based on these discussions, this study has continued the practice of assuming no climate change, as climate trends are not considered when preparing PMP estimates (WMO 2009, Section 1.1.1).

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