Appendix K
Temporal Analysis Memo

AECOM
1255 Broad Street, Suite 201
Clifton, NJ 07013
Tel: 973-883-8500
aecom.com

Project name:
NJDEP Flood Risk Project - Update the New Jersey Probably Maximum Precipitation (PMP)

Project ref:
Additional Storm Analysis / Temporal Distribution

To:
Joseph Ruggeri, P.E., CFM, NJDEP;
Clint Oman, NJDEP;
Russell Ray, NJDEP;
Sarah Hatala, NJDEP

From:
Anping Zheng
Bhavin Gandhi

Date:
June 23, 2022, Final Revision December 9, 2024

CC:
FILE

Technical Memorandum

Subject: Additional Analyses on Temporal Distributions Using NJ PMP Tool in Runoff Modeling

Introduction

AECOM evaluated and tested the proposed NJ PMP tool developed by Applied Weather Associates (AWA) and presented its findings to NJDEP in May 2021. As a result, AWA revised the tool and released a newer version for further testing. AECOM, in coordination with AWA and NJDEP, conducted additional analyses of selected storms to determine appropriate temporal PMP distributions for New Jersey using the available hydrologic models for a limited number of dams. AECOM conducted an initial analysis and provided the results to NJDEP on August 6, 2021. Following review, NJDEP requested further analyses/testing to include additional typical dams (1 large and 2 small dams) and various temporal distributions. Following discussions with NJDEP and AWA on September 27 and November 19, 2021, the analysis approach was agreed to on December 1, 2021. A draft memorandum was prepared by AECOM in June 2022 to summarize the preliminary results of these additional analyses. Following thorough discussions among NJDEP, AECOM and AWA, it was determined that the NJ PMP Tool should be slightly adjusted to allow exceedances of any interim PMP depths by a 5% buffer, which was implemented in the final version of the tool in May 2024. The intent of adding this buffer is to ensure that all basin hydrologic analyses have a sufficient number of temporal patterns to apply to the PMP depths and that the resulting PMF presents a reasonable outcome for the given location.

This memorandum presents the results of these additional analyses on five selected dams across New Jersey where the temporal patterns were investigated and the 5% buffer was applied. These evaluations were completed using HEC-HMS modeling for the PMF condition with various temporal distributions as outlined in the Scope of Work (SOW) as well as recommendations of appropriate PMP depths and temporal distributions for use in the runoff modeling. **Table 1** lists five dams selected for testing.

Table 1 – List of Five Dams for Testing of Temporal Distributions in Runoff Modeling

Dam Name (NID #)	Drainage Area (square miles)	City / Township	Physiographic Province
Shongum Lake Dam (NJ00351)	3.11	Randolph	Highlands
Orange Reservoir Dam (NJ00361)	4.65	West Orange	Piedmont
Englishtown Lake Dam (NJ00619)	6.71	Manalapan	Outer Coastal Plain
Duhernal Lake Dam (NJ00381)	95.10	Old Bridge	Inner Coastal Plain
Lake Lenape Dam (NJ00450)	205.00	Hamilton	Outer Coastal Plain

Table 2 presents a list of temporal distributions evaluated in this study for various storm types and durations generated by the NJ PMP Tool along with several conventional rainfall distributions. Brief descriptions for some of the commonly used temporal distributions in this study are presented below.

Table 2 – List of Temporal Distributions Evaluated in Runoff Modeling

Task #	Storm Duration	Storm Type	Temporal Distribution
Task 1	6 Hr and 12 Hr	Local, General, Tropical Storms	Controlling Storm from NJ PMP Tool with Associated Temporal Distribution
		Local Storm	Duration Event with NJ PMP Tool 90th Percentile & 10th Percentile Rainfall / Distribution
	24 Hr	Local, General, Tropical Storms	Controlling Storm from NJ PMP Tool with Associated Temporal Distribution
			Duration Event with NJ PMP Tool 90th Percentile & 10th Percentile Rainfall / Distribution
	72 Hr	General and Tropical Storms	Controlling Storm from NJ PMP Tool with Associated Temporal Distribution
			Duration Event with NJ PMP Tool 90th Percentile & 10th Percentile Rainfall / Distribution
	6, 12, 24 and 72 Hr	Conventional Method	HMR-51 rainfall depth using HMR 52 rainfall distribution (Critically Stacked)
			HMR-51 rainfall depth using Army Corps' EM rainfall distribution
			HMR-51 rainfall depth using NRCS Type III distribution
		–	Duration Event with 90th & 10th Percentile Normalized PMF Flows*
Task 2	2 Hr and 3 Hr	Local Storm	Controlling Storm from NJ PMP with associated temporal distribution
			Controlling Storm from NJ PMP with Army Corps' EM distribution
			Controlling Storm from NJ PMP with NRCS Type III distribution
			Duration Event from NJ PMP with Synthetic Distribution
		–	Duration Event with 90th & 10th Percentile Normalized PMF Flows*

*Results are statistical estimates of hydrologic model output data from various duration events (excluding HMR51/52 storms).

The 2-hour Synthetic Distribution

The 2-hour synthetic distribution was developed based on historical storms utilized in PMP development which combined NEXRAD weather radar data at 5-minute increments along with hourly and sub hourly rain gauge data and were analyzed using SPAS. This SPAS-NEXRAD 5-minute data was used to derive ratios of the greatest 15-, 30-, and 45-minute accumulations during the greatest 1-hour rainfall accumulation. The incorporation of NEXRAD weather radar allowed for explicit evaluation of sub hourly rainfall accumulation patterns with greater accuracy and spatial coverage. The first hour precipitation is placed in the middle and utilized the stacked 5-min-interval sub-hourly data. The second hour is evenly distributed both in the front and at the end.

Critically Stacked Distribution

A “critically stacked” temporal distribution was developed as a synthetic rainfall distribution based on HMR 52 procedures, so the description herein also applies to the HMR 52 distribution. The critically stacked temporal pattern yields a significantly different distribution than actual distributions associated with the storms used for PMP development in this study. 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. The critically stacked procedure (i.e., HMR 52 distribution) has often been chosen in the past for PMP runoff modeling because it represents a worst-case design scenario and ensures PMP depths are equaled at all durations. However, it does not represent a physically possible storm environment. This is supported by AWA’s work analyzing the rainfall accumulation patterns associated with hundreds of PMP-types storm events across North America. In no instance has any storm produced the critically stacked temporal pattern as provided in HMR 52. Therefore, when sufficient observed storm patterns are available for a given study, those should be used in place of the critically stacked/HMR 52 pattern to develop temporal patterns which represent the location and storm type(s) being analyzed in a realistic manner. These observed patterns can be developed using meteorological judgement, statistical analyses, and/or application of the actual observed pattern. All of these options were applied in this study.

10th / 90th Percentile Distributions

Both 10th and 90th percentile distributions are derived based on Huff Curve Methodology which is a probabilistic representation of accumulated storm depths for corresponding accumulated storm durations expressed in dimensionless form. The 10th percentile curve indicates that 10% of the corresponding SPAS storms had distributions that fell below and to the right of the 10th percentile curve (back-loaded). The 90th curve indicates that 10% of the corresponding SPAS storms had distributions that fell above and to the left of the 90th curve (front-loaded).

USACE Engineer Manual EM 1110-2-1411 Distribution

The USACE developed a temporal distribution as presented in Engineer Manual 1110-2-1411 (March 1965), which assumes a 24-hour standard project storm duration. The 24-hour storm period is divided into four 6-hour periods. The maximum 6-hour period is placed in the 3rd 6-hour period of the 24-hour storm. The remaining rainfall is evenly distributed around the maximum 6-hour period with the 12-hour PMP rainfall occurring over 12 hours and 24-hour PMP rainfall occurring over the 24-hour storm duration. The EM 1110-2-1411 distribution is similar to the critically stacked pattern as described above. For NJ PMP Tool, AWA developed a 6-hour EM curve that has the same distribution pattern as presented in EM 1110-2-1411. This is due to a relatively short lag time for most of the basins in New Jersey.

"Pass/Fail" Test for Temporal Distributions

It should be noted that when a specific-duration storm with a particular temporal distribution is generated by the NJ PMP Tool, the PMP rainfall depth for an interim (shorter) duration may exceed the computed PMP value for that duration. The NJ PMP Tool generates one consolidated Excel file as the tool output under each specific folder corresponding to each storm type (local, general and tropical). Within each Excel file, there is a tab titled "Temporal_Distribution_Check_Stormtype" (referred to as "check table" hereinafter). Each check table includes a "Check_duration" cell to test if the precipitation value for an interim storm duration within a particular temporal distribution exceeds the PMP value for that duration (referred to as a "pass/fail" test). If an exceedance occurs, that cell in the check table will have "Fail" as the assigned value; otherwise, a "Pass" will be assigned. If a given temporal pattern has at least one "Fail" value in the "pass/fail" test, it is deemed invalid and should not be applied to the hydrological model.

Ten watersheds throughout New Jersey were tested initially using the NJ PMP Tool, which generated a variety of temporal distributions for applications to hydrologic models as appropriate. Five watersheds with available hydrologic models were selected for further testing on the effects of temporal distributions on the runoff modeling results which are shown in this memorandum. An examination of the check tables generated for these temporal distributions for the three storm types indicated that there was a number of temporal distributions that failed the "pass/fail" test. For some basins, there are few or no temporal patterns for local storms that are valid for hydrologic modeling.

To address this issue, NJDEP, AWA and AECOM had thorough discussions and conducted investigations for each storm duration and the applicable temporal patterns at the five selected watersheds as shown in Table 1. This evaluation showed that in a majority of cases the interim PMP depths were exceeded by very small amounts (less than 5%). Therefore, implementation of a 5% buffer in the check tables was proposed to correct the issue. AECOM also investigated other options such as setting up a spreadsheet to distribute any excess rainfall through the rest of the hyetograph, step-by-step, until the full PMP distribution is achieved. However, in the end the option of implementing the 5% buffer was considered a better alternative.

As a result, it was ultimately decided that a 5% buffer for the PMP depth exceedance at any storm duration was acceptable. This was presented and discussed with the study review board, who concurred with this adjustment. It is important to note that this is specific to this study. For other study locations, a similar analysis can be completed if those studies determine that additional temporal patterns are required. Therefore, a final revision was applied to the NJ PMP Tool to allow exceedance of any interim PMP depth by up to 5% to be considered to pass the "pass/fail" test. Please refer to Chapter 12 of the New Jersey Probable Maximum Precipitation Study Final Report (AWA, June 2024).

Comparison of Hydrologic Modeling Results with PMP and Temporal Distributions

As discussed above, AECOM conducted hydrological analyses of the five watersheds with the various rainfall distributions, that passed the modified "pass/fail" test, in their respective HEC-HMS models to evaluate the effects of the temporal distributions on the PMF runoff hydrographs. Key hydrologic parameters in the modeling results include peak inflow (cfs), peak outflow (cfs), inflow volume (ac-ft) and maximum water surface elevation (WSEL, ft) at the dam. A comparison of the results is summarized below.

HMR 51 PMP Depth with Three Temporal Distributions

As presented in the previous memorandum to NJDEP, the PMP depth for each watershed was estimated using the conventional Hydrological Reports Nos. 51 (HMR 51) from the National Oceanic and Atmospheric Administration (NOAA) as the basis for comparison to the results from NJ PMP Tool. In this additional analysis, the HMR 51 PMP depth with three temporal distributions were analyzed for all storms from 6-hour to 72-hour: the conventional HMR 52 distribution, the USACE EM distribution and the NRCS Type III distribution.

For three out of the five dams evaluated, the HMR 51 depth with EM distribution yields the lowest peak inflow, outflow and WSEL for all storm durations. The ratios of peak inflows resulting from the EM distribution to those from the HMR 52 distribution typically range from 67% to 95% and the differences of peak WSELs between the two distributions range from -1.46 ft to -0.24 ft. For the other two dams, all the EM distributions failed the “pass/fail” test; hence, those are not analyzed in the HEC-HMS model. **Table 3** presents the comparison results among the three temporal distributions.

The resultant hydrologic parameters from the NRCS Type III distribution are similar to those from the HMR 52 distribution for all dams except for the 12-hour storm at Lake Lenape Dam. The ratios of peak flows resulting from the NRCS Type III distribution to those from the HMR 52 distribution typically range from 93% to 111% and the difference of peak WSELs between the two distributions range from -0.42 ft to +0.88 ft.

Overall, the results indicate that the peak flows and WSELs from the HMR 51 depth with the HMR 52 distribution could be utilized as the basis for comparison to those from the NJ PMP Tool temporal distributions. The comparisons are categorized by the size of the drainage area for each dam: 1) less than 10 square miles; and 2) greater than 10 square miles up to 200 square miles.

<u>Dams with Watershed Drainage Areas less than 10 Square Miles</u>

As shown in **Table 1**, Shongum Lake Dam, Orange Reservoir Dam and Englishtown Lake Dam all have a drainage area between 3 and 7 square miles. For these dams, AECOM’s previous experiences on this study indicate that the local storms tend to yield the highest peak flows and WSELs at the dam.

Based on AWA’s definition, a local storm is defined as a storm event that occurs over a small area in a short time period. Precipitation rarely exceeds 6 hours in duration. Frequently, local storms will last only 1 or 2 hours and precipitation will occur over areas generally less than 100 square miles. For local storms, The PMP Tool calculated PMP depths at the critical durations of 1-, 2-, 3-, 4-, 5-, 6-, 12-, and 24-hours and temporal distributions were provided for 2-hour (synthetic distribution) and 6-hour (10th percentile, 90th percentile and EM distributions).

According to AWA, a general storm is defined as a storm event that produces precipitation longer than 6 hours, is associated with a major synoptic weather feature and exhibits lower rainfall accumulation intensities compared to local storms. A tropical storm is defined as a storm event that is a direct result of a tropical system, either landfalling or directly offshore and a warm core circulation, and occurs during the appropriate season, June through October.

The storm events that control the PMP depths for each storm type; local, general, and tropical were also evaluated, with their observed temporal distributions as analyzed through the SPAS process used as additional temporal pattern. In addition, AECOM developed several local storm temporal distributions for durations of 12- and 24-hours based on their respective PMP depths and the relevant 6-hour distribution pattern.

It should be noted that the 72-hour general storm and the 72-hour tropical storms generally have much lower peak flows and WSELs at these dams as compared to the local storms. This is expected given the relatively small area size of these basins. Therefore, these storms were not included in the comparison.

Table 3 – Comparisons of PMF Peak Flows and WSELs for HMR 51 PMP Depth with Three Conventional Temporal Distributions

Dam	Storm Duration	Temporal Distribution Comparison	Ratio		Max. WSEL Difference (ft)
			Peak Inflow	Peak Outflow	
Shongum Lake Dam	6 Hr	EM vs. HMR52	76.8%	83.4%	-0.76
		NRCS Type III vs. HMR52	101.2%	100.3%	0.01
	12 Hr	EM vs. HMR52	66.6%	69.7%	-1.46
		NRCS Type III vs. HMR52	100.4%	99.5%	-0.02
	24 Hr	EM vs. HMR52	76.1%	80.6%	-0.98
		NRCS Type III vs. HMR52	94.5%	93.1%	-0.35
	72 Hr	EM vs. HMR52	76.6%	81.5%	-0.94
		NRCS Type III vs. HMR52	95.8%	94.8%	-0.26
Orange Reservoir Dam	6 Hr	EM vs. HMR52	81.2%	80.9%	-0.58
		NRCS Type III vs. HMR52	101.8%	101.5%	0.04
	12 Hr	EM vs. HMR52	69.5%	69.2%	-0.95
		NRCS Type III vs. HMR52	101.1%	100.5%	0.01
	24 Hr	EM vs. HMR52	82.6%	82.2%	-0.54
		NRCS Type III vs. HMR52	96.2%	95.4%	-0.13
	72 Hr	EM vs. HMR52	81.6%	81.5%	-0.56
		NRCS Type III vs. HMR52	96.0%	95.1%	-0.13
Englishtown Lake Dam	6 Hr	EM vs. HMR52	94.9%	95.1%	-0.24
		NRCS Type III vs. HMR52	100.2%	100.2%	0.01
	12 Hr	EM vs. HMR52	79.7%	80.1%	-1.08
		NRCS Type III vs. HMR52	97.5%	97.5%	-0.13
	24 Hr	EM vs. HMR52	93.5%	93.7%	-0.35
		NRCS Type III vs. HMR52	93.7%	93.8%	-0.35
	72 Hr	EM vs. HMR52	92.3%	92.7%	-0.43
		NRCS Type III vs. HMR52	92.7%	92.8%	-0.42
Duhernal Lake Dam	6 Hr	EM vs. HMR52	N/A	N/A	N/A
		NRCS Type III vs. HMR52	111.0%	109.2%	0.88
	12 Hr	EM vs. HMR52	N/A	N/A	N/A
		NRCS Type III vs. HMR52	101.4%	101.4%	0.14
	24 Hr	EM vs. HMR52	N/A	N/A	N/A
		NRCS Type III vs. HMR52	99.3%	99.0%	-0.11
	72 Hr	EM vs. HMR52	N/A	N/A	N/A
		NRCS Type III vs. HMR52	97.2%	96.8%	-0.41
Lake Lenape Dam	6 Hr	EM vs. HMR52	N/A	N/A	N/A
		NRCS Type III vs. HMR52	110.8%	110.8%	0.35
	12 Hr	EM vs. HMR52	N/A	N/A	N/A
		NRCS Type III vs. HMR52	57.8%	57.7%	-2.55
	24 Hr	EM vs. HMR52	N/A	N/A	N/A
		NRCS Type III vs. HMR52	100.8%	100.8%	0.03
	72 Hr	EM vs. HMR52	N/A	N/A	N/A
		NRCS Type III vs. HMR52	97.6%	97.6%	-0.12

1. N/A – comparisons not available due to EM distributions failing the “pass/fail” test.

Table 4 – Comparisons of PMF WSELs for Temporal Distributions for Dams with Drainage Areas Less than 10 Square Miles

Dam	Storm Duration	PMP Depth (in)	Temporal Distributions	Peak Inflow (cfs)	Peak Outflow (cfs)	Max. WSEL (ft)
Shongum Lake Dam (DA=3.1 sq. mi.)	2 Hr	14.60	Local Storm 2Hr Synthetic	15,857	13,390	707.39
	6 Hr	25.60	HMR 51/52	17,495	12,858	707.20
		28.07	LS 6Hr EM	14,903	11,961	706.88
		28.07	LS 6Hr 10th Percentile	11,530	10,725	706.44
		28.07	6Hr Local Control Storm 1406	14,017	10,235	706.26
	12 Hr	29.92	HMR 51/52	17,825	13,510	707.43
		31.84	LS 12Hr 10th Percentile	11,702	10,976	706.53
		31.84	12Hr Local Control Storm 1534	12,947	10,734	706.44
		31.84	LS 12Hr EM	12,706	10,105	706.22
	24 Hr	33.29	HMR 51/52	18,370	14,171	707.67
		31.90	LS 24Hr EM	15,224	12,385	707.03
		31.90	24Hr Local Control Storm 1406	14,796	11,320	706.65
		31.90	LS 24Hr 10th Percentile	11,704	10,979	706.53
Orange Reservoir Dam (DA=4.7 sq. mi.)	2 Hr	14.65	Local Storm 2Hr Synthetic	21,165	20,827	338.04
	6 Hr	25.90	HMR 51/52	21,567	21,201	338.08
		27.99	LS 6Hr EM	18,945	18,569	337.71
		27.99	6Hr Control Storm 1534	16,735	16,605	337.42
		27.99	LS 6Hr 10th Percentile	16,163	16,126	337.35
	12 Hr	30.29	HMR 51/52	21,517	21,203	338.08
		31.78	12Hr Local Control Storm 1534	16,729	16,599	337.42
		31.78	LS 12Hr 10th Percentile	16,322	16,288	337.37
		31.78	LS 12Hr EM	15,697	15,407	337.24
	24 Hr	33.71	HMR 51/52	21,587	21,275	338.09
		31.78	LS 24Hr EM	19,220	18,842	337.75
		31.78	24Hr Local Control Storm 1534	16,728	16,599	337.42
		31.78	LS 24Hr 10th Percentile	16,321	16,288	337.37
Englishtown Lake Dam (DA=6.7 sq. mi.)	2 Hr	14.70	Local Storm 2Hr Synthetic	8,412	8,221	74.79
	6 Hr	26.63	HMR 51/52	16,295	16,005	77.26
		28.04	LS 6Hr EM	16,405	16,144	77.30
		28.04	LS 6Hr 10th Percentile	16,270	16,000	77.26
		28.04	6Hr Control Storm 1534	15,911	15,676	77.16
	12 Hr	31.13	HMR 51/52	17,618	17,340	77.68
		31.70	LS 12Hr 10th Percentile	17,222	16,972	77.56
		31.70	12Hr Local Control Storm 1534	16,501	16,303	77.35
		31.70	LS 12Hr EM	14,313	14,172	76.69
	24 Hr	34.63	HMR 51/52	18,164	17,887	77.85
		31.70	LS 24Hr 10th Percentile	17,222	16,972	77.56
		31.70	24Hr Local Control Storm 1534	16,501	16,303	77.35
		31.70	LS 24Hr EM	14,313	14,172	76.69

1. Red color values denote the highest WSEL at each dam (excluding the HMR 51/52 distribution).

Table 4 presents a summary of results for storm durations of 2-hour, 6-hour, 12-hour, and 24-hour and the top 3 temporal distributions that produced the highest WSELs, along with the HMR 51/52 distribution which serves as the basis for comparison. The data are arranged by the resulting WSELs in descending order for each storm duration at the dam.

The results indicated that the 2-hour local storm synthetic distribution has the highest WSEL among all temporal distributions (excluding HMR 51/52) for all storm durations for 2 out of 3 dams (Shongum Lake Dam and Orange Reservoir Dam). In the cases of both dams, the peak WSEL from the 2-hour synthetic distribution approaches or even slightly exceeds the WSELs from the HMR 51/52 distribution for all durations.

For the 6-hour storm which is another typical duration for a local storm, two out of the three most frequently used temporal distributions generated by the NJ PMP Tool – the EM distribution and 10-percentile distribution are readily available for use in the HEC-HMS modeling for all three dams with the adjusted “pass/fail” test. The 90th-percentile distribution fails the test even with the conservative application of the 5% buffer and is not available for use. Several local controlling storm patterns also yield comparable WSELs, as shown in Table 4. The EM distribution produces the highest WSEL for all 3 dams, followed by the 10th-percentile storm and controlling storm distributions.

For the 12-hour storm, either the 10th percentile or the controlling storm pattern generates the highest water level. For the 24-hour storm, either the EM distribution or the 10^{th}-percentile pattern yields the highest WSEL at the dam, followed closely by the controlling storm distributions.

The results also indicate that for all patterns and storm durations except the 2-hour storm, the 24-hour EM distribution has the highest WSEL for two dams (Shongum Lake Dam and Orange Reservoir Dam), followed closely by the 6-hour EM distribution. For Englishtown Lake Dam, both the 12-hour and 24-hour 10th-percentile distributions yield the same highest WSELs at 77.56 ft. The peak water level resulting from the 6-hour EM pattern is only 0.26 feet lower at 77.30 ft.

Similar to **Table 4**, **Table 5** presents a summary of results for local storm durations up to 24-hour and the top 3 temporal distributions that produce the highest peak inflows, along with the HMR 51/52 distribution. The data are arranged by the resulting peak inflows in descending order for each storm duration at each dam. The 90th-percentile normalized PMF flow, a statistical indicator when normalizing all the calculated PMF flow data, is also included for each storm duration.

Table 5 clearly shows that for Orange Reservoir Dam and Englishtown Lake Dam, the list of temporal distributions based on peak inflows is the same as in **Table 4** which is based on peak WSELs. For Shongum Lake Dam, the list in **Table 5** is slightly different from **Table 4**; the controlling storm 1534 make the list for the 6-hour, 12-hour and 24-hour durations. It should be noted that the temporal distribution resulting in the highest peak inflow for a particular dam generally matches the one with the highest WSEL.

Overall, various local storm durations and temporal distributions except the 90th-percentile pattern could be selected as the candidate PMP storms for dams with a drainage area less than 10 square miles as they all yield similar WSELs based on the results of 3 basins tested. Among the temporal distributions, the local storm 2-hour synthetic pattern seems to have the potential to yield the highest WSEL.

Table 5 – Comparisons of PMF Peak Inflows for Various Temporal Distributions for Dams with Drainage Areas less than 10 Square Miles (arranged by Peak Inflow in Descending Order)

Dam	Storm Duration	PMP Depth (in)	Temporal Distributions	Peak Inflow (cfs)	Peak Outflow (cfs)	Max. WSEL (ft)
Shongum Lake Dam (DA=3.1 sq. mi.)	2 Hr	14.60	Local Storm 2Hr Synthetic	15,857	13,390	707.39
	6 Hr	25.60	HMR 51/52	17,495	12,858	707.20
		28.07	LS 6Hr EM	14,903	11,961	706.88
		28.07	6Hr Local Control Storm 1406	14,017	10,235	706.26
		28.07	6Hr Local Control Storm 1534	11,677	9,454	705.98
		90th Percentile Normalized PMF Flow		14,460		
	12 Hr	29.92	HMR 51/52	17,825	13,510	707.43
		31.84	12Hr Local Control Storm 1534	12,947	10,734	706.44
		31.84	LS 12Hr EM	12,706	10,105	706.22
		31.84	LS 12Hr 10th Percentile	11,702	10,976	706.53
		90th Percentile Normalized PMF Flow		12,851		
	24 Hr	33.29	HMR 51/52	18,370	14,171	707.67
		31.9	LS 24Hr EM	15,224	12,385	707.03
		31.90	24Hr Local Control Storm 1406	14,796	11,320	706.65
		31.90	24Hr Local Control Storm 1534	12,975	10,758	706.45
		90th Percentile Normalized PMF Flow		14,614		
Orange Reservoir Dam (DA=4.7 sq. mi.)	2 Hr	14.65	Local Storm 2Hr Synthetic	21,165	20,827	338.04
	6 Hr	25.90	HMR 51/52	21,567	21,201	338.08
		27.99	LS 6Hr EM	18,945	18,569	337.71
		27.99	6Hr Control Storm 1534	16,735	16,605	337.42
		27.99	LS 6Hr 10th Percentile	16,163	16,126	337.35
		90th Percentile Normalized PMF Flow		18,061		
	12 Hr	30.29	HMR 51/52	21,517	21,203	338.08
		31.78	12Hr Local Control Storm 1534	16,729	16,599	337.42
		31.78	LS 12Hr 10th Percentile	16,322	16,288	337.37
		31.78	LS 12Hr EM	15,697	15,407	337.24
		90th Percentile Normalized PMF Flow		16,566		
	24 Hr	33.71	HMR 51/52	21,587	21,275	338.09
		31.78	LS 24Hr EM	19,220	18,842	337.75
		31.78	24Hr Local Control Storm 1534	16,728	16,599	337.42
		31.78	LS 24Hr 10th Percentile	16,321	16,288	337.37
		90th Percentile Normalized PMF Flow		16,728		
Englishtown Lake Dam (DA=6.7 sq. mi.)	2 Hr	14.70	Local Storm 2Hr Synthetic	8,412	8,221	74.79
	6 Hr	26.63	HMR 51/52	16,295	16,005	77.26
		28.04	LS 6Hr EM	16,405	16,144	77.30
		28.04	LS 6Hr 10th Percentile	16,270	16,000	77.26
		28.04	6Hr Control Storm 1534	15,911	15,676	77.16
		90th Percentile Normalized PMF Flow		16,378		
	12 Hr	31.13	HMR 51/52	17,618	17,340	77.68
		31.70	LS 12Hr 10th Percentile	17,222	16,972	77.56
		31.70	12Hr Control Storm 1534	16,501	16,303	77.35
		31.70	LS 12Hr EM	14,313	14,172	76.69
		90th Percentile Normalized PMF Flow		17,078		
	24 Hr	34.63	HMR 51/52	18,164	17,887	77.85
		31.70	LS 24Hr 10th Percentile	17,222	16,972	77.56
		31.70	24Hr Local Control Storm 1534	16,501	16,303	77.35
		31.70	LS 24Hr EM	14,313	14,172	76.69
		90th Percentile Normalized PMF Flow		16,501		

1. Red color values denote the highest inflow at each dam (excluding the HMR 51/52 distribution).

Dams with Watershed Drainage Areas greater than 10 Square Miles

Duhernal Lake Dam and Lake Lenape Dam have a drainage area of 95 and 205 square miles, respectively. For the former dam, results indicate that most of local storms would fail the “pass/fail” test even after the 5% buffer was applied, except for the 2-hour synthetic pattern; therefore, a number of general and tropical storms were utilized in the runoff modeling. For the latter dam, some local storm patterns were applied in the hydrologic modeling for comparison purpose only because local storms are typically not applicable for a basin area larger than 100 square miles.

Table 6 presents a summary of results for storm durations of 2-hour, 6-hour, 12-hour, 24-hour, and 72-hour and the top 3 temporal distributions that produced the highest WSELs for the PMF condition, along with the HMR 51/52 rainfall/distribution which serves as the basis for comparison. The data are arranged by each dam, storm duration and the resulting WSEL in descending order.

The results indicated that the 2-hour local storm synthetic distribution has the highest WSEL among all temporal distributions (including HMR 51/52) for all storm durations for Duhernal Lake Dam. In this case, the peak water surface elevation from the 2-hour synthetic distribution even exceeds the WSEL from the 72-hour HMR 51/52 distribution by 0.42 feet.

For storms longer than the 2-hour duration at Duhernal Lake Dam, no local storm patterns were available for hydrologic modeling due to the “pass/fail” test. Instead, various general storm and tropical storm patterns were used and all produced much lower WSELs compared to the HMR 51/52 distribution.

As to Lake Lenape Dam, for the 6-hour storm, the 10th-percentile local storm distribution produces comparable WSELs to the HMR 51/52 result. For the 12-hour storm, the 10th-percentile pattern generates the highest water level; however, it is much lower than the WSEL obtained from HMR 51/52.

For the 24-hour storm, both general and tropical storms have the top 3 WSELs for both dams. It should be noted that the general storm 24-hour 10th-percentile pattern yields the highest WSEL for all distributions and durations events for Lake Lenape Dam except for the 12-hour HMR 51/52 distribution.

For the 72-hour storm, the top 3 WSELs are generally lower than the 24-hour distribution for Duhernal Lake Dam. As to Lake Lenape Dam, the 72-hour patterns generally produce comparable or slightly higher WSELs as compared to the 24-hour and 12-hour distributions, except for the general storm 24-hour 10th-percentile pattern.

It should be noted that for both dams with drainage areas greater than 10 square miles, the order of peak inflows in the comparison table always corresponds to that of the peak WSELs for a particular temporal distribution in **Table 6**.

Comparisons were made among four temporal distributions including the general storm 24-hour 10th-percentile, tropical storm 24-hour 10th-percentile, local storm 2-hour synthetic and local storm 6-hour 10th-percentile, for Lake Lenape Dam (see Figure 1). The resulting outflow hydrographs from these distributions were plotted in Figure 2. It should be noted that for watersheds with an area over 100 square miles such as Lake Lenape Dam, local storm is generally not applicable. The two local storms plotted are for comparison purpose only. As shown in Figure 2, the peak outflows occur during the latter part of the 72-hour modeling runtime due to the various lag times among the 5 sub-basins, ranging from 6.5 hours to 23.9 hours.

Table 6 – Comparisons of PMF Peak Flows and WSELs for Temporal Distributions for Dams with Drainage Areas Greater than 10 Sq Mi (arranged by Max. WSEL in Descending Order)

Dam	Storm Duration	PMP Depth (in)	Temporal Distributions	Peak Inflow (cfs)	Peak Outflow (cfs)	Max. WSEL (ft)
Duhernal Lake Dam (DA=95.1 sq. mi.)	2 Hr	11.20	Local Storm 2Hr Synthetic	131,847	123,992	**28.07**
	6 Hr	20.60	HMR 51/52	88,136	82,746	23.67
		14.00	6Hr Tropical Controlling Storm 1491	37,492	35,723	17.67
		14.20	6Hr General Controlling Storm 1339	34,675	33,039	17.30
		22.80	Local Storm 6Hr EM	N/A	N/A	N/A
	12 Hr	24.40	HMR 51/52	104,742	98,234	25.41
		24.56	12Hr Tropical Controlling Storm 1491	81,929	78,008	23.12
		16.50	12Hr General Controlling Storm 1339	60,523	58,133	20.72
		25.00	Local Storm 12Hr EM	N/A	N/A	N/A
	24 Hr	28.01	HMR 51/52	114,699	108,239	26.44
		16.80	GS 24Hr 10th Percentile	90,712	89,025	24.39
		24.57	TS 24Hr 10th Percentile	83,383	79,144	23.25
		24.57	TS 24Hr Controlling Storm 1491	81,975	78,051	23.12
	72 Hr	33.57	HMR 51/52	126,996	119,852	27.65
		24.58	TS 72Hr Controlling Storm 1491	91,603	87,635	24.23
		24.58	TS 72Hr 10th Percentile	83,401	79,163	23.25
		24.58	TS 72Hr 90th Percentile	73,300	72,015	22.43
Lake Lenape Dam (DA=205 sq. mi.)	2 Hr	9.22	Local Storm 2Hr Synthetic	42,083	41,948	20.75
	6 Hr	18.79	HMR 51/52	31,505	31,398	19.70
		18.75	LS 6Hr 10th Percentile	31,592	31,486	19.71
		14.10	6Hr General Controlling Storm 1339	14,395	14,329	17.66
		12.61	6Hr Tropical Controlling Storm 1491	13,393	13,332	17.51
	12 Hr	22.55	HMR 51/52	69,568	69,473	23.12
		20.95	LS 12Hr 10th Percentile	36,645	36,525	20.22
		20.95	12Hr Local Controlling Storm 1489	33,574	33,467	19.91
		21.48	12Hr Tropical Controlling Storm 1491	32,611	32,509	19.82
	24 Hr	26.34	HMR 51/52	48,438	48,293	21.34
		16.60	GS 24Hr 10th Percentile	65,508	65,384	**22.79**
		21.49	LS 24Hr 10th Percentile	37,663	37,543	20.32
		21.40	TS 24Hr 10th Percentile	37,584	37,473	20.32
	72 Hr	32.41	HMR 51/52	58,568	58,446	22.22
		22.10	TS 72Hr 10th Percentile	38,621	38,514	20.42
		22.10	TS 72Hr Synthetic	38,240	38,138	20.38
		22.10	TS 72hr 90 Percentile	38,214	38,108	20.38

1. N/A – data not available due to temporal distributions failing the "pass/fail" test.
2. Red color values denote the highest WSEL at each dam (excluding the HMR 51/52 distribution).

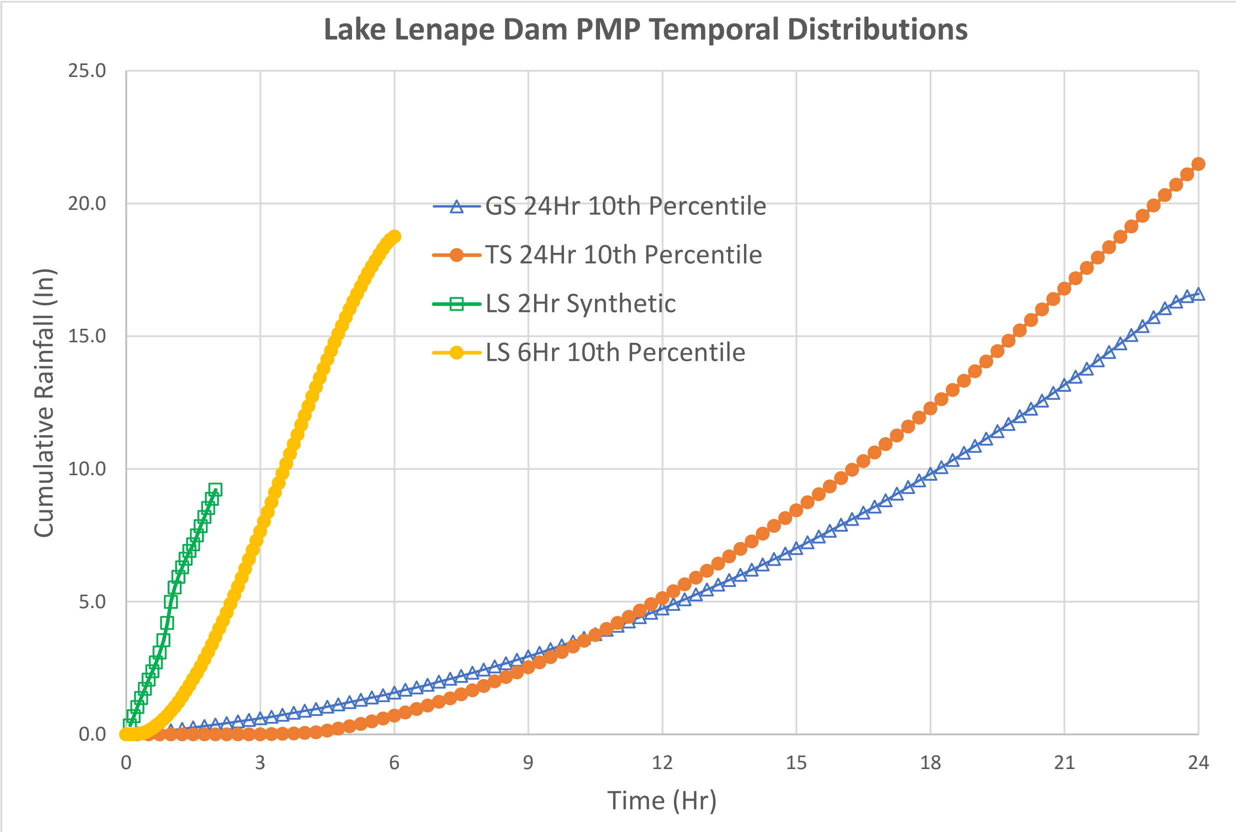

Figure 1: Comparison of Four Temporal Distributions for Lake Lenape Dam

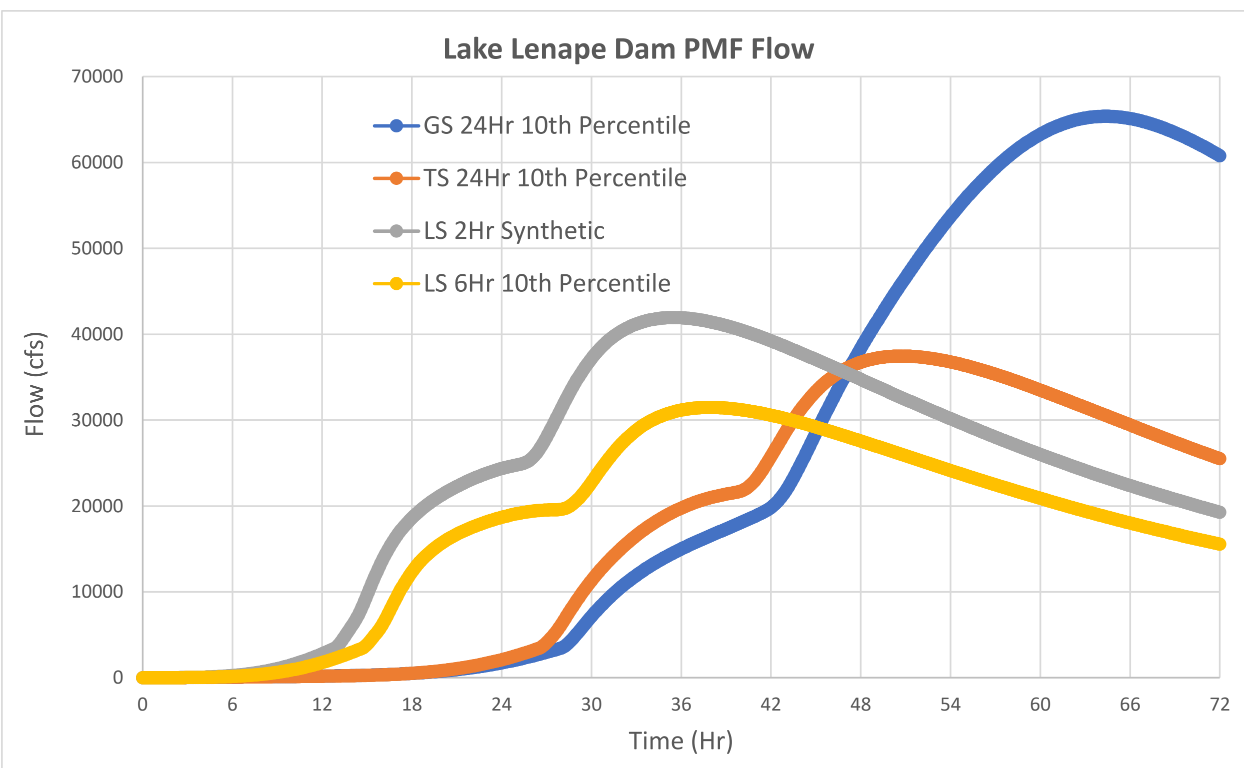

Figure 2: Lake Lenape Dam PMF Hydrographs Resulting from Four Temporal Distributions

Selection of Candidate Temporal Distributions

Based on the results of hydrologic models for the five different watersheds across New Jersey as described above, various temporal distributions were selected that can be applied to the hydrologic models to determine a reasonable PMF for a given watershed.

AECOM, in coordination with AWA, conducted research on various statewide PMP studies performed recently and the temporal distributions recommended by each state for use in the runoff modeling. **Table 7** presents a summary of these studies and the recommended distributions unless otherwise noted. Eight out of nine effective statewide PMP studies that provided temporal distributions have selected either the synthetic pattern, 10th-percentile, 90th-percentile or controlling storms as the recommended distributions. The Pennsylvania PMP study implemented a mix of the synthetic pattern, 10th-percentile, 90th-percentile, controlling storms and the EM distributions. According to AWA, the EM distribution is only used in PA because it is the legacy product that has been used in the state before. Other states do not recommend the EM distribution as it is outdated, does not use the recent storm data and radar data that have been made available since early 1990s, and is deemed overly conservative (i.e., similar to the HMR 52 distribution). Therefore, AECOM recommends that the EM distribution not be considered for the candidate PMP temporal distribution.

For dams with a drainage area less than 10 square miles, AECOM recommends the 2-hour synthetic, the 6-hour local storm 10th-percentile, the 12-hour local storm 10th-percentile and the 6-hour and 12-hour controlling storm distributions as the candidate PMP storms and temporal distributions.

For dams with a drainage area greater than 10 square miles, the hydrologic model demonstrates varying trends for the study dams based on the location, size and basin response time for various temporal distributions and does not have common temporal distributions to be considered for the PMP storm. Generally, local storms still dominate the PMP for dams with a drainage area between 10 and 100 square miles, but the effects of general storms and tropical storms increase dramatically once the watershed becomes sufficiently large, especially when greater than 100 square miles. This also follows the meteorological environments and rainfall accumulation patterns associated with each storm type and represents the expected meteorological environments. In this case, the local 24-hour, general 24-hour and tropical 24-hour storms combined with the 10th-percentile distribution as well as the 12-hour general and tropical controlling storms would be preferrable over the 72-hour duration storms. Previous testing of the NJPMP Tool indicates that the majority of 72-hour PMP precipitation occurs during the first 24-hour period.

AECOM has applied the above criteria for selection of the PMP storm and duration on the test of another dam previously studied and having an available HEC-HMS Model (New Market Pond Dam with a drainage area of 22 square miles). Results indicate that the 2-hour local storm synthetic distribution yields the highest WSEL among all temporal distributions (including HMR51/52) for all storm durations.

Conclusions and Recommendations

Although the comparisons of hydrologic modeling results for the five dams tested using NJ PMP Tool-derived depths and temporal distributions were made based on the size of the drainage area, AECOM and NJDEP have decided that the final procedure for the tool should create a set of common temporal distributions for use and evaluation in the hydrologic models, regardless of the drainage area size. This is to ensure that the NJ PMP Tool is simple, straightforward and results are replicable and defendable.

Therefore, AECOM recommends that the proposed use of the NJ PMP tool involve making multiple runs of a basin hydrologic model utilizing ten recommended temporal distributions as shown in **Table 8**. The rainfall distribution that results in the highest peak water surface elevation at the dam shall be selected as the PMP storm.

Table 7 – Summary of PMP Temporal Distributions Recommended for Use in Runoff Modeling Resulting from Statewide PMP Studies

PMP Study Name	Local Storm Patterns			General Storm Patterns			Tropical Storm Patterns		
	Name	Time Step	Total Duration	Name	Time Step	Total Duration	Name	Time Step	Total Duration
Arizona Statewide PMP	LS 6-hour Synthetic	10-min	6-hour	GS/TS 72-hour Synthetic	6-hour	72-hour	GS/TS 72-hour Synthetic	6-hour	72-hour
Nebraska Statewide PMP	None Provided			None Provided			None Provided		
Ohio Statewide PMP	None Provided			None Provided			None Provided		
Wyoming Statewide PMP	2-hour West of Divide Synthetic	10-min	2-hour	72h West of Divide Synthetic	1-hour	72-hour	N/A		
	6-hour East of Divide Synthetic	10-min	6-hour	72h East of Divide Synthetic	1-hour	72-hour			
	24-hour Hybrid East of Divide Synthetic	1-hour	24-hour	24-hour Hybrid East of Divide Synthetic	1-hour	24-hour			
TVA Dams	None Provided			None Provided			None Provided		
Texas Statewide PMP	Based on a formula provided by Texas Commission on Environmental Quality.								
Virginia Statewide PMP	None Provided			None Provided			None Provided		
Colorado and New Mexico Statewide PMP	2-hour Stacked	5 min	2-hour	72h Synthetic East	15 min	72-hour	72h Synthetic East	15 min	72-hour
	6h Synthetic East	5 min	6-hour	72h Synthetic West	15 min	72-hour	72h Synthetic West	15 min	72-hour
	6h Synthetic West	5 min	6-hour						
	24h Synthetic Hybrid	5 min	24-hour						
Pennsylvania Statewide PMP	2-hour Synthetic	5 min	2-hour	3-hour Controlling Storm	60 min	3-hour	3-hour Controlling Storm	60 min	3-hour
	3-hour Controlling Storm	60 min	3-hour	6-hour Controlling Storm	60 min	6-hour	6-hour Controlling Storm	60 min	6-hour
	6-hour Controlling Storm	60 min	6-hour	12-hour Controlling Storm	60 min	12-hour	12-hour Controlling Storm	60 min	12-hour
	12-hour Controlling Storm	60 min	12-hour	24-hour Controlling Storm	60 min	24-hour	24-hour Controlling Storm	60 min	24-hour
	24-hour Controlling Storm	60 min	24-hour						
Arkansas-Louisiana-Mississippi-Oklahoma PMP	2-hour	5 min	2-hour	72h 10th Percentile	15 min	72-hour	72h 10th Percentile	15 min	72-hour
	2-hour Center	5 min	2-hour	72h 90th Percentile	15 min	72-hour	72h 90th Percentile	15 min	72-hour
	6h 10th Percentile	5 min	6-hour	72h Synthetic	15 min	72-hour	72h Synthetic	15 min	72-hour
	6h 90th Percentile	5 min	6-hour	6h Controlling Storms	1 hour	6-hour	6h Controlling Storms	1 hour	6-hour
	6h Synthetic	5 min	6-hour	24h Controlling Storms	1 hour	24-hour	24h Controlling Storms	1 hour	24-hour
	24h Hybrid 10th Percentile	5 min	24-hour	72h Critically Stacked	15 min	72-hour	72h Critically Stacked	15 min	72-hour
	24h Hybrid 90th Percentile	5 min	24-hour						
	24h Hybrid Synthetic	5 min	24-hour						
	6h Critically Stacked	5 min	6-hour						
North Dakota Statewide PMP	2-hour	5 min	2-hour	24h 10th Percentile	15 min	24-hour	N/A		
	6h 10th Percentile	5 min	6-hour	24h 90th Percentile	15 min	24-hour			
	6h 90th Percentile	5 min	6-hour	24h Synthetic	15 min	24-hour			
	6h Synthetic	5 min	6-hour	24h Hybrid 10th Percentile	15 min	24-hour			
				24h Hybrid 90th Percentile	15 min	24-hour			
				24h Hybrid Synthetic	15 min	24-hour			
Puerto Rico PMP*	N/A			72h 10th Percentile	15 min	72-hour	72h 10th Percentile	15 min	72-hour
				72h 90th Percentile	15 min	72-hour	72h 90th Percentile	15 min	72-hour
				72h Synthetic	15 min	72-hour	72h Synthetic	15 min	72-hour
				6h Controlling Storms	1 hour	6-hour	6h Controlling Storms	1 hour	6-hour
				24h Controlling Storms	1 hour	24-hour	24h Controlling Storms	1 hour	24-hour
				72h Critically Stacked	15 min	72-hour	72h Critically Stacked	15 min	72-hour
Maryland Statewide PMP*	2-hour	5 min	2-hour	24h 10th Percentile	15 min	24-hour	24h 10th Percentile	15 min	24-hour
	6h 10th Percentile	5 min	6-hour	24h 90th Percentile	15 min	24-hour	24h 90th Percentile	15 min	24-hour
	6h 90th Percentile	5 min	6-hour	24h Synthetic	15 min	24-hour	24h Synthetic	15 min	24-hour
	6h EM	5 min	6-hour	24h Controlling Storms	1 hour	24-hour	24h Controlling Storms	1 hour	24-hour
	6h Controlling Storms	1 hour	6-hour	24h Critically Stacked	15 min	24-hour	24h Critically Stacked	15 min	24-hour
	6h Critically Stacked	5 min	6-hour	48h 10th Percentile	15 min	48-hour	48h 10th Percentile	15 min	48-hour
				48h 90th Percentile	15 min	48-hour	48h 90th Percentile	15 min	48-hour
				48h Synthetic	15 min	48-hour	48h Synthetic	15 min	48-hour
				72h 10th Percentile	15 min	72-hour	72h 10th Percentile	15 min	72-hour
				72h 90th Percentile	15 min	72-hour	72h 90th Percentile	15 min	72-hour
				72h Synthetic	15 min	72-hour	72h Synthetic	15 min	72-hour

* The temporal distributions listed in the table were selected for the PMP study. They are not the recommended ones for runoff modeling.

Table 8 – Recommended PMP Storm and Temporal Distributions for NJ PMP Tool

Local Storm*	General Storm	Tropical Storm
2-hour local storm synthetic 6-hour local storm 10th-percentile 12-hour local storm 10th-percentile 24-hour local storm 10th-percentile 6-hour local controlling Storm 12-hour local controlling Storm	24-hour general storm 10th-percentile 12-hour general controlling storm	24-hour tropical storm 10th-percentile 12-hour tropical controlling storm

*Local storm application in hydrologic modeling is limited to drainage areas less than 100 square miles.

Disclaimer

The hydrologic analyses were performed solely for the purpose of preparing this memorandum and determining the recommended storm temporal distributions.