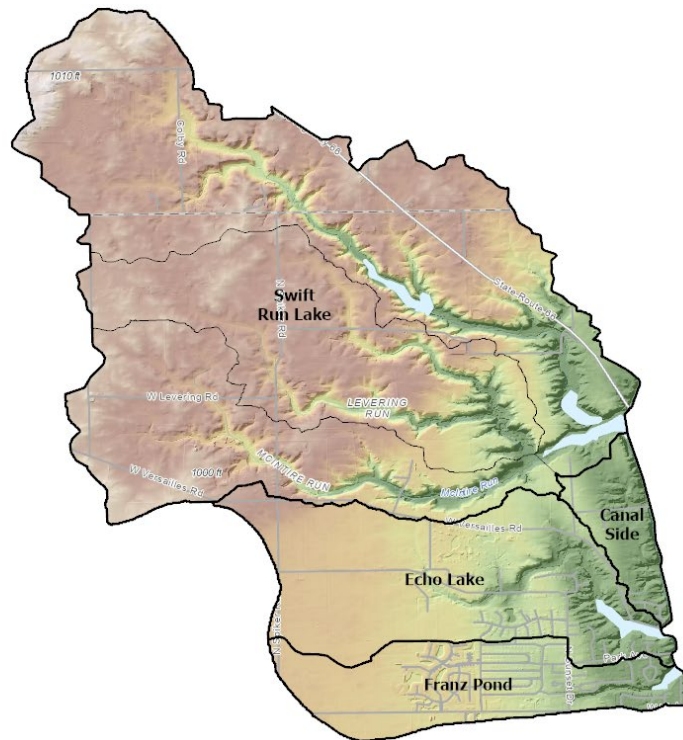




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## Site-Specific Probable Maximum Precipitation Development for Piqua, Ohio



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**Preparer Signature**



**Geoff Muhlestein**

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## Acronyms and Abbreviations

AEP	Annual Exceedance Probability
AMS	Annual Maximum Series
ARF	Areal Reduction Factor
ARI	Average Recurrence Interval
AWA	Applied Weather Associates
CDF	Cumulative Distribution Function
GEV	Generalized Extreme Value distribution
GHCN	Global Historical Climatology Network
GLO	Generalized Extreme Value distribution
GNO	Generalized Normal distribution
GPA	Generalized Pareto distribution
L-Cv	L-moment coefficient of L-variation
L-Kurtosis	L-moment ratio of kurtosis
L-Skewness	L-moment ratio of skewness
MAM	Mean Annual Maximum
MAP	Mean Annual Precipitation
NCDC	National Climate Data Center
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
PE3	Pearson Type III distribution
PF	Precipitation-Frequency
POR	Period of Record
PMP	Probable Maximum Precipitation
PRISM	Parameter-elevation Regressions on Independent Slopes Model
QC	Quality Control
RAWS	Remote Automated Weather Stations
RGC	Regional Growth Curve
RCM	Regional Climate Model
RH	Relative Humidity
Ta	Air Temperature
Td	Dew Point Temperature



## 2.0 PMP ESTIMATES

PMP depths are used in the computation of the Probable Maximum Flood (PMF), generally for the design of high-hazard structures. PMP depths developed in the study were focused on the area size of the contributing basins (ranging from 0.3 mi<sup>2</sup> to 7.4 mi<sup>2</sup>) as shown in Figure 2.1. AWA utilized our extensive database of storm analyses and PMP information from adjacent studies that are specifically relevant to this location to develop the site-specific PMP for the Piqua basins. This information was also compared against the previous PMP estimates to ensure reasonableness and accuracy.

Methods used to derive PMP values for this study included consideration of numerous extreme rainfall events that have been appropriately adjusted to each basin and representing each PMP storm type relevant for Piqua; local and general storms. Some storms exhibit characteristics of both storm types and are designated as “hybrid” events and run as both types for PMP calculations.

Storms used in previous studies have been reviewed in detail considered to develop the initial list of storms potentially applicable to this study. These were evaluated to determine which could potentially be important for PMP development for the basins and were considered transpositionable to this location. The large number of storm events provided an extensive database from which to derive the PMP depths within an acceptable range of uncertainty. The storms used for PMP development were compared to the grid points in the Ohio Statewide PMP study that were closest to the basin, grid points 7 and 13 (Ohio Statewide PMP Report Figure 1.4)<sup>1</sup>. This was checked for consistency and to add additional storms that were analyzed or updated since the Ohio Statewide PMP development.

As part of the PMP calculation process, each storm used for PMP development is maximized in place and transpositioned to the location of interest. The process of maximizing a storm is completed by identifying the air mass that provided moisture to the observed storm and quantifying that amount of moisture. Then comparing that observed moisture amount against the climatological maximum moisture which could have been available under ideal conditions. This ratio comparing the observed moisture against the maximum moisture becomes the in-place maximization factor (IPMF).

Both the observed storm and the idealized PMP storm are assumed to be saturated through the entire depth of the atmosphere and contain the maximum moisture possible based on the surface dew point. To quantify the amount of moisture associated with the observed storm and the climatological maximum value the moisture profile is assumed to follow the pseudo-adiabatic temperature profiles for both the historic storm and the PMP storm. The method assumed that a sufficient period of record was available to identify extreme storm events over a large region and that at least a few of those storms attained or came close to attaining the maximum storm efficiency possible for converting atmospheric moisture to rainfall.

The PMP development process assumes that if additional atmospheric moisture had been available, an individual storm would have maintained the same efficiency for converting atmospheric moisture to rainfall and therefore adding more moisture to the storm would result in more rainfall.

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<sup>1</sup> <https://www.appliedweatherassociates.com/wp-content/uploads/2023/09/ohio-statewide-pmp-final-report.pdf>

The amount of moisture is represented by available precipitable water in the atmosphere and is calculated by assuming a saturated atmospheric column based on observed dew points. Therefore, the ratio of the maximized rainfall amounts to the actual rainfall amounts would be the same as the ratio of the precipitable water calculated versus the climatological maximum precipitable water in the atmosphere associated with each storm.

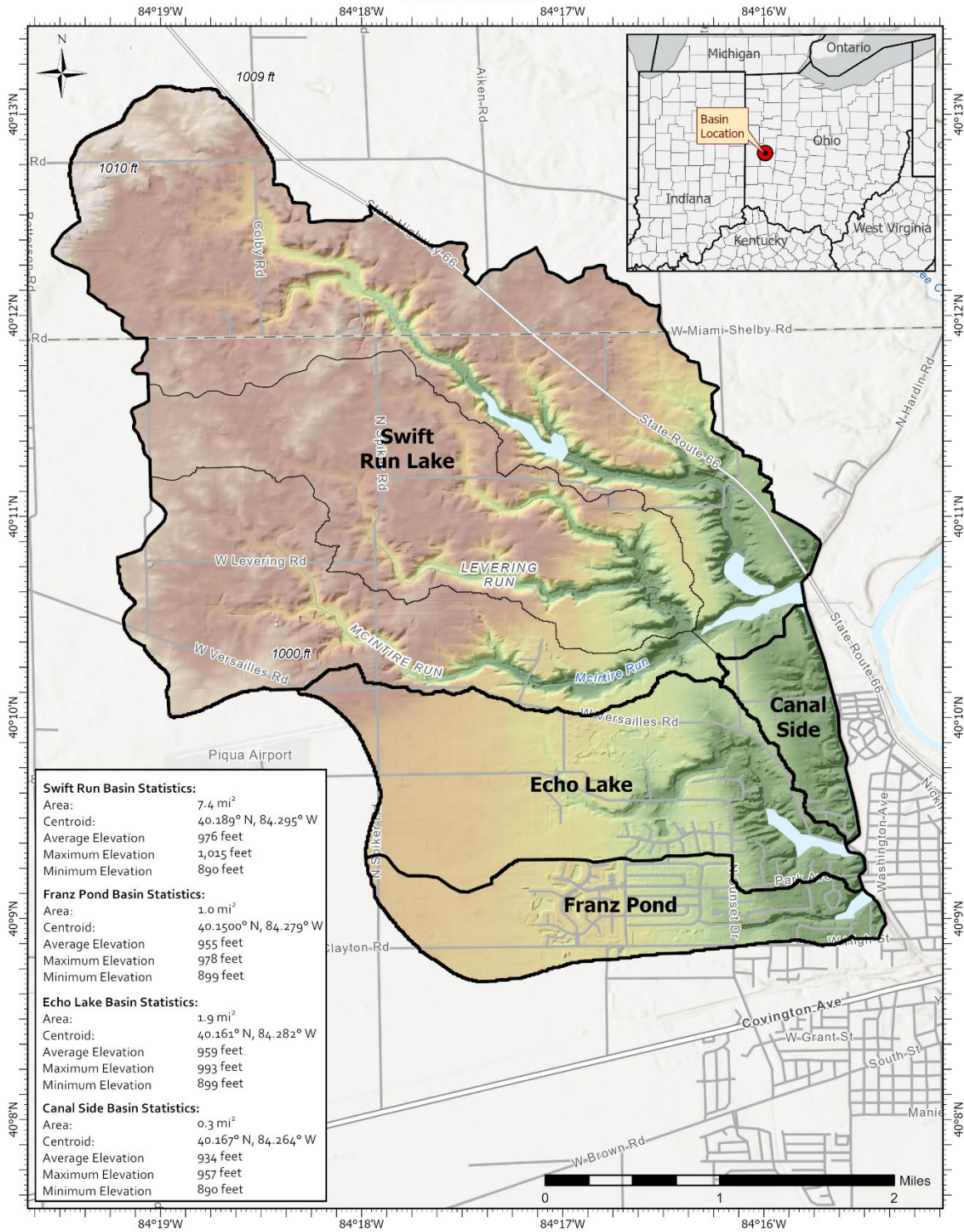
Current understanding of meteorology does not support an explicit evaluation of storm efficiency for use in PMP evaluation. To compensate for this, the period of record was extended to include the entire historic record of rainfall data (nearly 150 years for this study), along with a large geographic region from which to choose storms. Using the long period of record and the large geographic region, the assumption is that at least one storm with dynamics (storm efficiency) that approached the maximum efficiency for rainfall production used in the PMP development has been observed and included in the analysis. In essence, the process is trading time for space to capture PMP 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 (e.g., Schreiner and Riedel, 1978; Hansen et al., 1988; Hansen et al., 1994; Corrigan et al., 1999) and subsequently refined in the numerous site-specific, statewide, and regional PMP studies completed since the early 1990's (e.g., Tomlinson, 1993; Tomlinson et al, 2008; Tomlinson et al., 2013; Kappel et al., 2014; Kappel et al., 2015; Kappel et al., 2016; Kappel et al., 2018; Kappel et al., 2019; Kappel et al., 2020; Kappel et al., 2021; Kappel et al., 2023; Kappel et al., 2024).

Definitions of PMP are found in most of the HMRs issued by the National Weather Service (NWS) and the World Meteorological Organization (WMO, 2009). 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). The PMP is an estimate of an upper physical bound to the precipitation that the atmosphere can produce." Recently, the National Academy of Science supported a study "Modernizing Probable Maximum Precipitation" (2024) which included a suggested update to the definition to include consideration of probability estimate and climate change.

Since the early 1940s governmental agencies in the United States have developed methods to calculate PMP for various regions. These PMP values are used to calculate the PMF, which in turn, is often used for the design of significant hydraulic structures, such as high hazard dams. 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 associated hydrologic applications.

## Swift Run, Echo Lake, and Franz Pond Dams - Piqua, Ohio Basin Statistics



**Figure 2.1: Probable Maximum Precipitation study domain and basin characteristics**

To calculate PMP, the Total Adjustment Factor (TAF) for each storm must be applied to the Storm Precipitation Analysis System (SPAS) analyzed depth-area-duration (DAD) value (Hultstrand and Kappel, 2017) for the area size and duration of interest over each grid covering the basin of interest to yield a total adjusted rainfall value. The TAF is a product of each storm's (IPMF) and geographic transposition factor (GTF). The storm's total adjusted rainfall value is then compared with the other total adjusted rainfall depths of every storm in the database, for a given storm type, transposable to the target grid point. The largest adjusted rainfall depth becomes the PMP for that point at a given duration for that storm type. The basin average adjustment value and the TAF for each storm are provided in Table 2.1 and Figure 2.2 for local and hybrid storms and Table 2.2 and Figure 2.3 for general storms. This process must be repeated for each of the grid cells intersecting the input drainage basin for each applicable duration and storm type. The gridded PMP depths are calculated on a 30 arc-second spatial resolution grid network over the basins (Figure 2.4). The gridded PMP is averaged over the drainage basin of interest to derive a basin average.

**Table 2.1: Basin average storm adjustment factors-Hybrid and Local storms**

**Table 2.2: Basin Average Storm Adjustment Factors-General and Hybrid storms**





### PMP Grid Network (30 arc-second resolution) Swift Run, Echo Lake, and Franz Pond Dams

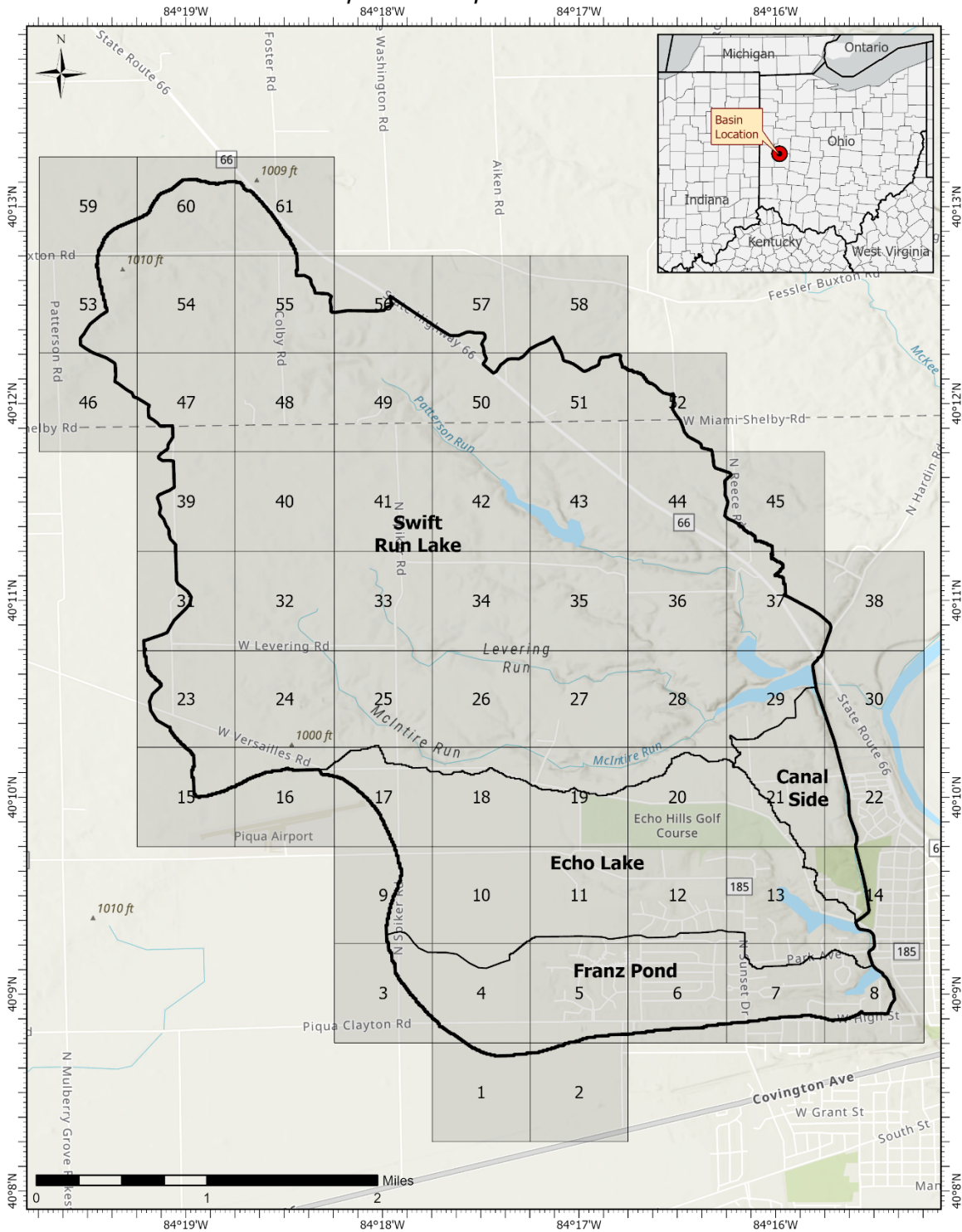


Figure 2.4: PMP grid network over the Piqua basins

This site-specific study provides basin-specific PMP depths based on the area-size of the basin and the durations most relevant for PMF evaluations. The PMP depths are calculated for the area-size of the basins (ranging from 0.3 mi<sup>2</sup> to 7.4 mi<sup>2</sup>). Depths are provided from 1-hour through 72-hours. This allowed for evaluation of peak runoff over the relatively small basins as well as evaluation of volume of rainfall over longer durations. Depth-duration charts for the adjusted rainfall depths over the Swift basin are provided in Figure 2.5 for local storms and Figure 2.6 for general storms. Hybrid storms are treated as both local and general storm types.

Note, the controlling storm for each duration can be determined from the depth-duration charts and it is important to note that several storms control PMP as the duration changes and there are generally several storms supporting the controlling storm PMP depths. Gridded PMP depths representing the overall basin area size are provided in Table 2.2.

The values in Table 2.3 and Table 2.4 are the actual PMP depths calculated for each basin and are the depths that should be utilized for subsequent PMF development. These represent depths that incorporate the current state-of-the-science methods for PMP development along with an updated storm database.

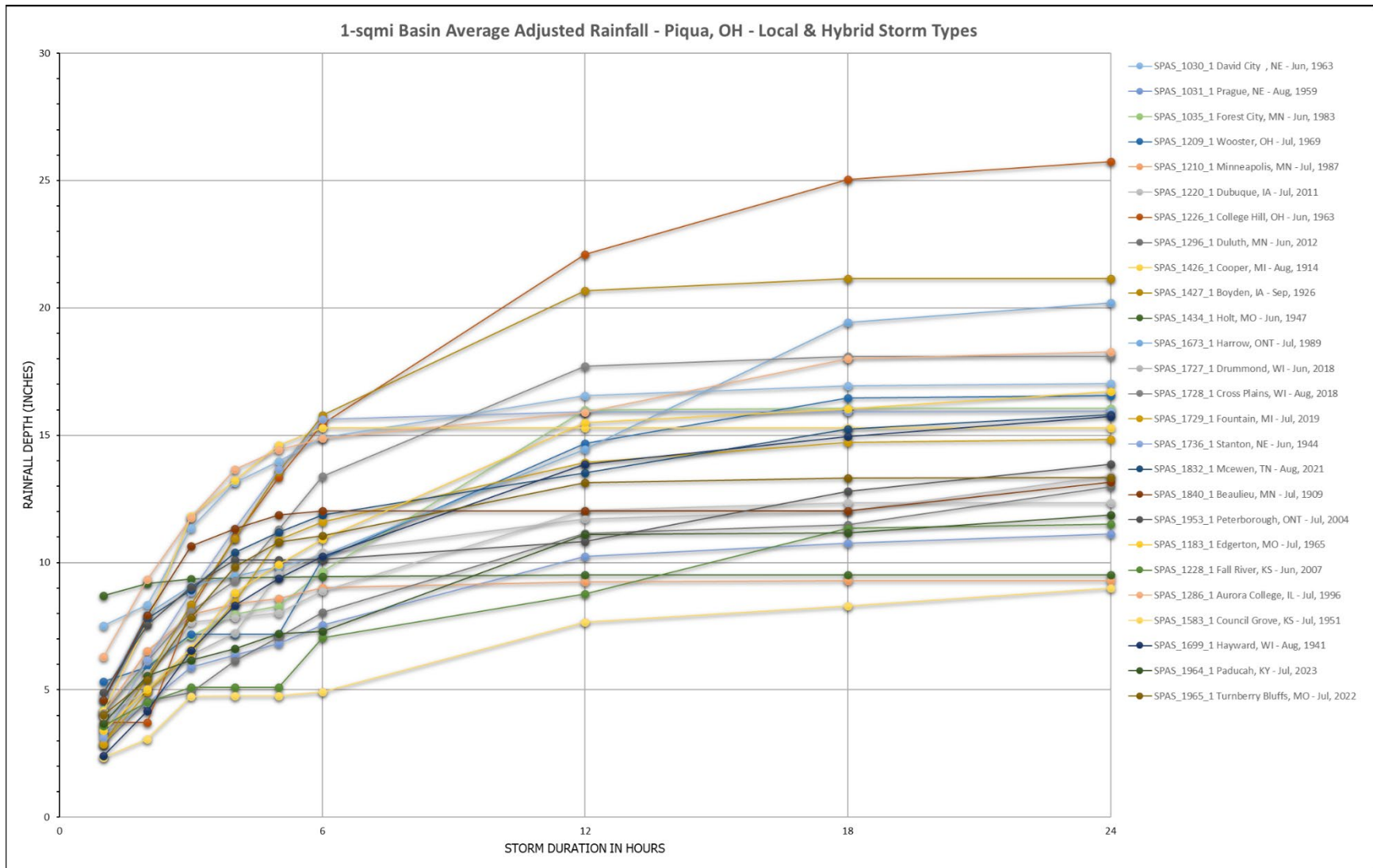


Figure 2.5: Local storm adjusted rainfall depth-area chart

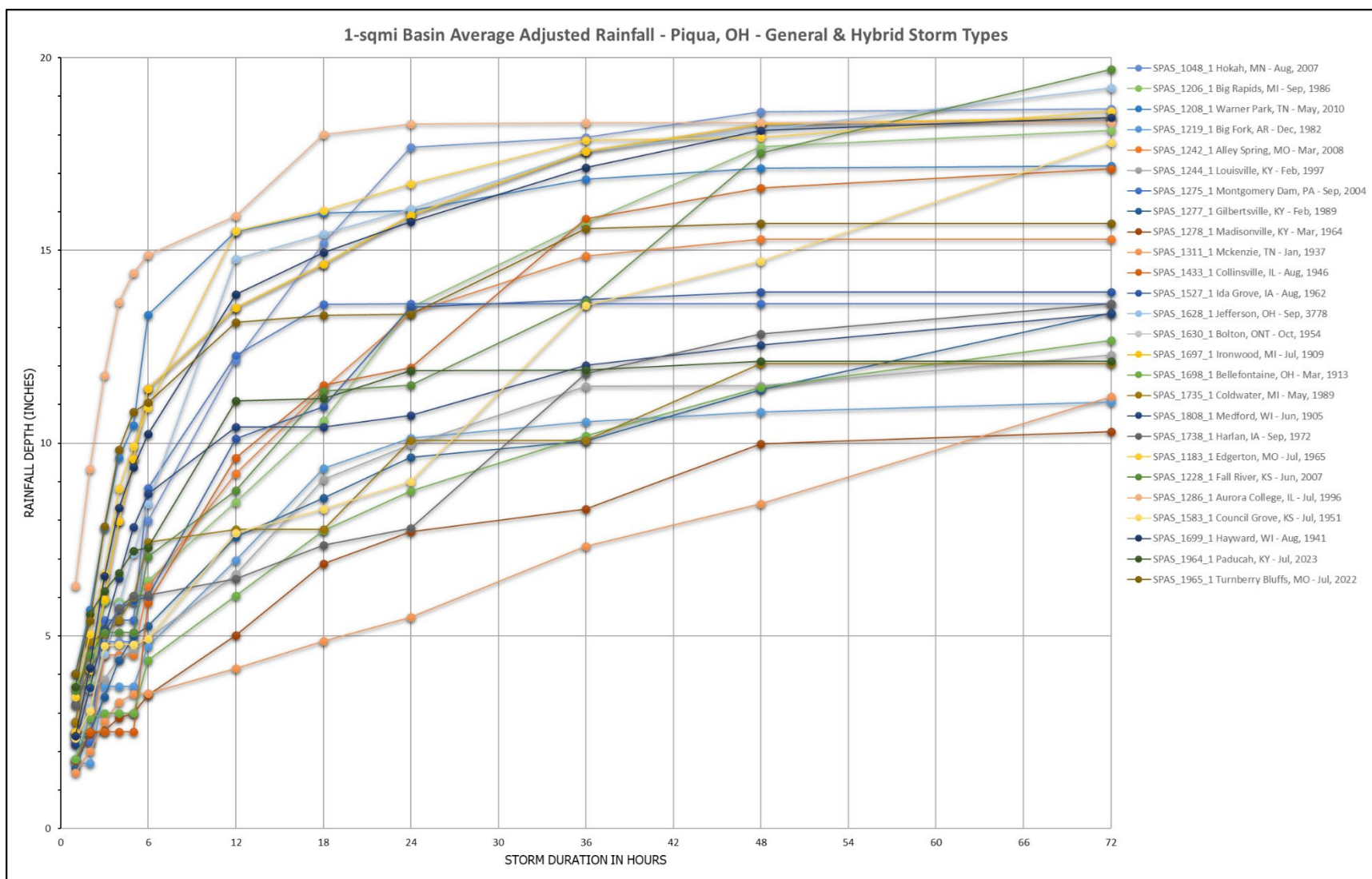


Figure 2.6: General storm adjusted rainfall depth-area chart

**Table 2.3: Basin average Local storm PMP depths**

Basin	Area (mi <sup>2</sup> )	1-hour	2-hour	3-hour	4-hour	5-hour	6-hour	12-hour	24-hour
Swift Run	7.4	8.25"	8.92"	11.35"	13.10"	14.02"	15.45"	19.26"	21.92"
Swift Run Lake Subbasin 1 (North)	7.4	8.25"	8.92"	11.35"	13.09"	14.03"	15.45"	19.26"	21.92"
Swift Run Lake Subbasin 2 (West)	7.4	8.25"	8.91"	11.35"	13.11"	14.01"	15.45"	19.27"	21.91"
Swift Run Lake Subbasin 3 (Southwest)	7.4	8.24"	8.94"	11.34"	13.14"	14.02"	15.44"	19.26"	21.92"
Echo Lake	1.9	8.63"	9.30"	11.77"	13.62"	14.53"	15.60"	21.69"	25.19"
Franz Pond	1.0	8.70"	9.38"	11.80"	13.71"	14.60"	15.80"	22.08"	25.73"
Canal Side	0.3	8.80"	9.45"	11.97"	13.90"	14.70"	16.50"	24.20"	27.50"

**Table 2.4: Basin average General storm PMP depths**

Basin	Area (mi <sup>2</sup> )	1-hour	2-hour	3-hour	4-hour	5-hour	6-hour	12-hour	24-hour	48-hour	72-hour
Swift Run	7.4	6.07"	8.92"	11.31"	13.10"	13.94"	14.40"	15.42"	17.89"	18.05"	19.45"
Swift Run Lake Subbasin 1 (North)	7.4	6.05"	8.92"	11.29"	13.09"	13.92"	14.38"	15.40"	17.87"	18.03"	19.43"
Swift Run Lake Subbasin 2 (West)	7.4	6.08"	8.91"	11.31"	13.11"	13.94"	14.41"	15.43"	17.89"	18.05"	19.46"
Swift Run Lake Subbasin 3 (Southwest)	7.4	6.09"	8.94"	11.34"	13.14"	13.96"	14.44"	15.45"	17.93"	18.09"	19.50"
Echo Lake	1.9	6.30"	9.30"	11.73"	13.62"	14.39"	14.87"	15.87"	18.28"	18.61"	19.77"
Franz Pond	1.0	6.30"	9.38"	11.80"	13.71"	14.48"	14.95"	15.95"	18.35"	18.72"	19.82"
Canal Side	0.3	6.40"	9.45"	11.97"	13.90"	14.63"	15.10"	16.10"	18.50"	18.87"	19.97"

## 2.1 Comparisons of PMP Results to Previous Estimates and Precipitation Frequency Depths

In the process of deriving PMP depths, certain aspects contain a range of possible outcomes and therefore the depths represent the best estimates. The parameters utilized in this study are standard to the PMP development process; however, it is of interest to assess the sensitivity of PMP depths to assumptions that were made and to the variability of input parameter depths.

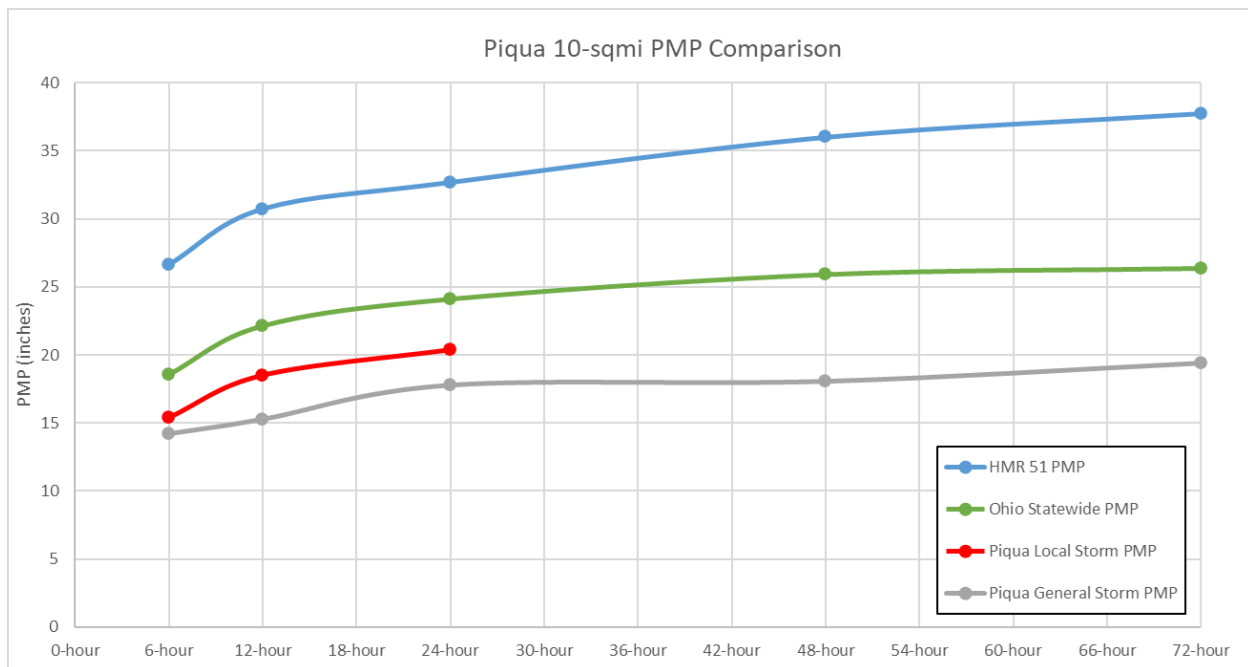
Direct comparison against the PMP depths provided in HMR 51 and the Ohio Statewide PMP study were made at each commonly available duration. Note, the gridded all-season PMP depths from previous studies are not delineated by storm type.

Unfortunately, working papers and notes from the HMR 51 PMP depths are not generally available in most cases. Therefore, direct comparisons with storm adjustments and applications are somewhat limited. Comparisons demonstrated reductions from the PMP depths from that report (Table 2.5). The differences are the result of an improved storm maximization methodology and dew point climatology, more accurate storm adjustments, and more accurate and focused storm transposition limits. These reductions are consistent with other PMP studies that have been completed within the HMR 51 domain since its publication. AWA PMP depths utilize an improved understanding of storm dynamics, updated climatologies to maximize storms, and more accurate transposition limits. Table 2.5 and Figure 2.7 provide the PMP depth comparisons made against the 10-square mile HMR 51 PMP depths over the Piqua basins.

**Table 2.5: Site-specific local storm 10-sqmi PMP compared with HMR 52**

Basin	Analysis					
	Area (mi <sup>2</sup> )	6-hour	12-hour	24-hour	48-hour	72-hour
HMR 51 PMP	10.0	26.64"	30.74"	32.70"	36.02"	37.76"
Piqua Basin PMP (LS)	10.0	15.38"	18.50"	20.38"	20.38"	20.38"
Percent Change		-42%	-40%	-38%	-43%	-46%

The 10-square mile gridded PMP depths were also extracted from the Ohio Statewide PMP Study and compared to the site-specific PMP developed for this study (Figure 2.7). Additionally, PMP depths were derived for the specific area-size of each individual basin for both studies and compared at the 6-hour and 24-hour durations (Table 2.6). The controlling storms vary with basin area-size and duration and as a result the difference in PMP also varies. At the 6-hour duration, site-specific PMP depths are generally 17-20% less than the Statewide study. At the 24-hour duration, the reduction is 11% over the largest basin, Swift Run (7.4 mi<sup>2</sup>). As the basin sizes decrease, the change from the Statewide PMP estimates also reduce. For 24-hour point estimates, the difference in PMP is negligible.



**Figure 2.7: Piqua PMP depth-duration comparison to previous studies**

The primary factor contributing to the reduction in PMP when compared to the Ohio Statewide Study is an updated methodology for calculating storm transposition adjustment factors. The current practice is to use the GTF; a ratio of the 100-year precipitation frequency climatology between the storm center and the target basin. This is a wholistic representation of all the physical processes that influence extreme rainfall for the storm type and duration. Previously, storm transposition was represented only by the elevation and moisture differences calculated using the moisture transposition factor (MTF), which quantifies the difference in available atmospheric at the target basin location versus the storm center. Other than surface and inflow barrier elevation, the MTF did not account for any additional physical or geographical processes that influence rainfall. For the controlling storms relevant to the Piqua basins, the GTF generally produces a lower, and more representative adjustment factor.

There are additional factors contributing to difference from the Ohio Statewide Study that should also be considered. The Ohio Statewide Study calculated PMP specifically at 23 grid point locations across the domain, then nearest (grid points #7 and #13) being ~50 miles from the Piqua basins. This necessitated spatially interpolating the PMP at the closest grid points to estimate the

depths at Piqua. Furthermore, the Statewide study provided values at the 1-square mile and 10-square mile area-sizes, necessitating areal interpolation at the basin sizes while the site-specific PMP depths were calculated explicitly for the basin area sizes. Additionally, depth-duration envelopment curves were applied to PMP at each grid point for the Statewide Study. This envelopment added approximately 7% to the PMP estimate at 24-hours and ~15% at 72-hours. Envelopment at shorter durations was negligible. The site-specific methodology of calculating PMP did not necessitate adding an envelopment curve. Additional factors contributing to differences, to a lesser degree, include an updated dew point climatology used to maximize storms, updated SPAS analyses used to develop storm depth-area-duration curves, and refined transposition limits and storm typing. Finally, while not directly contributing to a decrease in PMP, the addition of new storms strengthened the storm database allowing for a more robust analysis.

**Table 2.6: AWA PMP compared to the Ohio Statewide PMP depths for each basin**

Sub basin	Area (mi <sup>2</sup> )	Ohio Statewide PMP (2013)		Piqua Site-Specific PMP (Local Storm)		Percent Change	
		6 hr	24 hr	6 hr	24 hr	6 hr	24 hr
n/a	1	19.8"	27.7"	15.8"	25.8"	-20%	-7%
n/a	10	18.5"	24.1"	15.4"	20.4"	-17%	-15%
Swift Run Lake	7.42	18.67"	24.57"	15.45"	21.92"	-17%	-11%
Echo Lake	1.95	19.42"	26.66"	15.60"	25.19"	-20%	-5%
Canal-side	0.37	19.80"	27.70"	16.50"	27.50"	-17%	-1%
Frantz Pond	1.05	19.77"	27.62"	15.80"	25.73"	-20%	-7%

The ratio of the PMP to 100-year return period precipitation depths is generally expected to range between two and four, with depths 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 6-hour and 24-hour 1-square mile PMP depth was compared directly to the NOAA Atlas 14 100-year 6-hour and 24-hour precipitation depths. The comparison produces a ratio of PMP to 100-year rainfall. Table 2.7 provides the PMP to 100-year rainfall ratios for 6-hour local storm PMP and 24-hour general storm PMP. These ratios follow similar patterns seen in adjacent PMP studies. These ratios are in reasonable proportion for the study area and demonstrate the PMP depths are at appropriately rare levels.

**Table 2.7: Basin Average 1-mi<sup>2</sup> PMP compared to basin specific Precipitation Frequency estimates**

	Basin Average PMP	NOAA Atlas 100- year	
		Precipitation	Ratio
General 24-hour (Point Depth)	18.26"	5.83"	3.13
Local 6-hour (Point Depth)	14.61"	4.29"	3.41
Local 24-hour (Point Depth)	25.75"	5.83"	4.42

### 3.0 TEMPORAL DISTRIBUTIONS

Numerous PMP temporal distribution patterns have been developed and provided for application to the Piqua basin PMP depths to provide incremental and accumulated hypothetical design storm rainfall depths considered appropriate for use in PMF development. These patterns include 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile Huff Curve and synthetic temporal distributions that were originally developed during the Oklahoma-Arkansas-Louisiana-Mississippi Regional PMP study (2019) and the patterns from the western portion of the Pennsylvania Statewide PMP study (2019) and are considered applicable to the Piqua PMP. Additionally, the accumulation patterns of each Piqua PMP controlling storm were assessed as additional temporal distribution patterns. Of these, only the Boyden, IA Sep. 1926 (SPAS 1427) 6-hour pattern and the Aurora College, IL July 1996 24-hour pattern were directly applicable as PMP temporal distribution patterns. In total, 17 different temporal distribution patterns of varying storm duration and timestep lengths are provided with this study (Figure 3.1 through Figure 3.7). Each of these patterns were applied to the Piqua basins PMP to ensure they did not result in accumulation rates that would exceed interim PMP depths at any intermediate duration. Additionally, existing temporal distribution patterns recommended by the Ohio DWR guidance may also be applied to the PMP depths for PMF development.

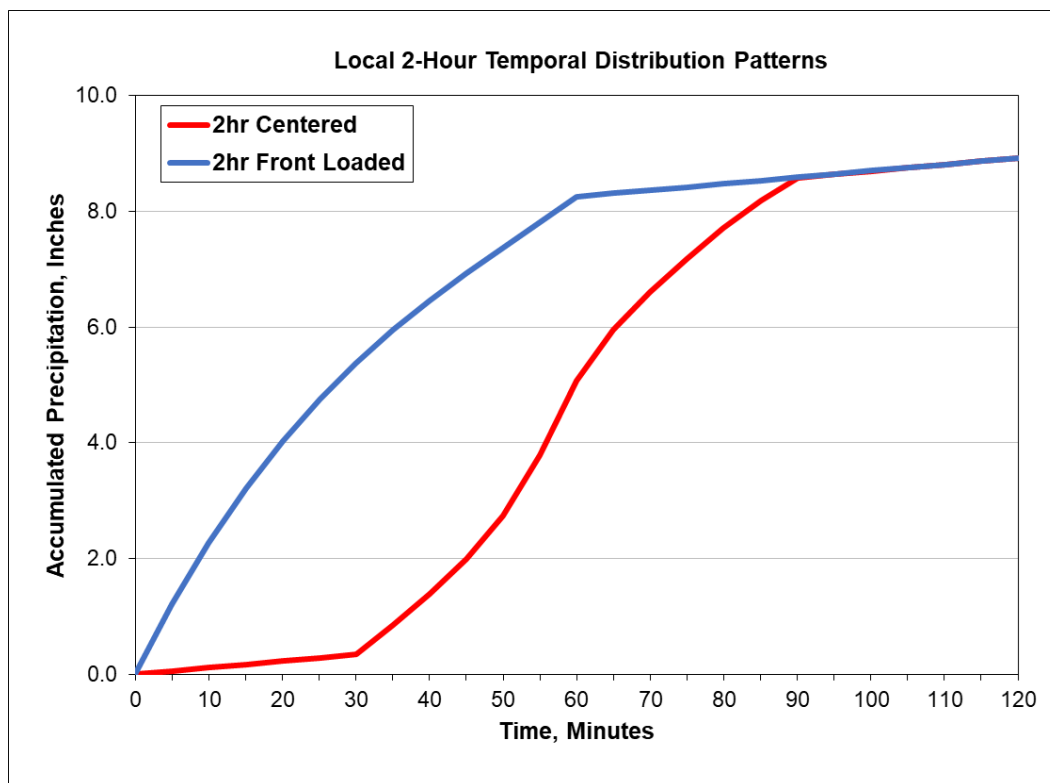


Figure 3.1: 2-hour temporal distributions applied to the Swift Run basin PMP

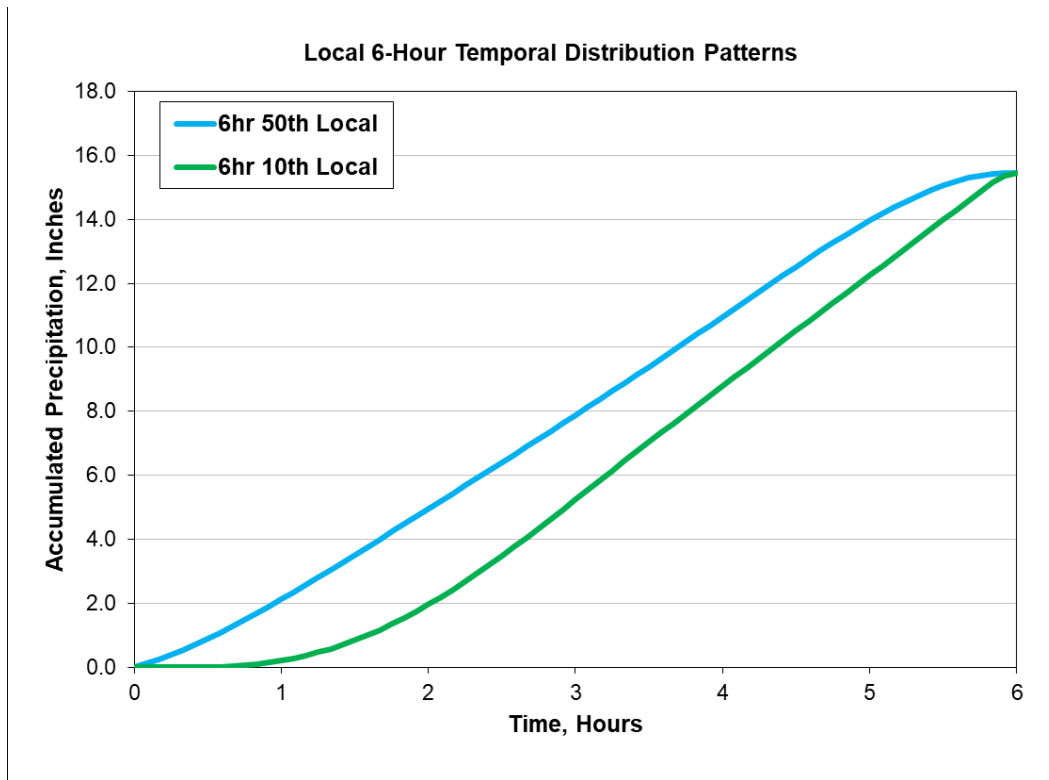


Figure 3.2: 6-hour temporal distributions applied to the Swift Run basin PMP

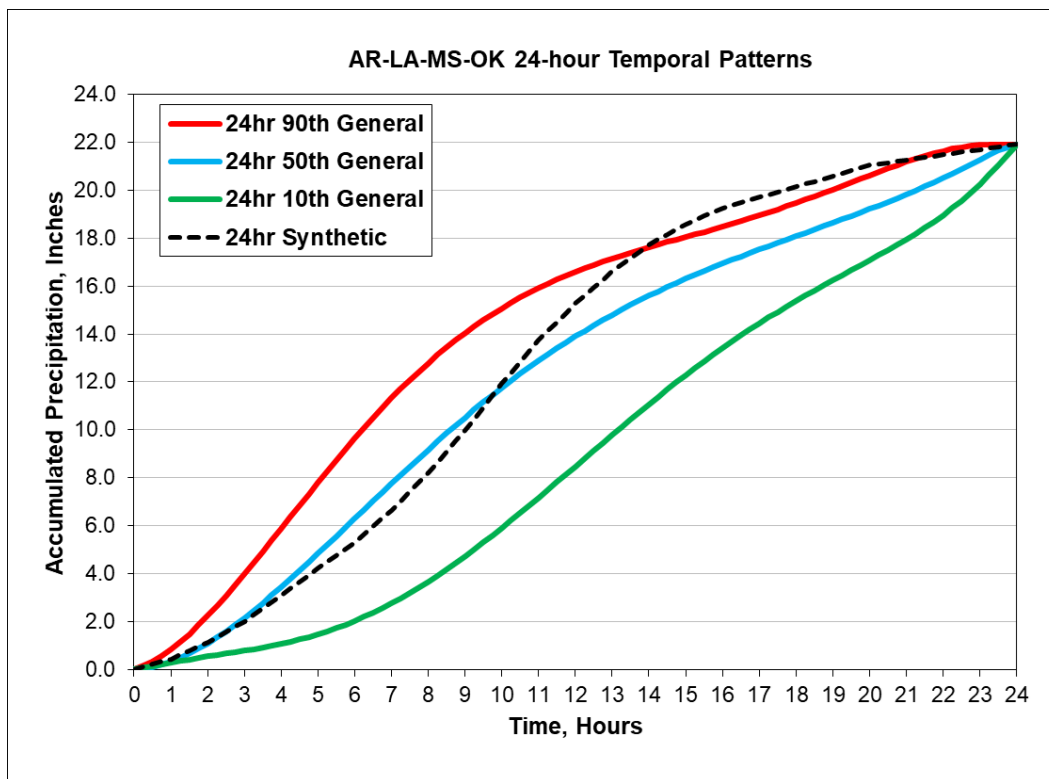


Figure 3.3: 24-hour AR-LA-MS-OK temporal distributions applied to the Swift Run basin PMP

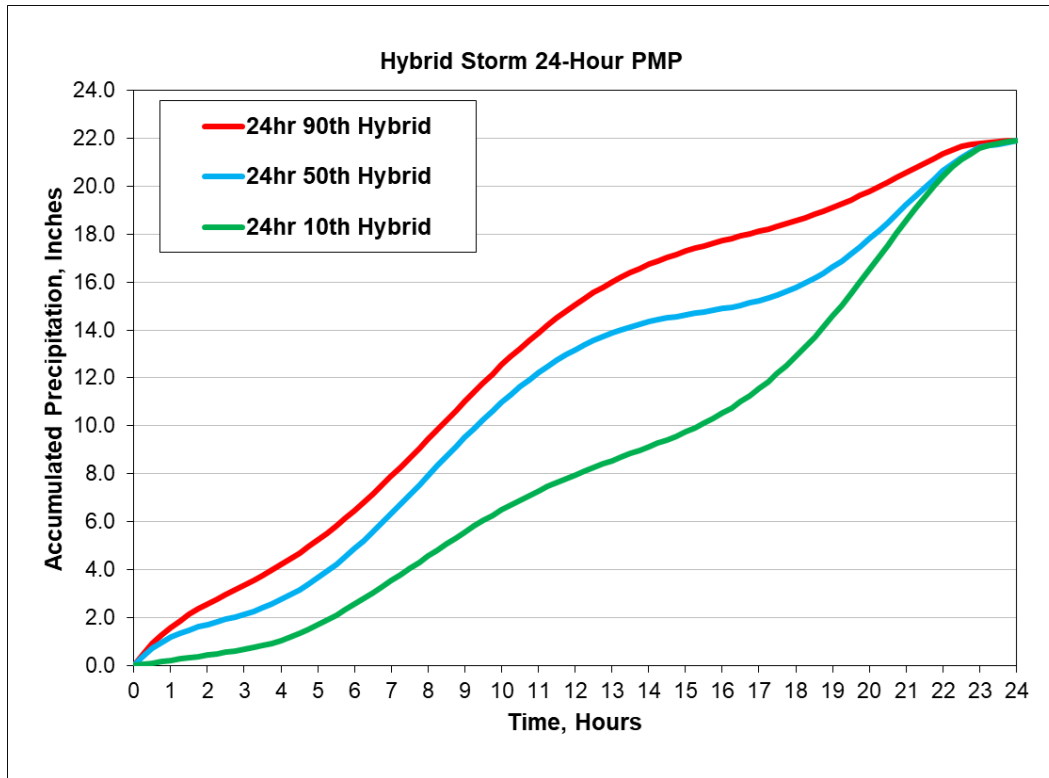


Figure 3.4: 24-hour hybrid AR-LA-MS-OK temporal distributions applied to the Swift Run basin PMP

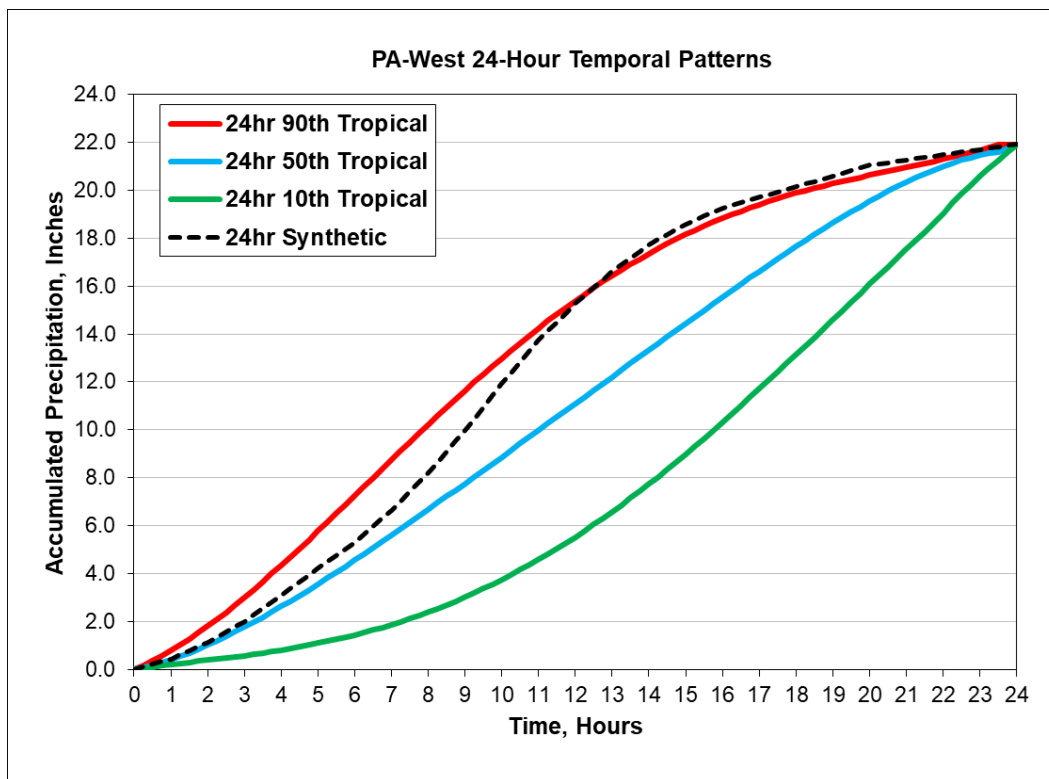


Figure 3.5: 24-hour PA-West temporal distributions applied to the Swift Run basin PMP

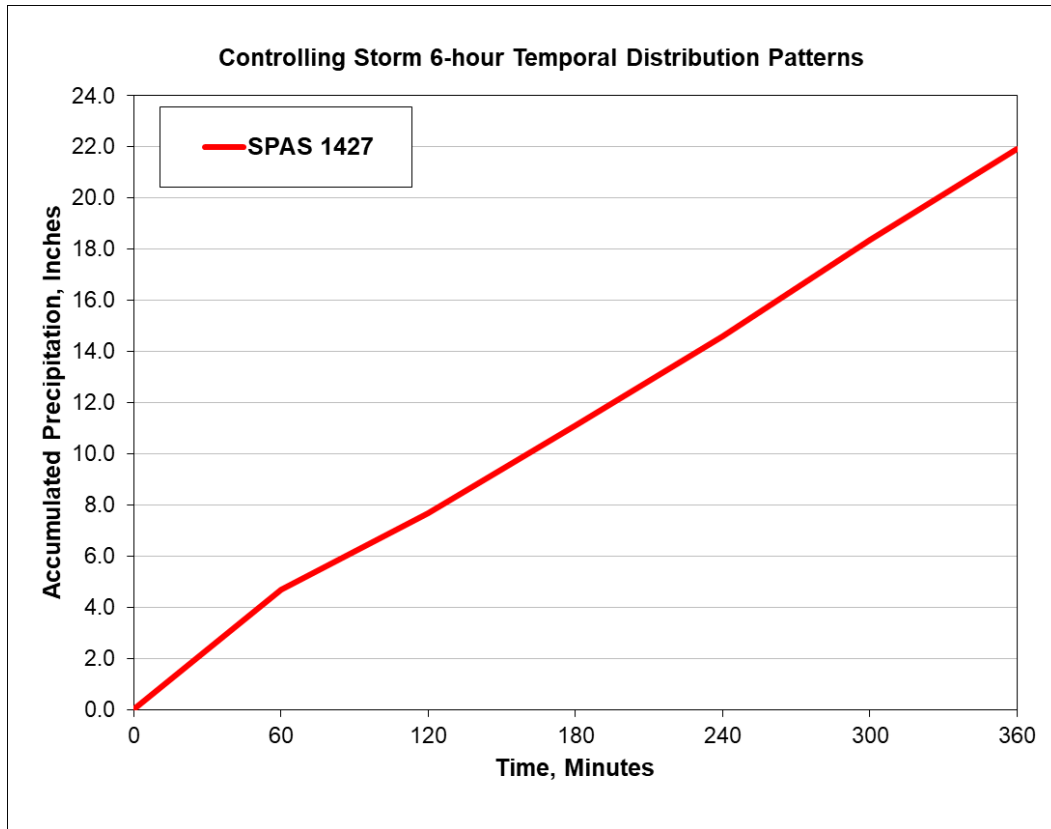


Figure 3.6: 6-hour controlling storm temporal distribution applied to the Swift Run basin PMP

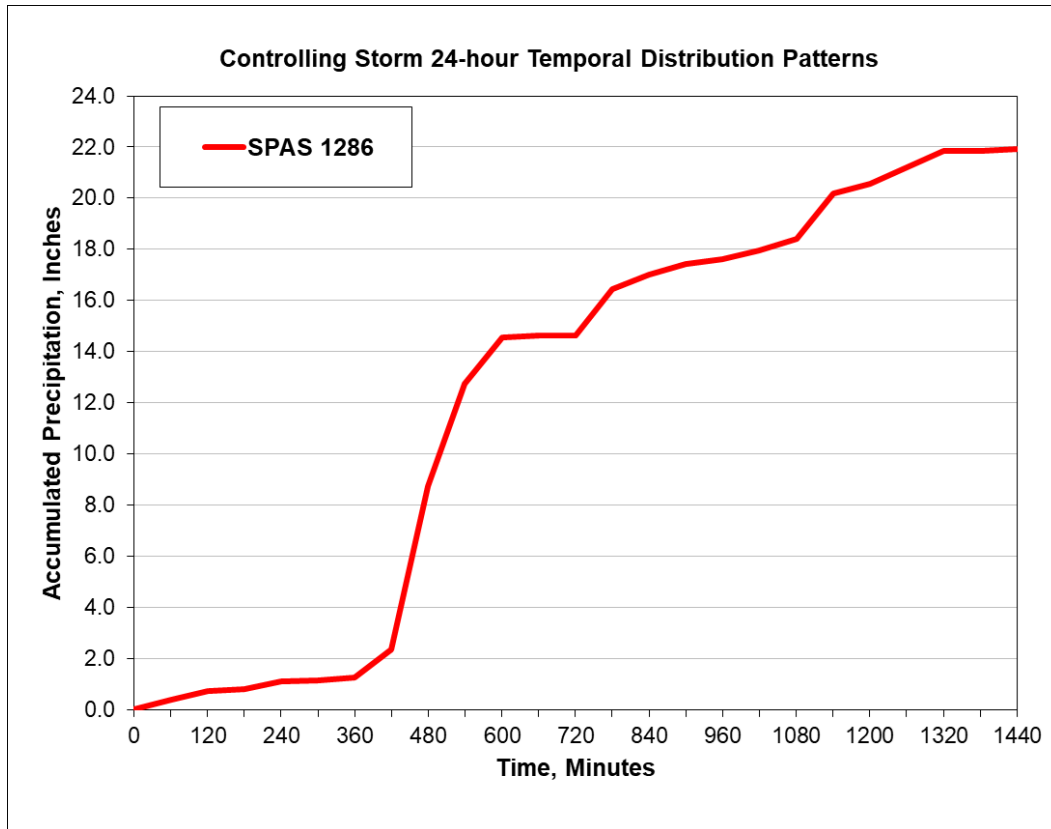


Figure 3.7: 24-hour controlling storm temporal distribution applied to the Swift Run basin PMP

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