Flood Analysis for the World-Record-Setting July 1942 "Smethport" Storm

Supporting the Pennsylvania Probable Maximum Precipitation Study

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Author Note
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ABSTRACT

The Division of Dam Safety, Pennsylvania Department of Environmental Protection (PA DEP), is currently developing a Probable Maximum Precipitation (PMP) Study for the Commonwealth of Pennsylvania. The PMP depths for Pennsylvania, particularly along the western edge of the Allegheny Mountains, are greatly influenced by the exceptional magnitude of a world-record-setting storm that occurred in July 1942 in the north-central region of Pennsylvania. Available data from this storm includes numerous measurements of rainfall depths exceeding 30 inches in 4.5 hours. The July 1942 storm is critical for PMP development in the region. However, there are uncertainties related to the quality of the rainfall data collected in this rural region of Pennsylvania. Therefore, a critical component of the study is a hydrologic and hydraulic simulation of the watershed's response to the July 1942 rainfall event, using a combination of lumped and distributed (2D) techniques. The purpose of the flood analysis was to substantiate the recorded rainfall or identify, isolate, and quantify observational uncertainties in the recorded rainfall and develop rainfall depth, spatial, and/or temporal patterns that better match observed flood data. This article describes the approach taken to develop and calibrate the flood models, comparisons between modeled and observed flood data, and results of iterations to refine our understanding of the rainfall magnitude, spatial patterns, and/or temporal patterns.

OBJECTIVE

The Division of Dam Safety, Pennsylvania Department of Environmental Protection (PA DEP), is currently sponsoring a Probable Maximum Precipitation (PMP) Study for the Commonwealth of Pennsylvania, led by Applied Weather Associates (AWA). Without an updated study, PMP data are typically obtained from one or more of a series of Hydrometeorological Reports (HMRs) prepared by the National Weather Service (NWS). Areas of the United States east of the 105th meridian are covered by HMR 51 (Schreiner, 1978), which provides generalized depth-area-duration PMP data; with additional generalized temporal and spatial formation in HMR 52 (Hansen, 1982). The outcome of the updated PMP study will enable users in Pennsylvania, many of whom are dam owners, to access site-specific hourly PMP data for areas as small as 1 km2 for evaluating the impact of the Probable Maximum Flood (PMF) on critical infrastructure (existing or planned), particularly high-hazard dams. The Pennsylvania PMP study uses a storm-based method to transposition and maximize extreme rainfall events in the region to create an envelope of depth-area-duration relationships unique to specific locations in the Commonwealth. Because it is storm-based, PMP depths for Pennsylvania, and much of the larger region covered by HMR 51, are greatly influenced by the exceptional magnitude of a storm that occurred on July 18, 1942 in the region of McKean County (PA), Potter County (PA), and Cattaraugus County

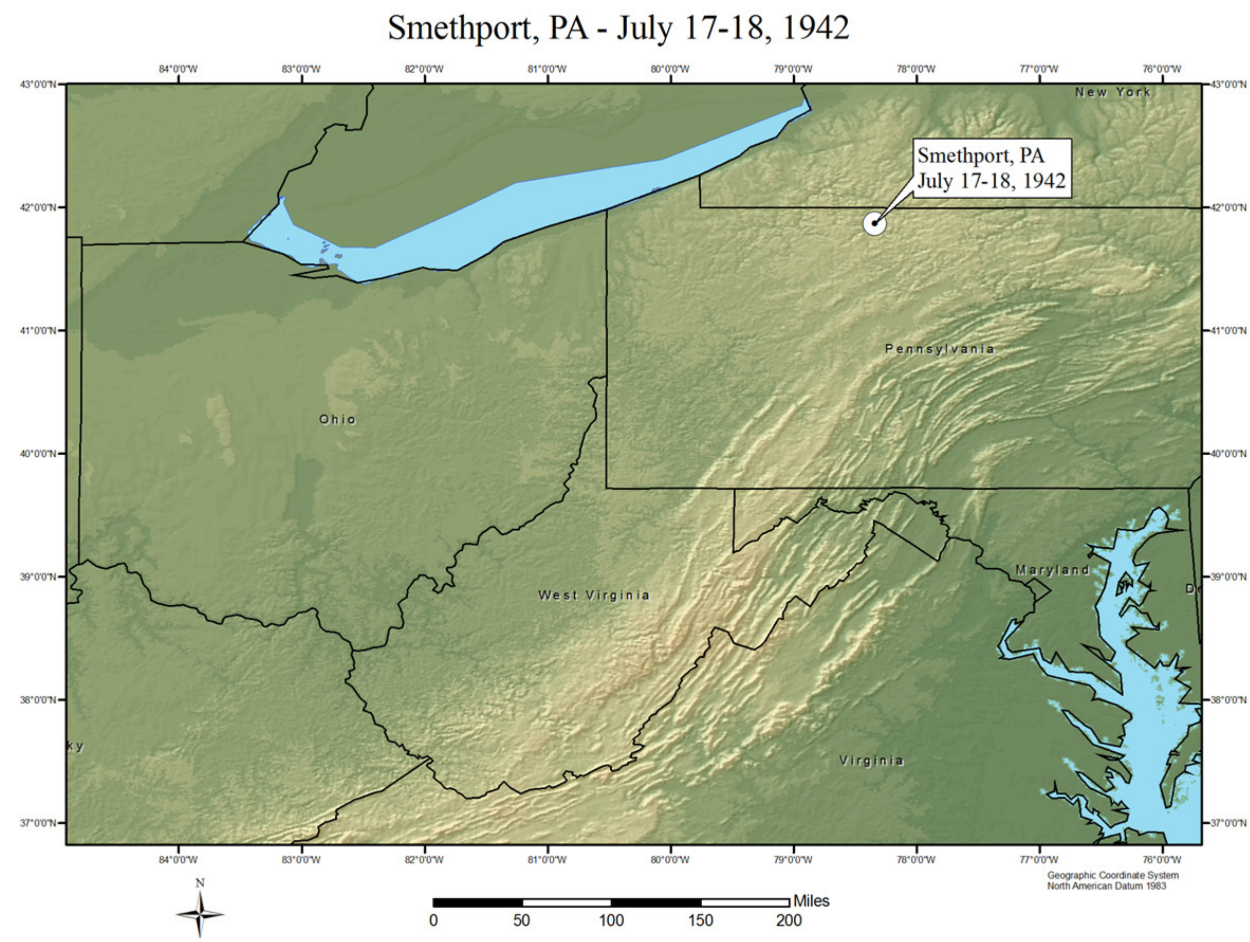

Figure 1: Location of July 1942 Storm Center

(NY). The storm-center occurred in the Smethport/Port Allegany region McKean County, PA. See Figure 1.

The focus of this article is on the characteristics of the July 1942 storm and the flood analysis that provided additional insights on the storm's rainfall accumulation patterns and magnitude. This is a groundbreaking approach which utilizes the immense amount of rain gauge observational data and post-flood high-water and peak flow measurements. Many of the rainfall observations are from non-traditional sources (i.e. bucket survey data) (Eisenlohr, 1952). However, these data sets are lacking in spatial coverage and temporal accumulation information, especially at the hourly level. The hydrologic information provides a way to back-calculate many of the of the unknown rainfall accumulation characteristics that are not captured by the rainfall observations, which were analyzed using AWA's Storm Precipitation Analysis System (SPAS). The outcome of the flood analysis was to substantiate the recorded rainfall or identify, isolate, and quantify observational uncertainties in the recorded rainfall and develop rainfall depth, spatial, and/or temporal patterns that better match observed flood data. The quality and accuracy of the rainfall data was not pre-judged; the flood analysis was conducted to be unbiased and reveal areas where improved accuracy to rainfall magnitude, temporal, and/or spatial patterns can be achieved. The ultimate result of this improved rainfall analysis would be a more accurate representation of the July 1942 rainfall in time, space, and magnitude. This would result in a more accurate estimation of PMP depths and PMF analyses.

The flood analysis involved the development of calibrated flood models to reproduce the flood and corroborate the recorded rainfall or provides explicit evidence that would support updated rainfall accumulation depth, timing, and/or spatial distributions. Sources of flood data included USGS streamflow gauge records and scientific reports from government agencies on the flood that contained peak flows, peak water surface elevations, time-to-peak, and flow hydrographs at key locations along the Allegheny River, its tributaries and small drainages at the storm center. Most of the official government data came from the USGS Water Supply Paper 1134-B (Eisenlohr, 1952) and Pennsylvania Department of Forestry and Waters Report (Commonwealth of Pennsylvania, Department of Forestry and Waters, 1943). Flood data was also collected during a site visit, when key locations were inspected to visualize high-water mark and other flood observations. The team met with individuals and historic societies with knowledge or records of the event for additional insight. The site visits focused on populated areas most severely affected by the flood, particularly Port Allegany, Coudersport, Smethport, Eldred, and Portville. Newspaper articles and photos provided visual markers of the flood and depth and time information.

DESCRIPTION OF THE JULY 1942 STORM

According to the National Oceanic and Atmospheric Administration (NOAA), the "Smethport" Storm of July 18, 1942, was a world-record setting event for the 3- and 4.5-hour durations at 28.5 and 30.8 inches, respectively (National Oceanic and Atmospheric Administration, 2017). See Figure 2. A significant number of rainfall observations were reported; however, most were unofficial "bucket surveys" that have uncertainties in the total reported rainfall and limited temporal information. See Figure 3 for the locations of the hourly gauges in the storm region and Figure 4 for all of the observation points (including bucket surveys) in the study area and vicinity of the storm center. As shown in Figure 5 through Figure 7, the hourly gauges in the areas surrounding the storm center near Smethport and Port Allegany show an initial intense burst of rain near midnight of July 18, 1942 followed by lower intense rainfall then a second significant rainfall period. (Note that midnight of July 18, 1942 corresponds to the end of Index Hour 47 on the hyetographs.) While significant number of total rainfall depths were recorded, including the "bucket surveys", only the scattered hourly gauges shown in Figure 3 and Figure 4 were available to provide temporal information. The flood analysis, discussed later in the article, provides key insights into the temporal patterns of the storm, particularly at and in the vicinity of the storm center.

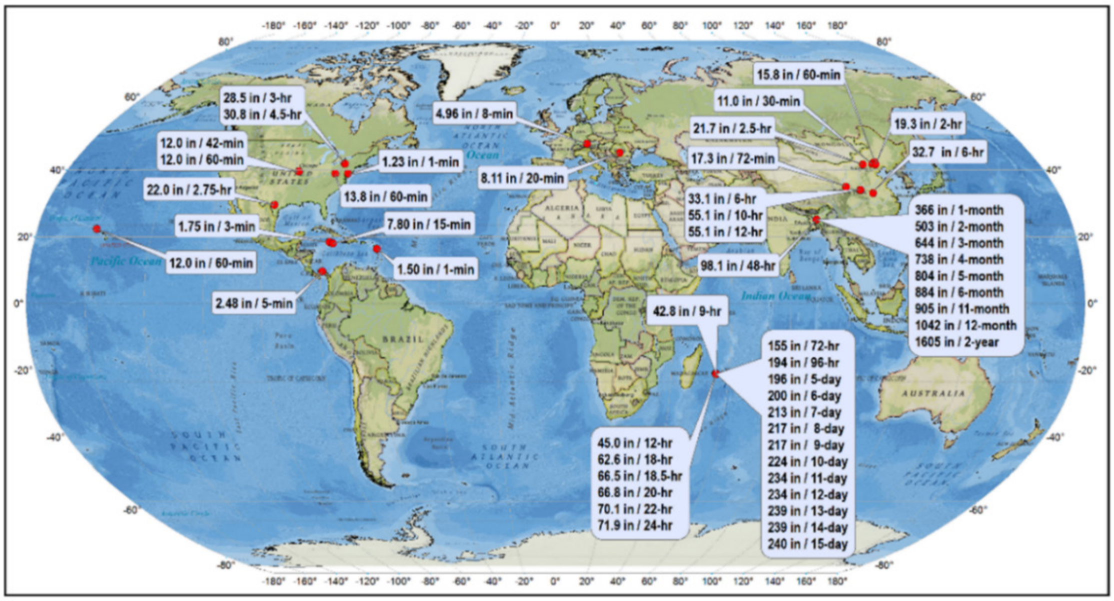

Figure 2: Greatest Observed Point Precipitation Values for the World (National Oceanic and Atmospheric Administration, 2017)

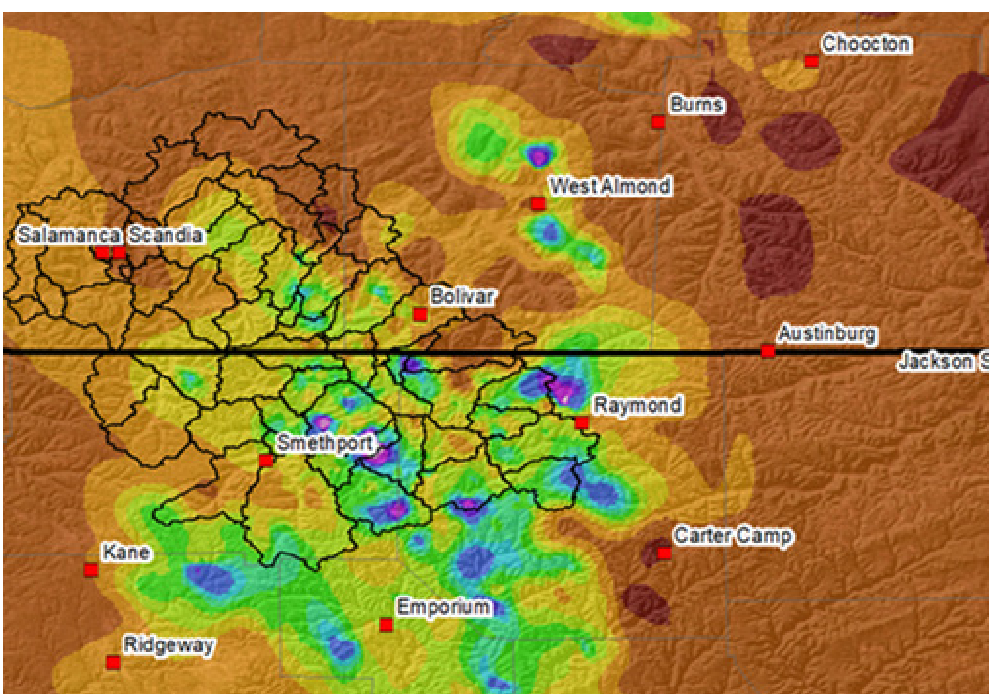

Figure 3: Location of Hourly Rain Gages in Storm Region New York/ Pennsylvania Border

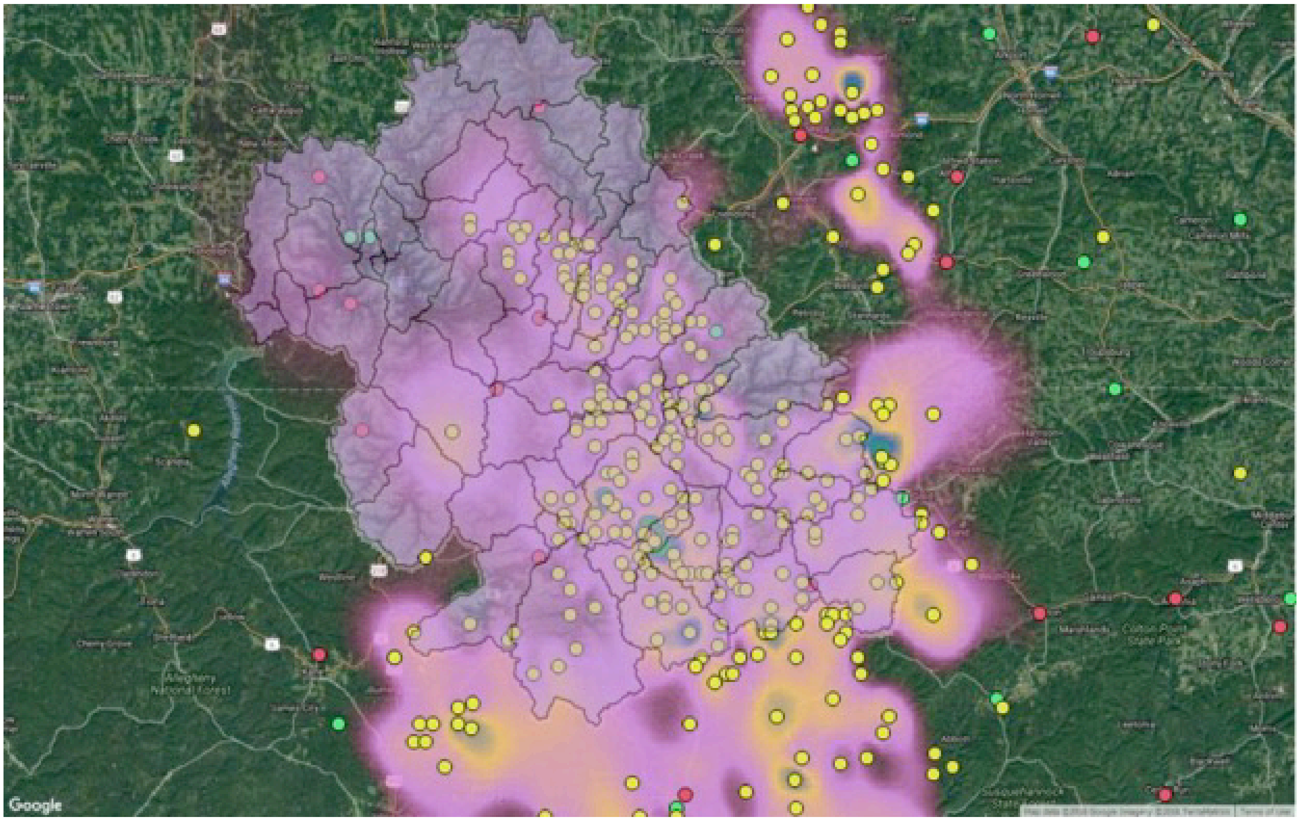

Figure 4: All Rain Gages in Study Area and Vicinity of Storm Center

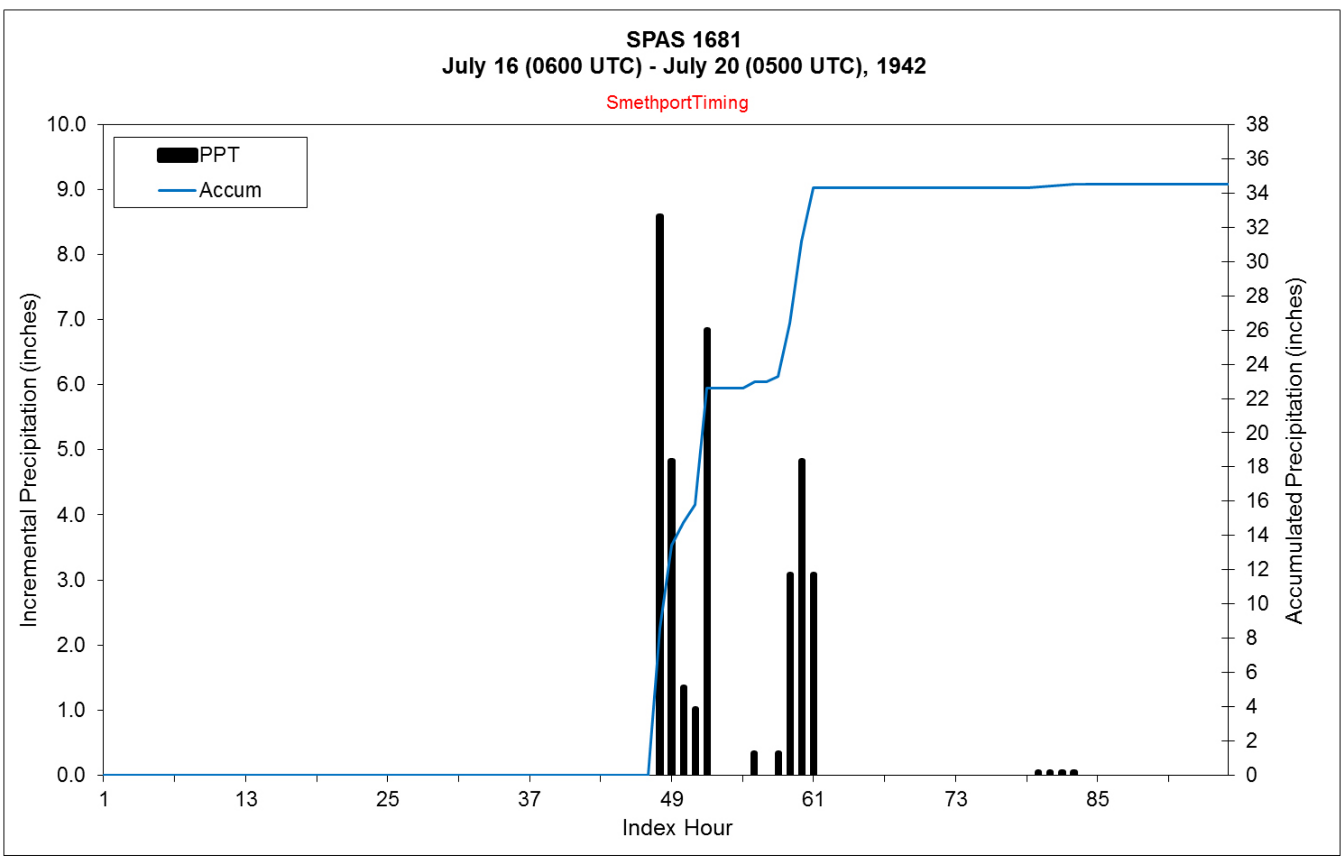

Figure 5: Rainfall Hyetograph at Smethport Hourly Gage

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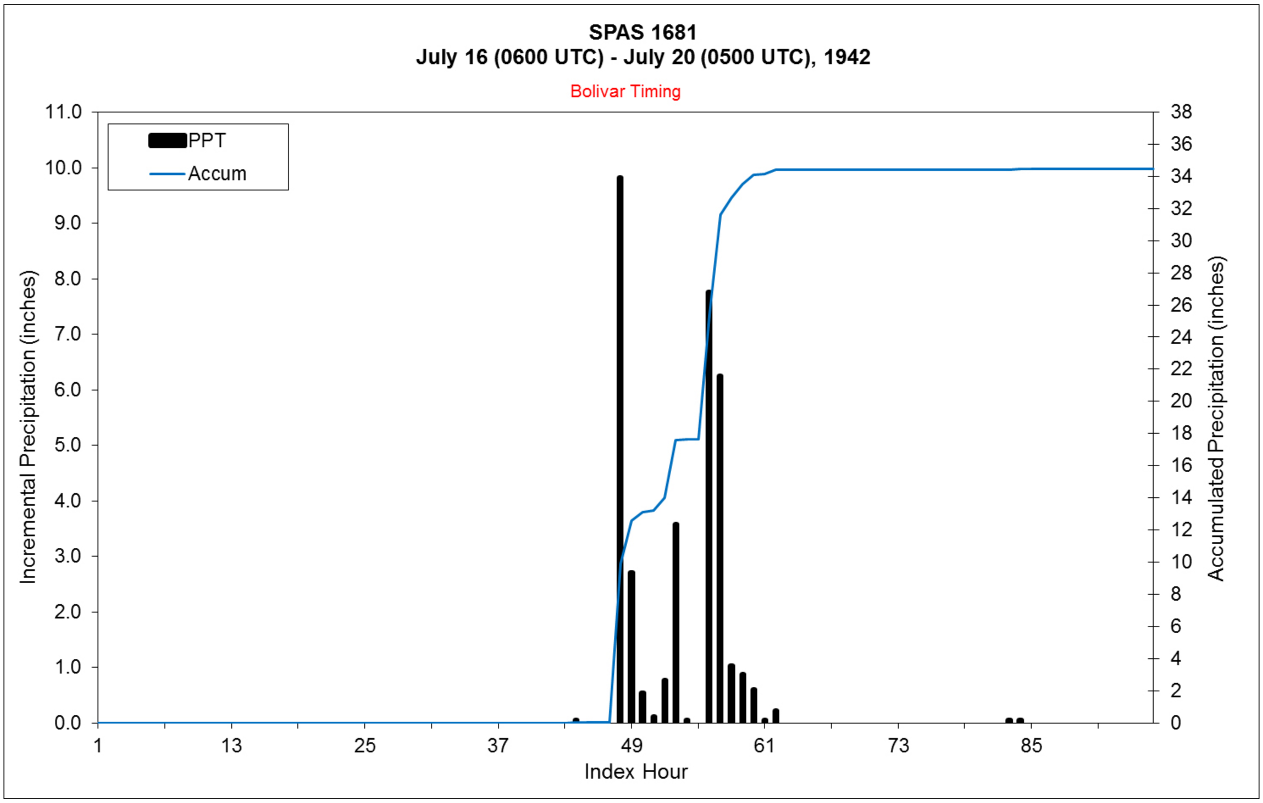

Figure 6: Rainfall Hyetograph at Bolivar Hourly Gage

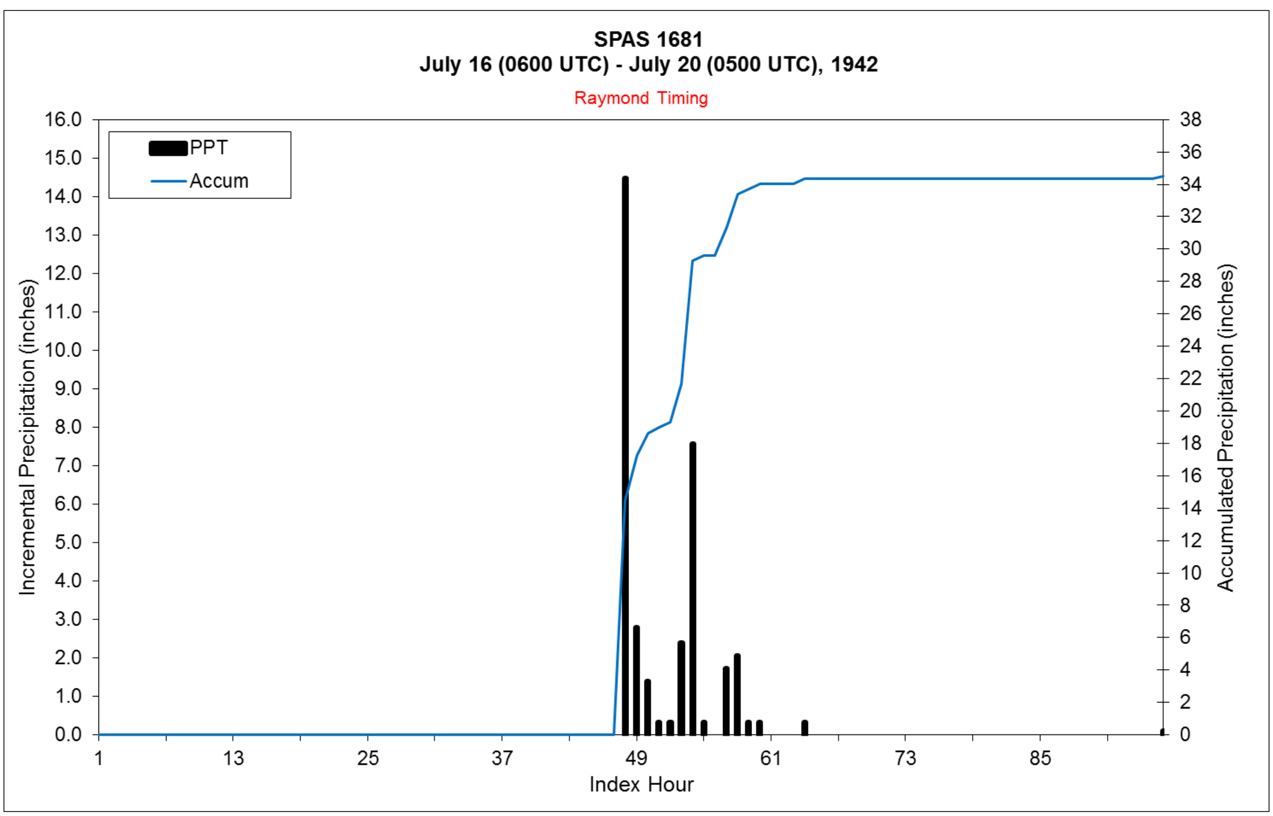

Figure 7: Rainfall Hyetograph at Raymond Hourly Gage

USE OF THE JULY 1942 STORM FOR PROBABLE MAXIMUM PRECIPITATION ESTIMATES

The Smethport storm is one of the few storms used in the series of HMRs where the NWS provided explicit discussions and an image of the transposition limits. Therefore, the limitations of where this storm was intended to be used are known. See Figure 8 from HMR 52, Figure 26 (Hansen, 1982). This image demonstrates that the NWS only intended for this storm to effect areas along and immediately to the west of the Appalachian Mountains where topographical and meteorological patterns are similar to the storm center location. However, HMR 51 implicitly allowed the storm to influence PMP values over almost the entire region covered by HMR 51. This is known because the PMP depths for 6, 12, and 24 hours slightly undercut the values at the Smethport storm center but are significantly greater than any other supporting storm throughout the remaining regions. This demonstrates that the PMP contours provided in HMR 51 envelop the Smethport storm center and follow a gradient through the overall region that is set by the Smethport storm center value. Therefore, the storm is implicitly influencing PMP depths throughout almost the entire HMR 51 region, far beyond the intended areas of influence as set by the NWS and far beyond the limits of where it could meteorologically occur. Because of this, the majority of infrastructure required to design to PMP values using HMR 51/52 (used to generate PMF hydrologic and hydraulic information) are influenced by this storm's values. Therefore, any adjustments to the Smethport storm rainfall depths,

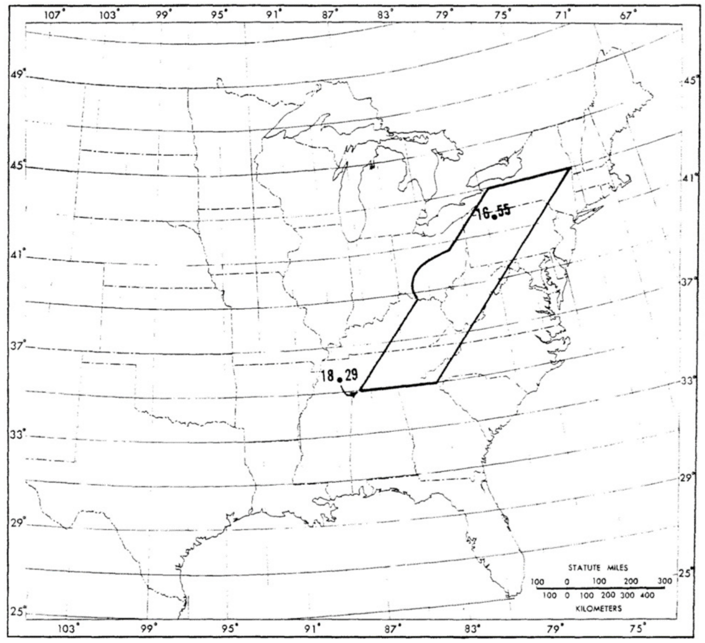

Figure 8: National Weather Service Transposition Limits of the Smethport Storm (from HMR 52 Figure 26)

storm adjustment values, and/or temporal accumulation patterns will have a direct effect on the design input for effected infrastructure.

During numerous site-specific, statewide, and regional PMP studies developed by AWA, updated transposition limits have been

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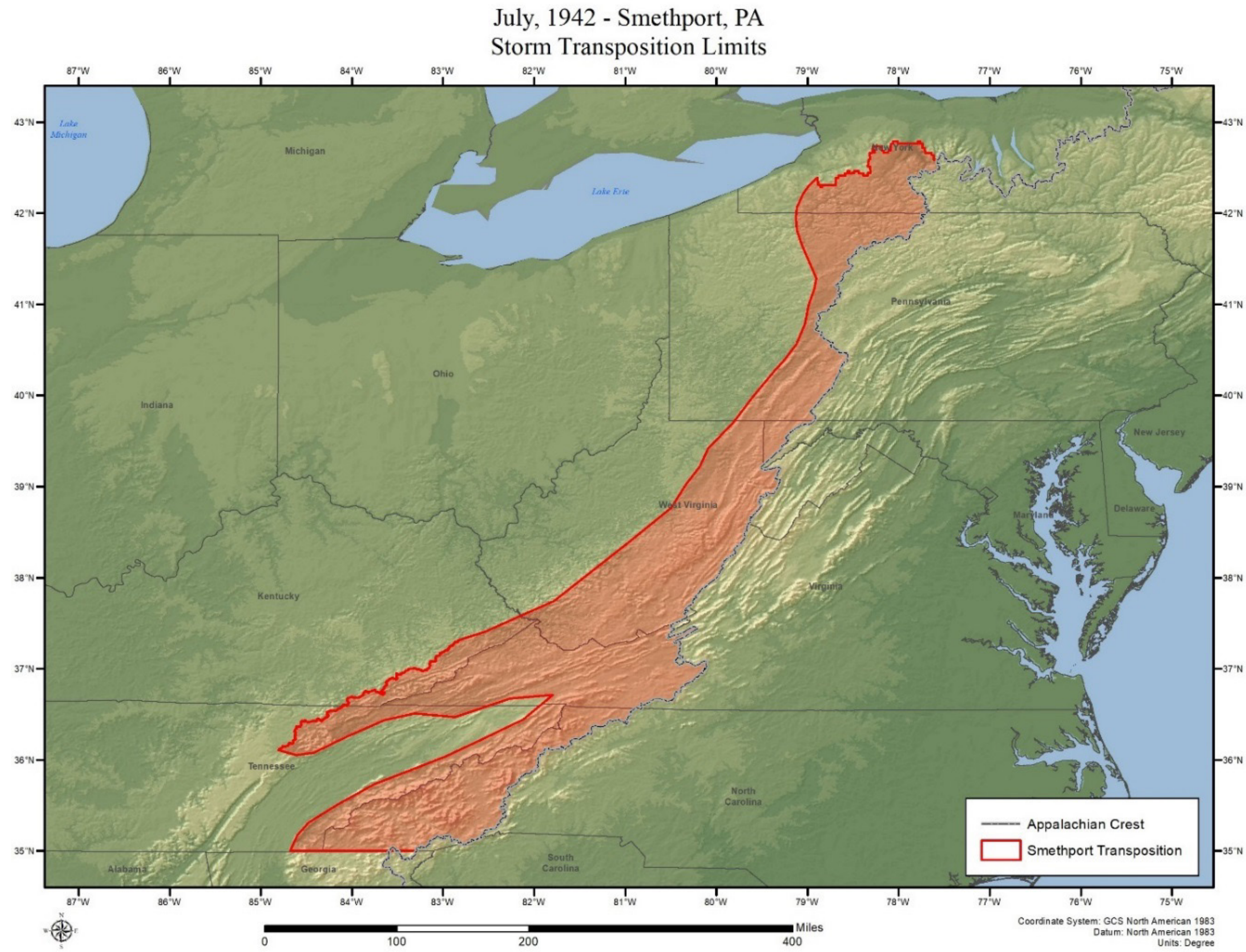

Figure 9: July 1942 Smethport PA Storm Transposition Limits

developed. These are based on a more accurate understanding of the meteorological and topographical interactions associated with the storm and the other areas in the region where the same combinations could occur. Use of these more accurate transposition limits have resulted in a more restricted influence of the Smethport storm. However, it still covers a significant region with critical infrastructure. The area of influence follows the western side of the Appalachian and Allegheny Mountains in southwestern New York, western Pennsylvania, central West Virginia, and eastern parts of Kentucky and Tennessee. See Figure 9.

Flood Model

DEVELOPMENT

The location of the heaviest rainfall (the storm center) during the July 1942 storm is located in the Upper Allegheny River Watershed, just upstream of the Allegheny Reservoir (as shown in Figure 10). The Upper Allegheny River Watershed also represents the domain of the flood model. The heaviest and most intense rainfall occurred over the Borough of Port Allegany, PA. The storm produced the largest discharges on record at several locations in the upper portions of the Allegheny River, Clarion River, and Sinnemahoning Creek watersheds. Discharges diminished in the lower reaches of major streams. See peak flow summary in Table 1. The domain of the flood model is defined by the Allegheny River 1,780 mi^2 watershed at Red House, NY (discontinued gauge number 03011500). The location of the gauge moved in October 1964 to its current location in Salamanca, NY, with a gauge number 03011020. The current gauge 03011020 maintains the systematic record prior to October 1964. Review of streamflow gauge records in the region indicate that the July 1942 flood was particularly significant for watersheds less than 500 mi^2, approximately corresponding to the Borough of Eldred, PA and USGS gauge number 03010500 along the Upper Allegheny River.

The flooding analysis of the 1,780 mi^2 watershed was accomplished using complementary models designed to make optimal use of current computational capacity. The entire study domain, to Red House, NY, was modeled with the USACE's HEC-HMS Version 4.2 software using the Runoff Curve Number (RCN) approach for loss/retention estimation and the Snyder Unit Hydrograph for runoff transformation. As part of the calibration process, the Unit Hydrograph in the HEC-HMS model was adjusted to reconcile the hydrograph from the 2D hydrologic/hydraulic models (discussed further below) and account for a non-linear watershed response in the calibration events. Distributed, 2-dimensional (2D) watershed models were developed for three (3) sub-watersheds within the study domain: Upper Allegheny River watershed Port Allegany,

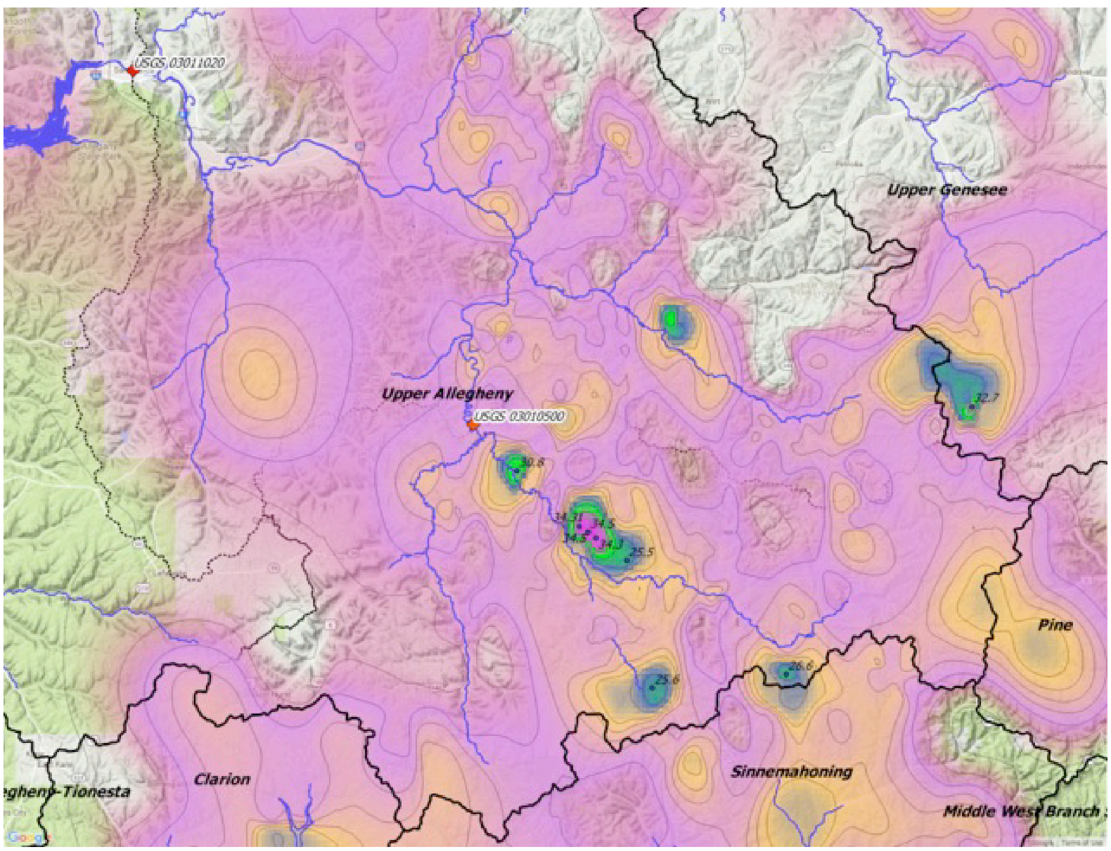

Figure 10: July 1942 Storm Pattern and Flood Model Domain

TABLE 1. PEAK FLOW SUMMARY

LOCATION	DRAINAGE AREA (mi2)	PEAK FLOW (cfs)	UNIT PEAK FLOW (cfs/mi2)
Port Allegany, PA	251	77,000	307
Eldred, PA	549	55,000	100
Olean, NY	1,167	44,000	38
Red House, NY	1,780	45,300	25

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PA (250 mi^2); Oswayo Creek watershed to its confluence with the Allegheny River (248 mi^2); and Tunungwant Creek watershed to its confluence with the Allegheny River (169 mi^2). These are the sub-watersheds, particularly the watershed to Port Allegany, where the most extreme rainfall measurements were recorded. A distributed 2D modeling approach has advantages over conventional lumped and semi-distributed hydrologic models. The distributed 2D modeling approach is more physically-based, making it flexible in modeling hydrologic and hydraulic responses to rainfall events of various magnitudes, intensities, spatial distributions, and temporal distributions. The 2D approach was chosen where the more concentrated rainfall occurred. Another important consideration in using the 2D approach is it reduces concerns over the application of generic non-linearity Unit Hydrograph adjustments in the HEC-HMS model, which introduces an unknown level of inaccuracy. Saghafian (Saghafian, 2006) provides additional discussion regarding non-linearity characteristics of Unit Hydrographs. Mesh sizes were kept relatively small (25 ft to 60 ft, with an average distance between the mesh nodes of 46 ft) to maintain accuracy, particularly to limit artificial retention of runoff in the watershed. This mesh size limitation made the 2D model computationally impractical for the entire 1,780 mi^2 watershed.

The computer software chosen to provide the distributed 2D watershed simulation was RiverFlow2D, developed by Hydronia, LLC. As stated in the Reference Manual, RiverFlow2D is a "combined hydrologic and hydraulic, mobile bed and pollutant transport finite-volume model for rivers, estuaries and floodplains. The model can integrate hydraulic structures such as culverts, weirs, bridges, gates and internal rating tables. The hydrologic capabilities include spatially distributed rainfall, evaporation, and infiltration." RiverFlow2D solves the shallow water equations (depth averaged/vertical integration of the Navier-Stokes equation) using a finite-volume scheme and, therefore, does not rely on the lumped unit hydrograph approach to estimate flow rates over time (hydrographs). Each triangulated mesh element is assigned individual parameters (rather than homogenous parameters for each sub-basin). Bed stresses use Manning friction law; turbulence and energy losses are implicit in the Manning n-value. Hydrologic capabilities include spatially distributed rainfall, evaporation, and infiltration.

Downstream of Port Allegany PA, 2D hydraulic modeling was also performed along the main-stem Allegheny River using the USACE HEC-RAS (Version 5.0.5). The HEC-RAS2D model extended upstream along unnamed and named Allegheny River tributaries, including Potato Creek, Cole Creek, Oswayo Creek, Olean Creek, and Tunungwant Creek, to account for the effects of backwater on flood attenuation. Outflow hydrographs from each HEC-HMS sub-watershed were directly linked, via the HEC-HMS DSS file, to the HEC-RAS2D model along external inflow boundaries with one exception; the outflow hydrograph from the Upper Allegheny RiverFlow2D model (at Port Allegany) was a manual input to HEC-RAS2D at the upstream inflow boundary. HEC-HMS parameters, specifically RCN and Snyder Parameters, were adjusted in the

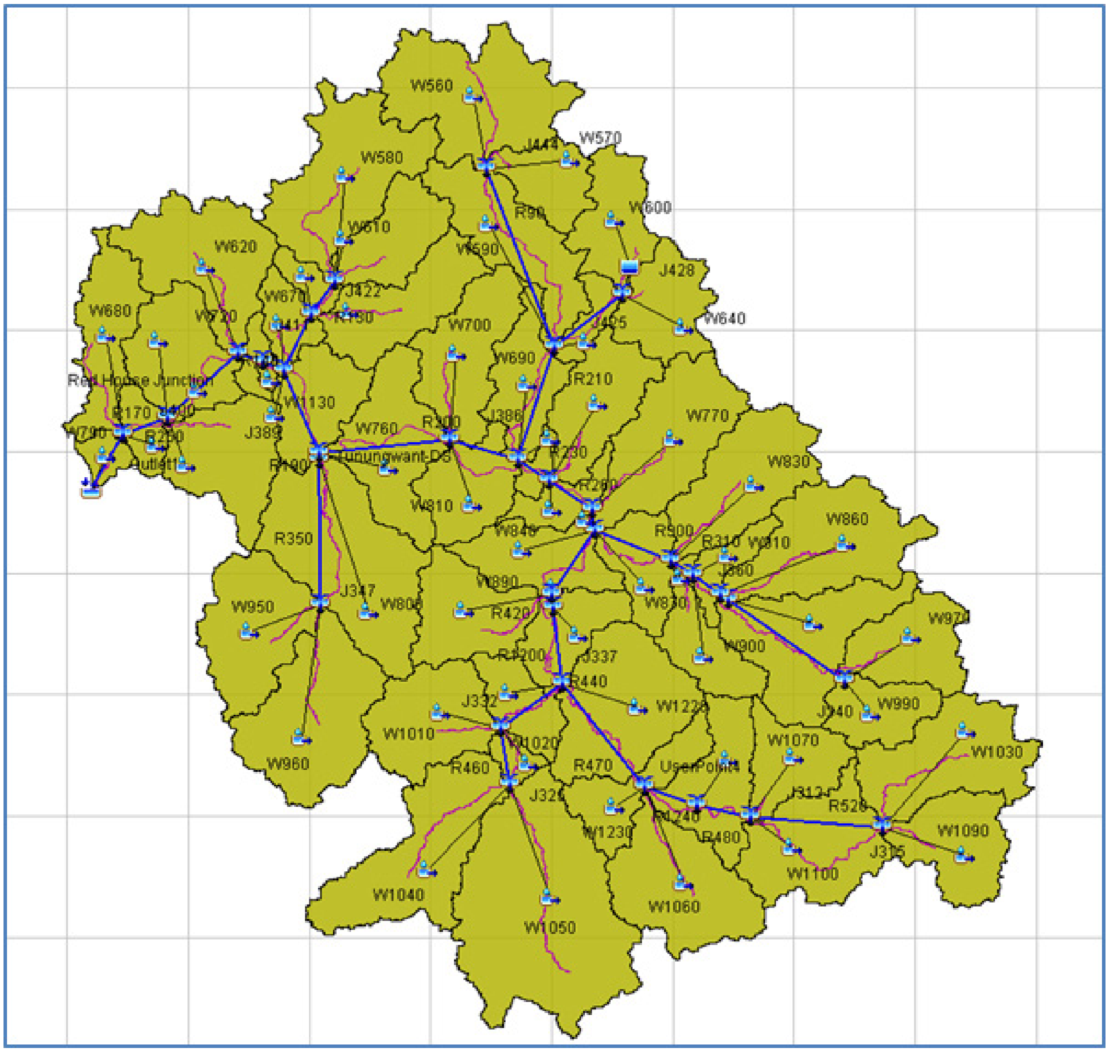

Figure 11: HEC-HMS Model Schematic

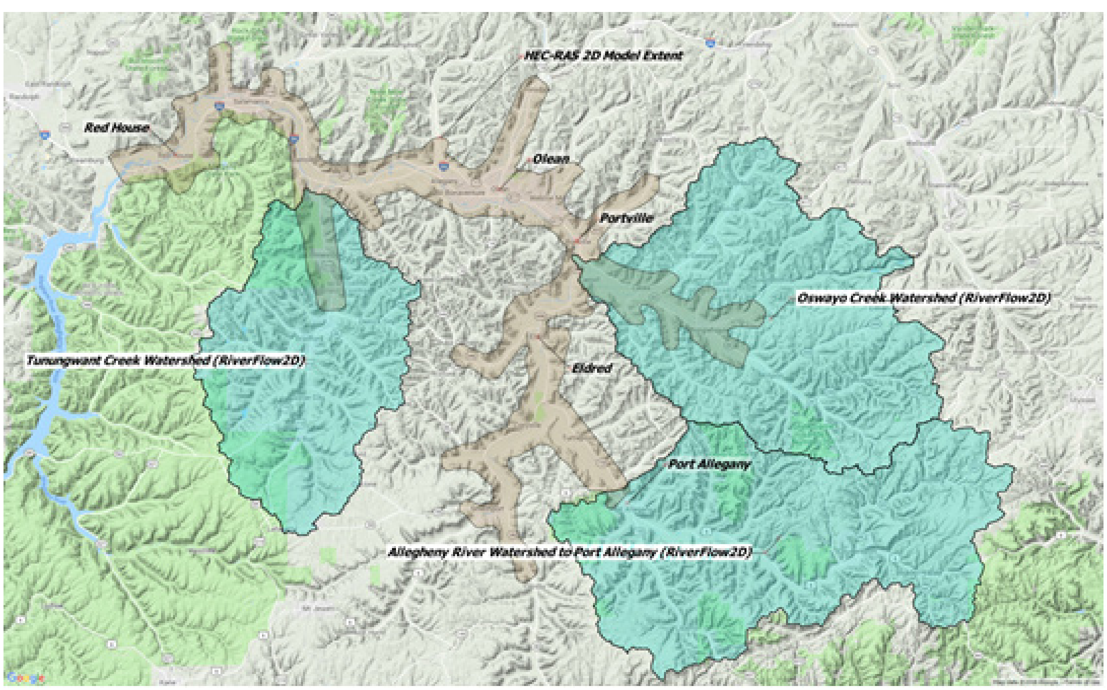

Figure 12: Areas Covered by 2D Models

Oswayo Creek and Tunungwant Creek watershed models to achieve a good hydrologic match with RiverFlow2D. The HEC-RAS2D model provided the ability to more accurately account for river and floodplain attenuation and flood profile data for comparison with high-water observations. See Figure 11 and Figure 12 for an illustration on how the HEC-HMS and 2D models relate to cover the watershed.

CALIBRATION

The 2D and HEC-HMS models were calibrated using three warm-season flood events in months with full vegetative growth to simulate canopy coverage comparable to July 1942. The September 2004 "Ivan" flood and June 2014 storms were selected for warm-season candidates and run through AWA's SPAS program to produce the hourly gridded rainfall data. Using post-1996 storm events allows the use of the NEXRAD data, providing a more reliable and comprehensive understanding of the spatial and temporal distribution for the calibration storms. Combining the NEXRAD data with the stream gauge data from these events, processed through SPAS (in 1-hour 1 km^2 gridded format), reduces uncertainty and improves the quality of the input data for the 2D and HEC-HMS models. In addition to post-1996 floods, the 1972 "Tropical Storm Agnes" flood was selected for calibration due to its significant effect on the region and the SPAS analysis which utilized a substantial amount precipitation and flood data. Note that the June 2014 storm was only significant to Port Allegany and, thus, only used to validate the RiverFlow2D model.

The non-linearity unit hydrograph issue became evident in applying an "Ivan" calibrated HEC-HMS model to the June 1972 "Agnes" storm. Additional adjustments to the "Ivan-calibrated" Snyder Unit Hydrograph parameters were required to achieve an acceptable level of agreement at Coudersport, Port Allegany, Eldred, and Olean for the "Agnes" calibration. Because the June 1972 "Agnes" flood was much larger in magnitude than the September 2004 "Ivan" flood, the "Agnes" calibrated Snyder Unit Hydrograph parameters were initially applied to the July 1942 storm in the HEC-HMS model. The "Ivan-Calibrated" RCNs were reduced by between 0% and 30% to achieve good runoff volume agreement for the "Agnes" flood. HEC-HMS model parameters were adjusted to provide good agreement with both streamflow gauge data and the three calibrated RiverFlow2D models for the "Agnes" flood. Calibration of the RiverFlow2D models also involved adjustments to Manning n-values to provide good agreement with the "Agnes" runoff responses and flood profiles provided by the USACE in their 1974 report (USACE, 1974).

Other considerations in developing and calibrating the models were the effect of dams and sub-surface flow interaction. Dams contained in the USACE National Inventory of Dams (NID) (USACE, 2016) database were queried to identify dams within the HEC-HMS model domain. Most of the dams are in sub-basins that drain to the Allegheny River at and downstream of Olean, NY. NID Identification differentiated between dams constructed prior to the July 1942 flood and between the July 1942 and June 1972 "Agnes" floods. Three "hypothetical" dams (representing the largest dams, lumped together for modeling purposes) were incorporated into the HEC-HMS model for the June 1972 "Agnes" flood to assess the effect of the dams on the flood hydrographs in the Allegheny River. Simplified assumptions were made for the HEC-HMS sensitivity runs. The results of the sensitivity analysis indicate that the dams had a relatively minor effect on the peak flow rates at and downstream of Olean, NY, decreasing peak flows by approximately 10% at the confluence of the Allegheny River and Olean Creek. However, most of the dams constructed before the June 1972 "Agnes" flood did not exist during the July 1942 flood. The only substantial dam constructed prior to the July 1942 flood was the Cuba Lake Dam located in the Olean Creek watershed (NID Identification NY00455 and NY00456). While not expected to significantly impact the July 1942 hydrographs in the Allegheny River downstream of Olean, NY, the Cuba Lake Dam was incorporated into the HEC-HMS model.

Review of the 2D modeling results suggested that the watershed is temporarily retaining runoff and gradually releasing volume from the storm in the later portion of the flood hydrograph. This delayed gradual release does not appear to be coming from floodwater retention structures/dams. Runoff being absorbed into a highly permeable upper layer of soil, including in the floodplain areas, and released during the receding side of the runoff hydrograph was considered as a possible explanation. The following features could provide possible explanations for this phenomenon:

- Unconsolidated glacial sediment deposits along the floodplain in the study reach.
- Formation of boulder and "kame" fields and other features along the glacial edge. See W. D. Seven (W.D. Seven, 1999) for further discussion.
- Fragipans – "dense subsurface soil layers that severely restrict water flow and root penetration" (J.G. Bockheim, 2012). See E. J. Ciolkosz, et. al. (Edward J. Ciolkosz, 2000) and J. G. Bockheim, et. al. (J.G. Bockheim, 2012) for further discussion.

It was hypothesized that some of the storm volume, represented in the model as a "loss", enters the riverine system via subsurface flow through highly permeable material overlain (e.g., unconsolidated deposits, "kame" fields, etc.) on a shallow layer of low permeable material (e.g., Fragipan). The hydrologic models do not physically represent this potential surface-subsurface flow interaction. The HEC-HMS model incorporates the "recession baseflow" technique to simulate potential entry of subsurface flow from storm volume. Therefore, the receding side of the HEC-HMS model hydrographs show a more gradual "tail". Comparatively, the RiverFlow2D model is only representing direct surface runoff and, therefore, shows a more rapidly declining receding side of the hydrographs. The effect of the subsurface flow on the calibration results appears to diminish with larger floods. This is evident by the improved performance of the 2D model for the June 1972 "Agnes" flood.

POST-CALIBRATION MODEL ADJUSTMENTS

Recognizing that some conditions between the calibration storms (particularly the June 1972 flood) and the July 1942 flood may vary (e.g. land use, structures, etc.), post-calibration adjustments were made to the models, as described below, prior to applying the July 1942 rainfall. These adjustments were made to reduce concerns that flow discrepancies can be attributed to factors other than uncertainties in the rainfall data.

- Reduced the "Ratio to Peak" for the baseflow regression to 0.2 of the values established for the calibration floods due to the significantly higher peak flows in portions of the watershed for the July 1942 flood.
- Manning n-values in the HEC-RAS2D model were originally based on National Land Cover Database (NLCD). These n-values lead to good agreement with the USACE peak water surface profile for the June 1972 "Agnes" flood. However, n-value adjustments were made for the July 1942 HEC-RAS2D model to account for significant land use changes within the floodplain, particularly between Olean, NY and Port Allegany, PA. Changes were primarily from cultivated farmland in 1942 to present-day and 1972 wooded conditions.
- Adjusted the approach embankment elevations and width of the Port Allegany Route 6 Bridge, which collapsed during the 1942 flood, from drawings obtained from PennDOT.
- Reductions were made to RCNs in the HEC-HMS model (by approximately 20% to 30%), from those calibrated for the "Agnes" flood, to achieve good runoff volume agreement for the July 1942 flood; except for sub-watersheds upstream of Port Allegany, PA and the Oswayo Creek watershed upstream of Shinglehouse, PA. RCNs for these sub-watersheds remained the same for both storms (between approximately 55 and 70). Reductions in RCNs were made in lieu of broad reductions in rainfall depths to maintain a level of conservatism in the analysis (not excessively reducing rainfall) and honor the significant bucket rainfall survey dataset.
- Due to fast-rising nature of the July 1942 hydrograph at Port Allegany, HEC-RAS2D runs were done using the "Full Momentum" equations to incorporate the "unsteady, advection, and viscous terms" (USACE Hydrologic Engineering Center, 2016) that are disregarded for the "Diffusion Wave" equations. Results from the "Full Momentum" runs show a slower rising limb of the hydrograph, which partially corrects the peak timing discrepancy.

July 1942 Flood Analysis

INITIAL FINDINGS

The next step was to apply the original rainfall parameters to the post-calibrated flood models for comparing with observed/measured flood data. Historical information on the July 1942 flood was collected and compiled to provide a basis for comparing the initial model results, using original rainfall, with what was observed during the flood. Desktop information collected included streamflow and stage data at USGS gauges along the Allegheny River, Geologic Survey Report 1134-B (Eisenlohr, 1952), a report from the Pennsylvania Department of Forestry and Waters (Commonwealth of Pennsylvania, Department of Forestry and Waters, 1943), and newspaper articles from an internet search. In addition, a site visit was conducted on August 24 and 25, 2017 to inspect key locations identified during the desktop review, including high-water mark locations, areas of greatest impact from the flooding, and other areas determined to be critical to the analysis. Original or copies of newspaper articles and photos provided visual markers of the flood and depth and time information. Information was geo-referenced to allow for comparison with the July 1942 flood models.

The 1-hour gridded (1 km^2) precipitation of the 1942 storm, generated using AWA's SPAS analysis of reported rainfall, was used as input in the flood models. The purpose of this task was to essentially replicate the 1942 flood with the hydrologic and hydraulic models, duplicating the stream and watershed conditions at that time. The results of the model, specifically flow, flood stage, and timing information, were compared with observations from historic records and provided insights on how well flood data corresponds to rainfall data. The objective was to identify watershed regions where reported rainfall agrees with the estimated runoff (flow rates and timing) and observed flooding, or regions where the historic records and model predictions are in disagreement (e.g., rainfall versus peak runoff). Consideration was given to the following in making comparisons to inform rainfall adjustments:

- At Bradford, PA, LiDAR shows significantly different channel and floodplain topographic characteristics than in 1942 due primarily to the construction of Route 219 through the city.
- Terrain data, used to construct the 2D hydraulic models, differ between PA and NY. PA terrain is based on LiDAR and NY terrain is based on the National Elevation Dataset (NED). While both represent present-day topographic conditions, the NED for NY is lower resolution than the PA LiDAR-based data. Initial comparisons at the LiDAR-NED transition in the DEM shows that more floodplain storage and attenuation may be available than currently represented by the NED.

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- The model domain contains several levee systems, listed in Table 2 (USACE, 2017). Most, except for the Eldred levee, were constructed after the July 1942 flood but before the June 1972 "Agnes" flood. The terrain built for the HEC-RAS2D model includes these levees. However, for the systems in New York (except a portion of the "South of Dodge Creek" levee in Portville, NY), the perception of the levees in the HEC-RAS2D terrain is limited by the resolution of the NED-based DEM. Where levees are perceived, the terrain was not manually adjusted to remove the levees for the July 1942 flood, although flooding is permitted to occur behind the levees. While there may be a minor local effect on the HEC-RAS2D model results (particularly for the PA levee systems where LiDAR is available and the levees are well defined in the DEM), a judgement was made that refinements to the DEM to remove the levees would not significantly affect the outcome of the July 1942 flood analysis (and related decisions regarding rainfall) and is not warranted.
- The effect of hysteresis was considered when comparing HEC-RAS2D hydrographs with observed hydrographs at Eldred and Red House for the July 1942 flood. HEC-RAS2D generates cumulative flow for grid cell faces along the user-defined "profile line" in the RAS Mapper to produce a hydrograph, which inherently accounts for the effect of hysteresis. The observed hydrograph, reported on Figure 42 of Water Supply Paper (WSP) 1134-B (Eisenlohr, 1952), was likely developed by an observer or gauge that recorded stage, which was then converted to flow using a pre-defined stage-discharge rating curve. The stage-discharge rating curve likely did not account for hysteresis effect at higher flows. This was considered when judging acceptability of the final hydrographs at Red House, NY (Figure 13).

TABLE 2. SUMMARY OF LEVEE SYSTEMS IN STUDY AREA

MUNICIPALITY	DESCRIPTION	YEAR COMPLETED
Coudersport	Right Bank Mill Creek	1955
Coudersport	Left Bank Allegheny River	1955
Port Allegany	Lillibridge Creek – Allegheny River	1950
Eldred	Right Bank Allegheny River & Right Bank Barden Brook	1987
Shinglehouse	Oswayo Creek	Unknown
Portville	North of Dodge Creek & Right Bank Allegheny River	1951
Portville	South of Dodge Creek & Right Bank Allegheny River	1951
Olean	Left Bank Olean Creek & Right Bank Kings Creek	1952
Olean	Right Bank Allegheny River & Olean Creek	1952
Olean	Left Bank Kings Creek	1952
Salamanca	Left Bank Allegheny River	1971
Salamanca	Left Bank Allegheny River	1971
Salamanca	Right Bank Allegheny River – West Salamanca	1971

RAINFALL ADJUSTMENTS

The evaluation of model and observed flood data, discussed above, led to iterating adjustments to the SPAS-generated rainfall data for the storm. These included adjustments to the timing, magnitude, and spatial patterns of the rainfall accumulation between observed data points. Each of these adjustments were made to better reconcile rainfall with the hydrology, informed by the calibrated flood models. All changes made to the previous rainfall accumulation patterns and magnitude were explicitly evaluated considering the acceptance of the Smethport rainfall as a world-record rainfall at the 4.5 and 6-hour durations. Most of the flood observations and records were at flood peaks (flows, water surface elevations, and time-to-peak). While peak flood data was helpful in corroborating or adjusting rainfall, a time-distributed representation of the flood (in the form of flow hydrographs) was only available at two USGS gauge locations along the main-stem Allegheny River; Eldred (PA) and Red House (NY). Because the Red House watershed encompassed the entire study domain and key rainfall locations, it represented a key comparison point in judging acceptance. With the rainfall and post-calibration model adjustments, the modeled flow hydrograph at Red House was able to improve as shown in Figure 13. A summary of rainfall adjustments made to the broader watershed are as follows:

- Revised the rainfall temporal pattern in the sub-watersheds between Coudersport and Port Allegany, deviating from front-loaded storm (timed based on HMR-56) to a pattern more consistent with the surrounding hourly gauges. See discussion below for additional refinements at the storm center.
- For the Mill Creek sub-watershed (just upstream of Coudersport PA), factors were applied to further adjust rainfall by reducing the 2 peak hourly depths and redistributing to the other hours to maintain the total rainfall volume. Also reduced Basin #5 (W1090) bucket surveys by 20%.
- After reviewing the quality of rainfall data, the spatial extent of the "Bradford 2A" gauge in the Tunungwant Creek Watershed was reduced. This gauge is located in the Bradford, PA area were rainfall collection was sparse. Spatial extend of other high-rainfall gauges seem to show a tighter spatial distribution.
- For the Oswayo Creek Watershed, re-distributed the 2 hours for the second peak over 4 hours in sub-watershed W830 and resolved high "ΔP's" (difference between the SPAS generated rainfall with observed).

Additional analysis of the rainfall and hydrologic record, particularly for the smaller watersheds, was conducted to refine the understanding of the magnitude and temporal patterns of rainfall in and around Port Allegany; the storm center and location of the most significant rainfall observation at Site 275 (Appolt Farm), where the 30.8-inches in approximately 5 hours was estimated. The estimated timing for this observation is shown in Figure 18. The timing applied at the Site 275 location in RiverFlow2D produces reasonable agreement with observed flood data at tributaries near Port Allegany (specifically, Lillibridge Creek and Twomile Creek). However, when this timing is allowed to influence a larger region, significantly higher flows and water surface elevations are produced in the Allegheny River near Port Allegany. From this, it was concluded that Site 275 timing would need to be significantly restricted in its influence and not allowed to influence the broader watersheds in the Port Allegany region.

Additional iterations were conducted to improve agreement in Twomile Creek, Lillibridge Creek, and Allegheny River; while attempting to hydrologically validate the Site 275 rainfall volume and timing (Figure 18). The additional iterations lead to the development of three (3) rainfall timing zones around the storm center (denoted as Storm Center Zones or SCZs); illustrated in Figure 14. Deviating from the original HMR-56 timing (Figure 15), SCZ 1 rainfall

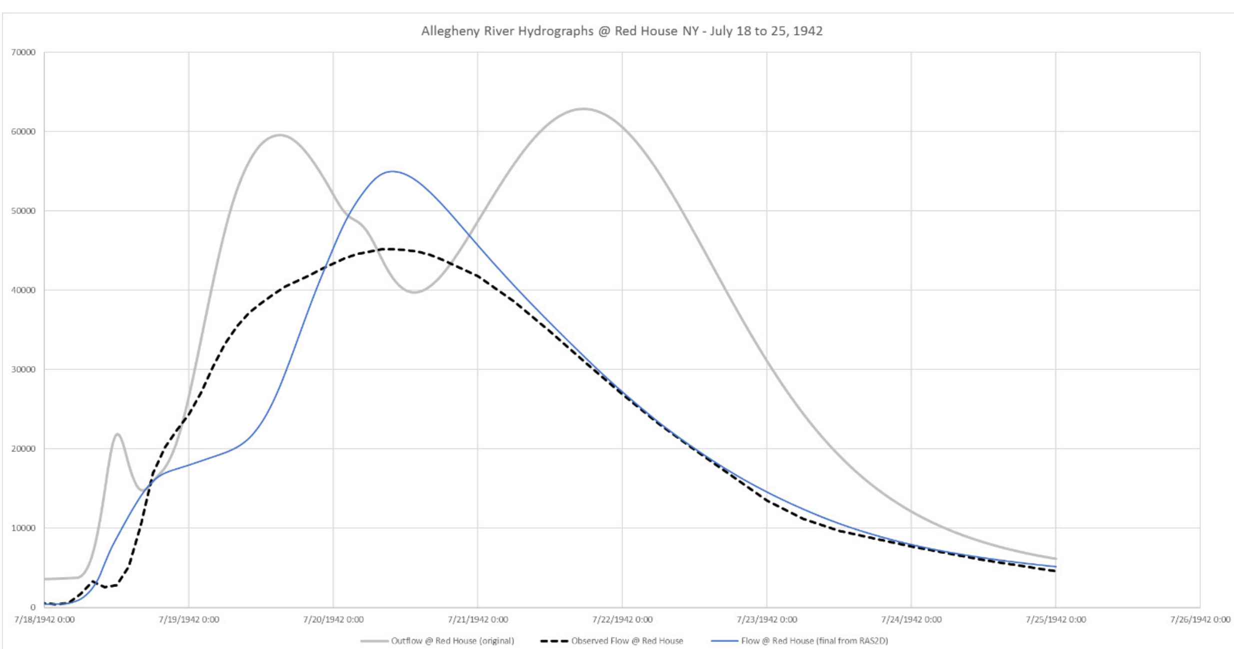

Figure 13: Hydrographs at Red House, NY

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corresponds closest to the "Bolivar" hourly gauge and covers the broader watersheds in the Port Allegany and Coudersport region (Figure 16). With other minor adjustments, the SCZ 1 "Bolivar" timing generally produced reasonable agreement between the model and observed flood data, both in the tributaries and main-stem Allegheny River, with one exception; the Twomile Creek flows was significantly underestimated in RiverFlow2D. Furthermore, as indicated in Figure 16, applying bucket surveyed rainfall to the "Bolivar" timed temporal pattern does not produce cumulative rainfall depths that correspond to the heaviest rainfall observation at Site 275 (Appolt Farm) of 30.8-inches in approximately 5 hours. Therefore, the SCZ 1 ("Bolivar" timed) rainfall was further adjusted locally, creating SCZ 2 and SCZ 3 rainfall timing, while honoring the Site 275 observation and other nearby bucket surveys and achieving reasonable agreement with observed flows in the tributaries and main-stem Allegheny River near Port Allegany. SCZ 3 (at the storm center) is timed to the Site 275 observation (Figure 18), with spatial limits defined in Figure 14. SCZ 2, developed as a transition from SCZ 1 to SCZ 3, is timed as a modified "Bolivar" hourly gauge (Figure 17) and was based on two key observations:

1) There was no record of high flows occurring in the early (overnight) hours of July 18 along Twomile Creek and Lillibridge Creek. The RiverFlow2D model shows that significant flows would have occurred in these tributaries as a direct result of the first intense rainfall (occurring between 12:00 AM and 1:00 AM on July 18) included in the "Bolivar" timed rainfall.
2) Page 67 of WSP-1134-B (Eisenlohr, 1952) states "the observer who recorded more than 30.8 inches of rain in 4 3/4 hours stated that it seemed to fall at a tremendous rate, but quite uniformly, for the greater part of the time. Also, the drops seemed to be exceptionally large and very close together. From her statement and the record of total rainfall at that point, it may be assumed that the rainfall at no time exceeded a rate of about 10 inches per hour and that there was no "streaming" for that rate and for that size drop."

Consequently, the SCZ 2 rainfall was developed by shifting 5 inches of the "Bolivar" timed rainfall from the first hour (between 12:00 AM and 1:00 AM) to the second heavy 2 hours of rainfall (between 8:00 AM and 10:00 AM) to set the rainfall in this period at 10 inches per hour. As discussed previously, the early burst of rain in the SCZ 1 timing, as indicated by the Bolivar gauge (along with other hourly gauges in the region), appears consistent with the hydrology of the broader watershed. Applying SCZ 2 or SCZ 3 timing (i.e., shifting more rainfall later in the storm) for the broader watershed increases runoff and produces overestimated flows and levels since, given the exponential-shaped loss function associated with the NRCS Direct Runoff Equation, higher runoff occurs later in the storm. The final iterations (Version 10) produced reasonably close matches to flood data while honoring the Site 275 and other bucket surveys in the Port Allegany Region. Modeled peak flows along the tributaries near Port Allegany were converted to unit (cfs per mi^2) flows and plotted (Figure 19) against observed unit flows in the same region (similar to Figure 43 of WSP-1134-B) showing good agreement.

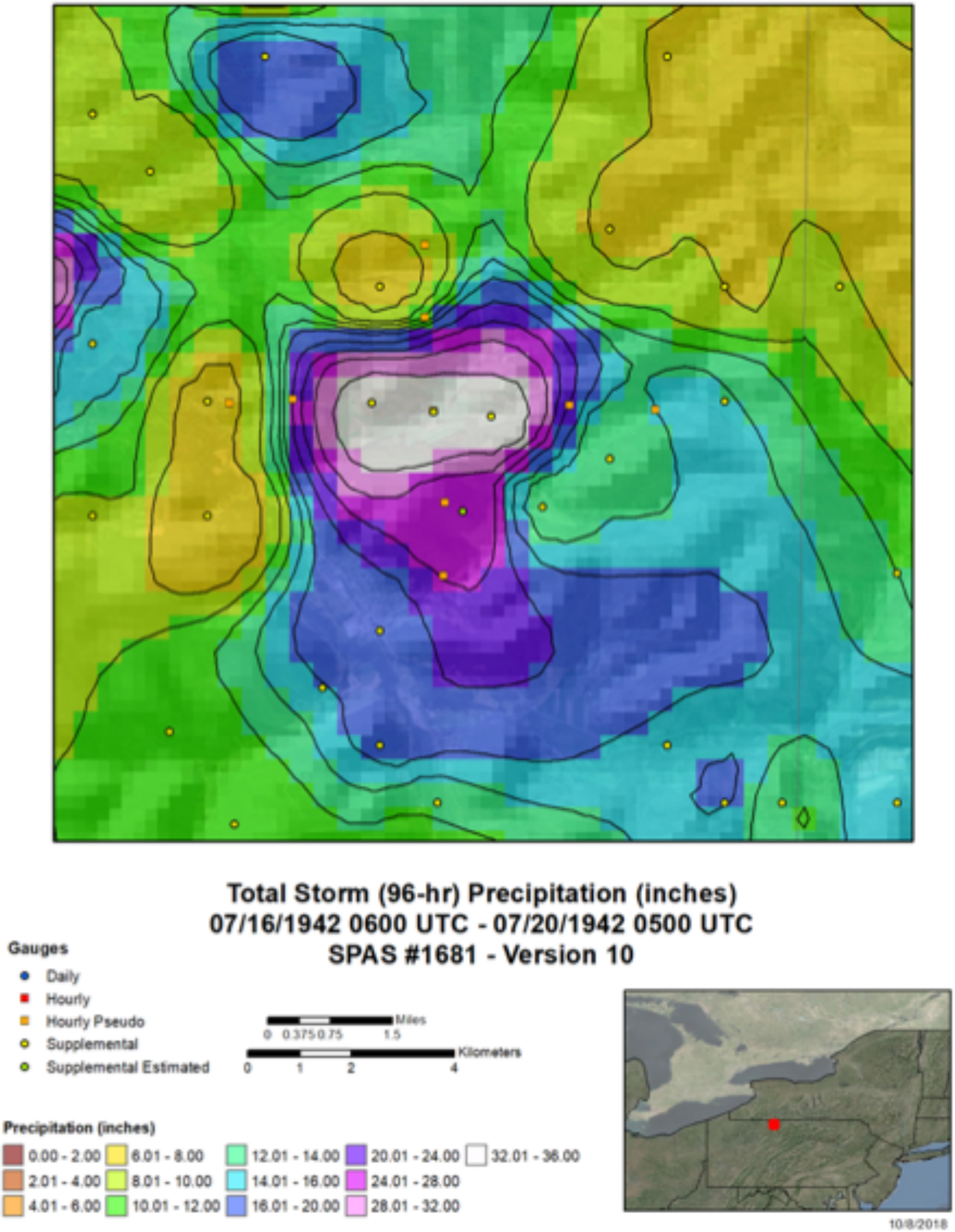

Figure 14: AWA's Total Storm Precipitation (96-hours) at Port Allegany, PA

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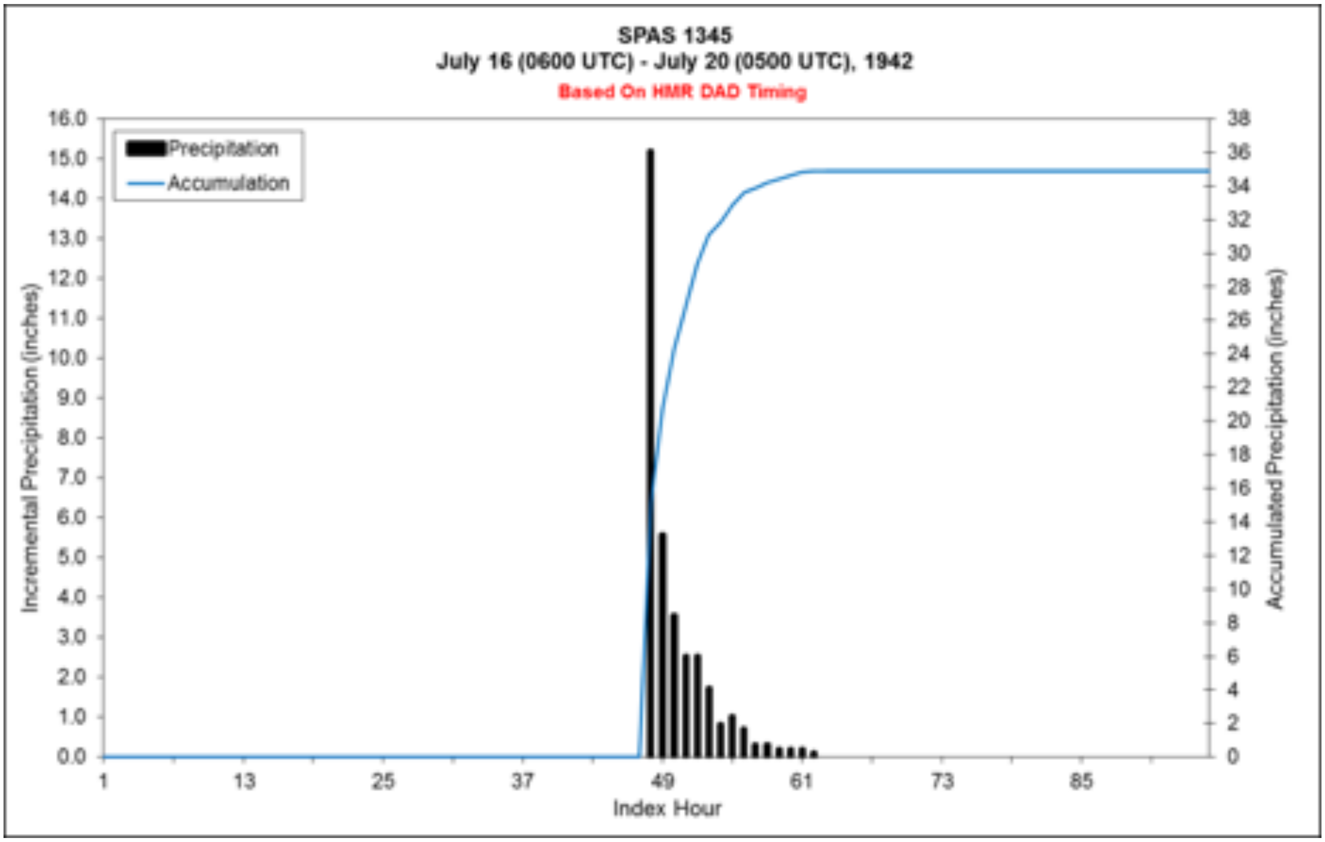

Figure 15: Original Temporal Pattern in Port Allegany, PA, Region (based on HMR-56 Timing)

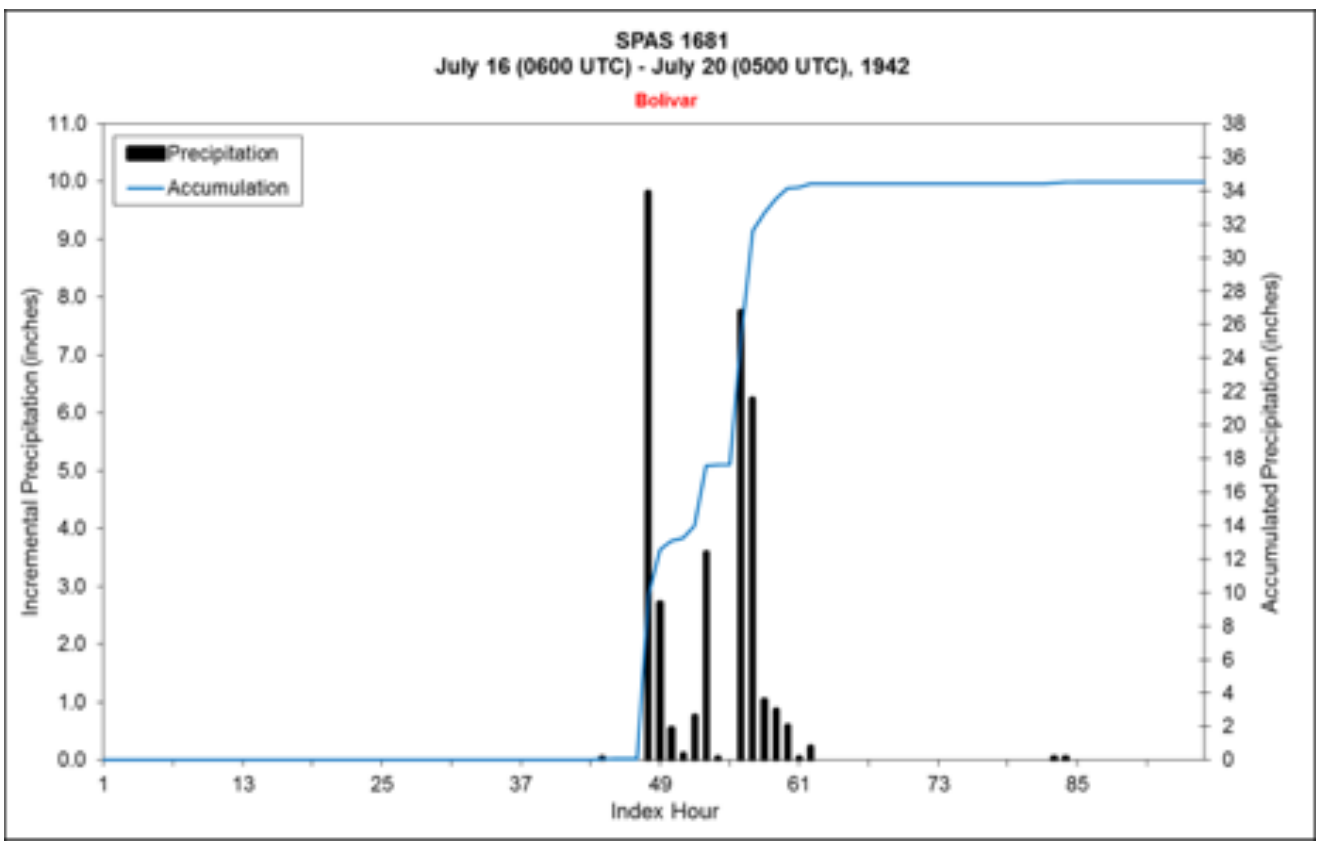

Figure 16: SCZ 1 Temporal Pattern (based on Bolivar Hourly Gage)

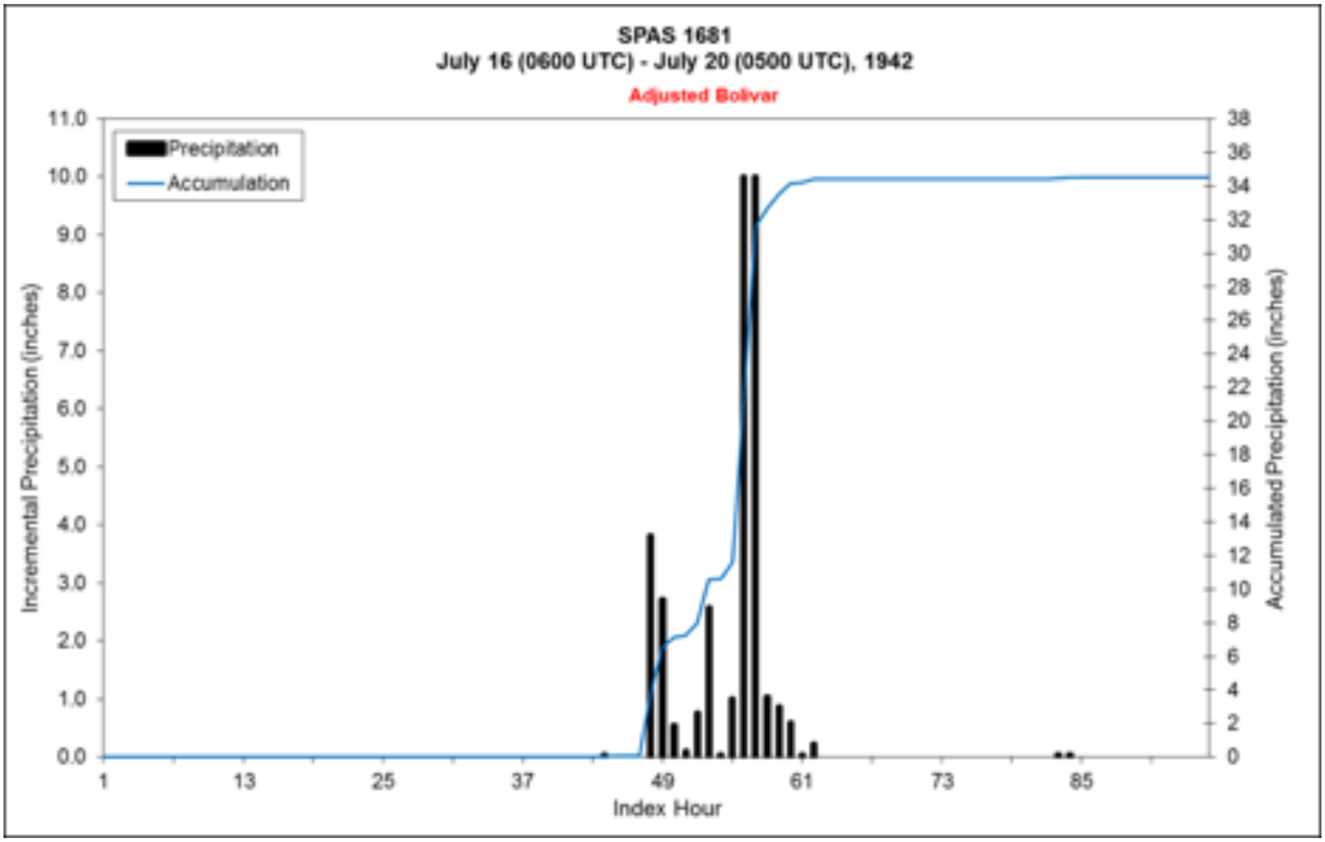

Figure 17: SCZ 2 Temporal Pattern (modified Bolivar Hourly Gage)

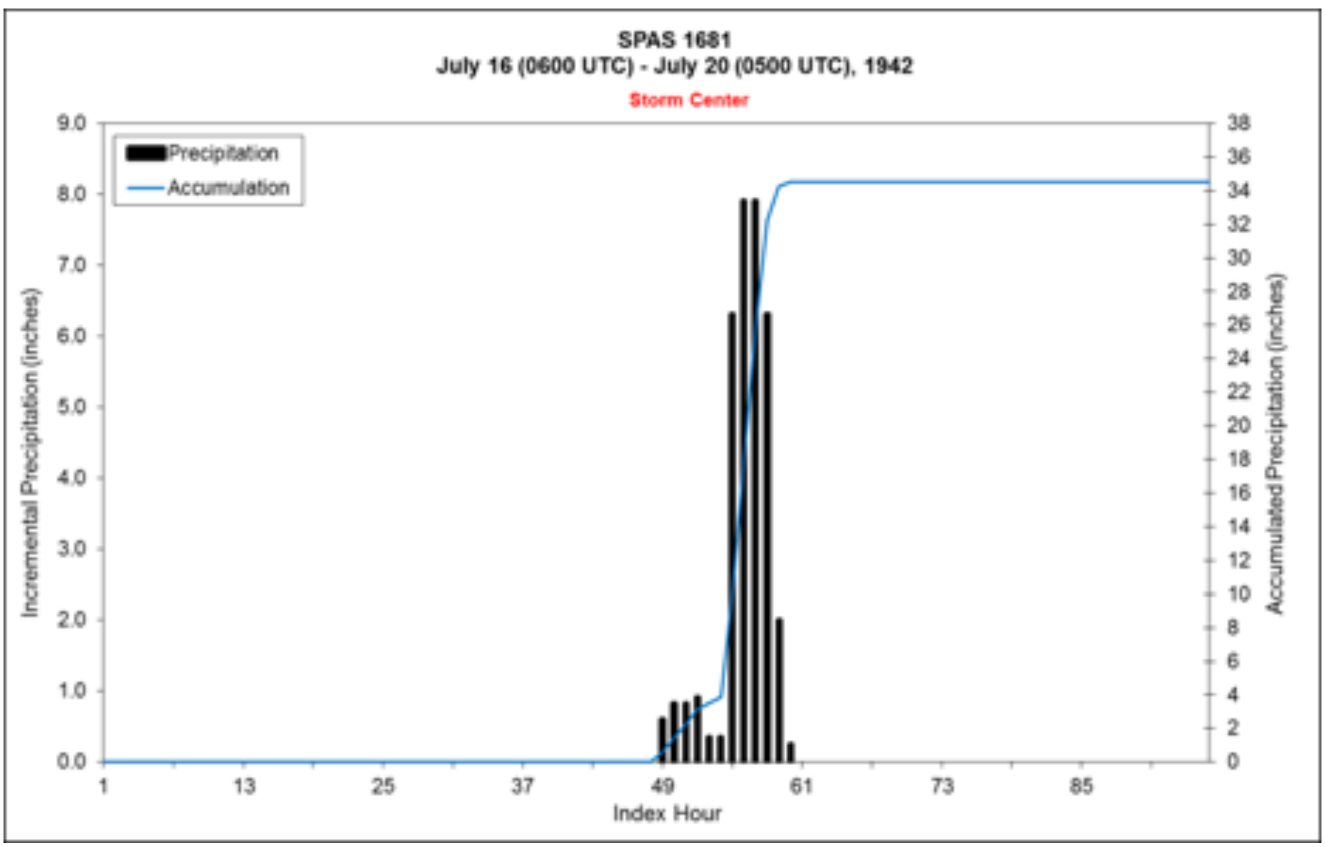

Figure 18: SCZ 3 Temporal Pattern (based on Site 275 (Appolt Farm) Report)

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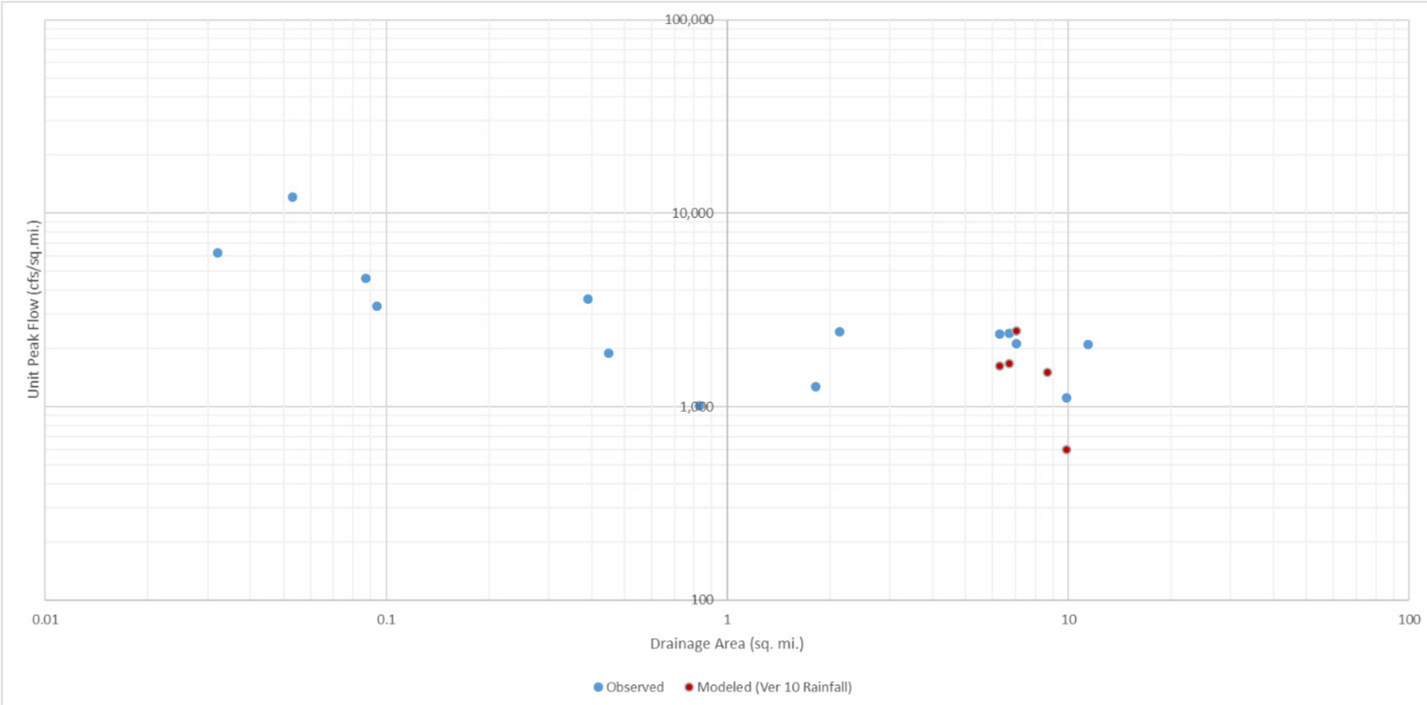

Figure 19: Comparison of Observed and Modeled Unit Peak Flows vs. Drainage Area for Watersheds near Port Allegany

INSIGHTS INTO THE STORM CENTER (SITE 275) OBSERVATION

Even after establishing hydrologically viable rainfall patterns for tributaries and the main-stem Allegheny River near the storm center at Port Allegany, an additional analysis was conducted to further assess the hydrologic viability of the Site 275 observation. As discussed above, the Site 275 timing does produce good agreement with observed flows in Twomile Creek and Lillibridge Creek but significantly overestimates flooding in the main-stem Allegheny River when broadly applied. The additional analysis utilizes observed flows in small drainages and assisted in defining the limits of SCZ 3 in Figure 14. The flow observation locations from small drainages and the Site 275 rainfall observation are shown on Figure 21. Estimated using the NRCS lag time equation, the smallest of these drainage areas have lag times well below 1 hour. As such, observed peak flows are likely governed by sub-hourly rainfall intensities.

Since sub-hourly rainfall patterns are not being defined by the AWA SPAS analysis of the July 1942 storm, an analysis was conducted using the Rational Method (with the Runoff Coefficient (C) calibrated to RiverFlow2D results) to estimate the hourly rainfall intensities needed to produce the observed flows at each location. (See Figure 20 for locations of observed flow locations.) The results, shown in Table 3, indicate that significant rainfall intensities (between 17 and 45 inches per hour) could have occurred at flow locations 016.20, 016.21, and 016.22,

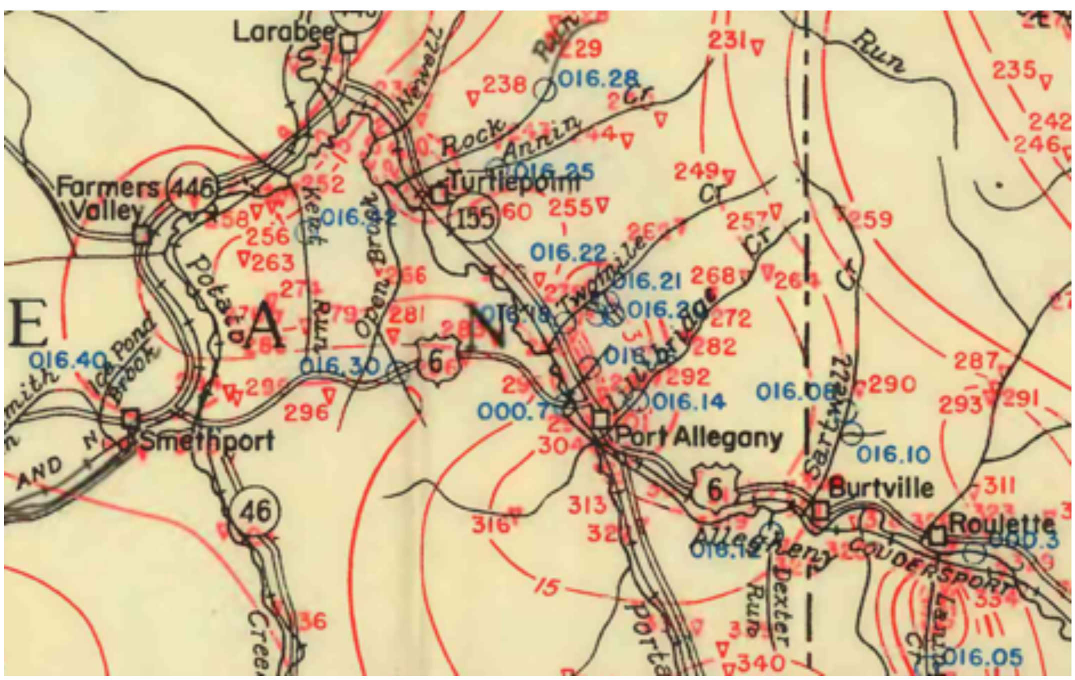

Figure 20: Water Supply Paper 1134-B, Plate 2 (Map of Flood Area showing Locations of Stream-Gaging Stations, Rainfall-Measurement Points, and Isohyetal Lines for July 17-18, 1942)

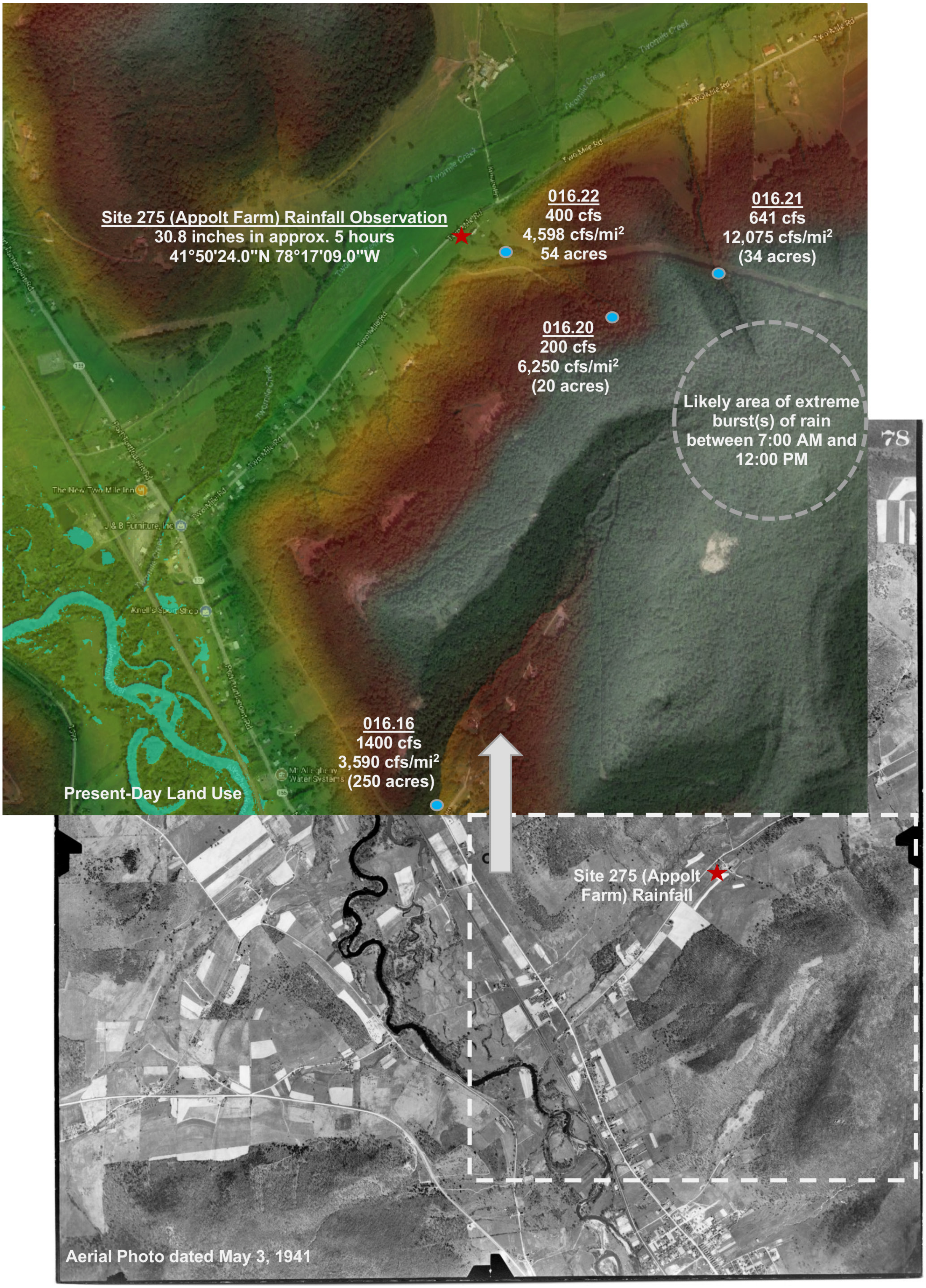

Figure 21: Map of Rainfall and Flow Observations at Storm Center

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TABLE 3. ESTIMATE OF RAINFALL INTENSITIES NEEDED TO PRODUCE OBSERVED FLOWS AT SMALL DRAINAGES NEAR PORT ALLEGANY (BASED ON RATIONAL METHOD)						
WATERSHED	POINT #	RATIONAL RUNOFF Coef (C)	PEAK INTENSITY (in/hr)	DRAINAGE AREA (acres)	PEAK FLOW (cfs)	FLOW PER SQ MILE (cfs/mi^2)
Port Allegany	016.16	0.35	16.1	250	1,406	3,606
Two Mile Run	016.20	0.42	23.2	20	200	6,236
Two Mile Run	016.21	0.42	45.0	34	641	12,096
Two Mile Run	016.22	0.42	17.1	56	400	4,596
Sartwell Creek	016.10	0.32	16.1	60	310	3,297

located near the Site 275 rainfall observation. Rainfall intensities for other surrounding flow locations, including within the Twomile Creek, Lillibridge Creek, and Sartwell Creek watersheds, were estimated to be between approximately 6 and 16 inches per hour; which is consistent with the "Bolivar" and "modified Bolivar" timing in Figure 16 and Figure 17, respectively. The significant rainfall intensities needed to produce observed flows at locations 016.20, 016.21, and 016.22 suggest that the Site 275 (Applot) observation is viable but probably included a combination of steady heavy rainfall (consistent with the statement on page 67 of WSP-1134-B, above) and significant short-bursts at intensities between 17 to 45 inches per hour, accumulating to 30.8 inches between 7:00 AM to 12:00 PM on July 18. These extreme bursts may seem to contradict the statement on page 67 of WSP-1134-B but it is likely that the extreme bursts occurred at very localized areas in the headwaters of the small drainages, where no direct observations were made. See Figure 21 for an illustration.

CONCLUSIONS

PMP depths across much of the region covered by HMR 51 are greatly influenced by the exceptional July 1942 storm in the Smethport/Port Allegany region of north-central Pennsylvania. The rainfall measurement dataset for this storm includes several "bucket surveys", which significantly influence the depth-area-duration characteristics of the storm. However, the quality of the "bucket survey" measurements is uncertain. Given the significance of this world-record-setting event in developing PMP values, an analysis of the resulting flood (using advanced modeling techniques and observed flood data) provided key insights into the rainfall observations. In some areas, the flood analysis corroborated the rainfall observations. In other areas, such as the upper Allegheny River (at and upstream of Port Allegany), Tunungwant Creek, and upper Oswayo Creek watersheds, flood data did not fully support the magnitude, spatial, and/or temporally information provided in the HMRs or as reported in hourly and "bucket survey" rainfall data.

Considering uncertainties in the flood models and quality of the flood data in addressing hydrologic differences, adjustments were made to the rainfall data until reasonable agreement was reached between the flood models, flood observations, and rainfall analysis. This combined the best aspects of the meteorological and hydrological analyses to produce the most accurate representation of the rainfall accumulation possible given the data available. Of particular focus was the location of the storm center near Port Allegany, PA, where the world-record-setting "bucket survey" rainfall that exceeded 30 inches in 4.5 hours was observed. From the flood analysis of the tributaries and small drainages at the storm center, it was concluded that the reported rainfall could have occurred, but its influence was very limited and there was a high-degree of spatial variability. The analysis led to refinements to the temporal and spatial patterns of the rainfall at the highly significant storm center. In the end, the flood analysis resulted in a more accurate depth-area-duration representation of this very important storm in Pennsylvania's PMP development.

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