# Hydrologic Modeling of Large Drainage Basins – Unique Challenges and Solutions

Damian M. Gomez, P.E., CFM, Gomez and Sullivan Engineers, D.P.C.

## Abstract

Modeling extreme floods in large area drainage basins can present unique challenges that are not typically of concern within smaller drainage areas. A case study of a recent hydrologic modeling effort that was performed for the Susquehanna River drainage basin will be presented. For the 27,000 square mile drainage basin, hydrologic models were developed and calibrated to historic events for two separate scenarios; precipitation only and rain-on-snow floods. Due to the large size of the basin, number of gaging stations, and diverse topography, climatology and geology of the basin, many common methods in hydrologic modeling could not be employed without modification. Using the Susquehanna River case study as an example, how these factors affect the development and calibration of a hydrologic model as well as evaluation of a design storm will be explored, challenges identified, and potential solutions discussed. Issues considered for calibration of a large area model include availability, density, consistency and accuracy of storm data (i.e. rainfall, snowpack, meteorology and stream flow), regional variation in model parameters and calibration storm characteristics, and applicability of common modeling methods. Unique design storm considerations for very large basins that will be discussed include size and duration of storm, spatial pattern, and placement of storm center.

## Introduction

Recently, a study was undertaken to update the Probable Maximum Flood (PMF) estimate for the Conowingo Dam, the last dam on the Susquehanna River before it enters the Chesapeake Bay. As part of the study, calibrated hydrologic models were developed for both precipitation only and rain-on-snow scenarios. Additionally, a snowmelt model was calibrated for the basin. The PMF re-evaluation achieved a variety of goals. The study incorporated the most recent hydrologic and meteorological data, including a site-specific Probable Maximum Precipitation (PMP) for both all-season and cool-season events in the basin. The study also evaluated the potential of a rain-on-snow event to control the PMF in the basin, a condition which was not assessed in the prior PMF study for the basin. Additionally, the re-evaluation of the PMF for the Susquehanna River Basin provided a fully documented analysis which could be readily updated should new information on the hydrology of the basin become available.

The drainage basin for Conowingo Dam covers an area of just over 27,000 square miles of southern New York, eastern Pennsylvania and northeastern Maryland. Developing a calibrated hydrologic model and evaluating the PMF for a basin of this size presented a series of unique challenges. Notably, evaluation of the PMF required the development of a design storm which was both longer and of a larger area than can be produced by the Hydrometeorological Report 52 (HMR52) computer program, as is typically used to spatially and temporally distribute the PMP for basins in the eastern United States. However, calibration of the model and inputs to the PMF hydrologic model also provided a number of uncommon challenges from selection of calibration events and data collection to organization of calibration data and efficient input of precipitation to the 80 modeled sub-basins for each of the various PMF scenarios evaluated. While it may not be expected that a rain-on-snow event would control the PMF for a basin which extends this far south (northern Maryland), several of the large floods which have occurred within the basin have been driven by rain-on-snow conditions. Therefore a detailed snowmelt model was developed for the basin, a rain-on-snow hydrologic model was calibrated and a series of rain-on-snow PMF scenarios were evaluated, which ultimately controlled the PMF for the basin. Additionally, some common hydrologic modeling methods were found to break down under the long duration design storm utilized in the study.

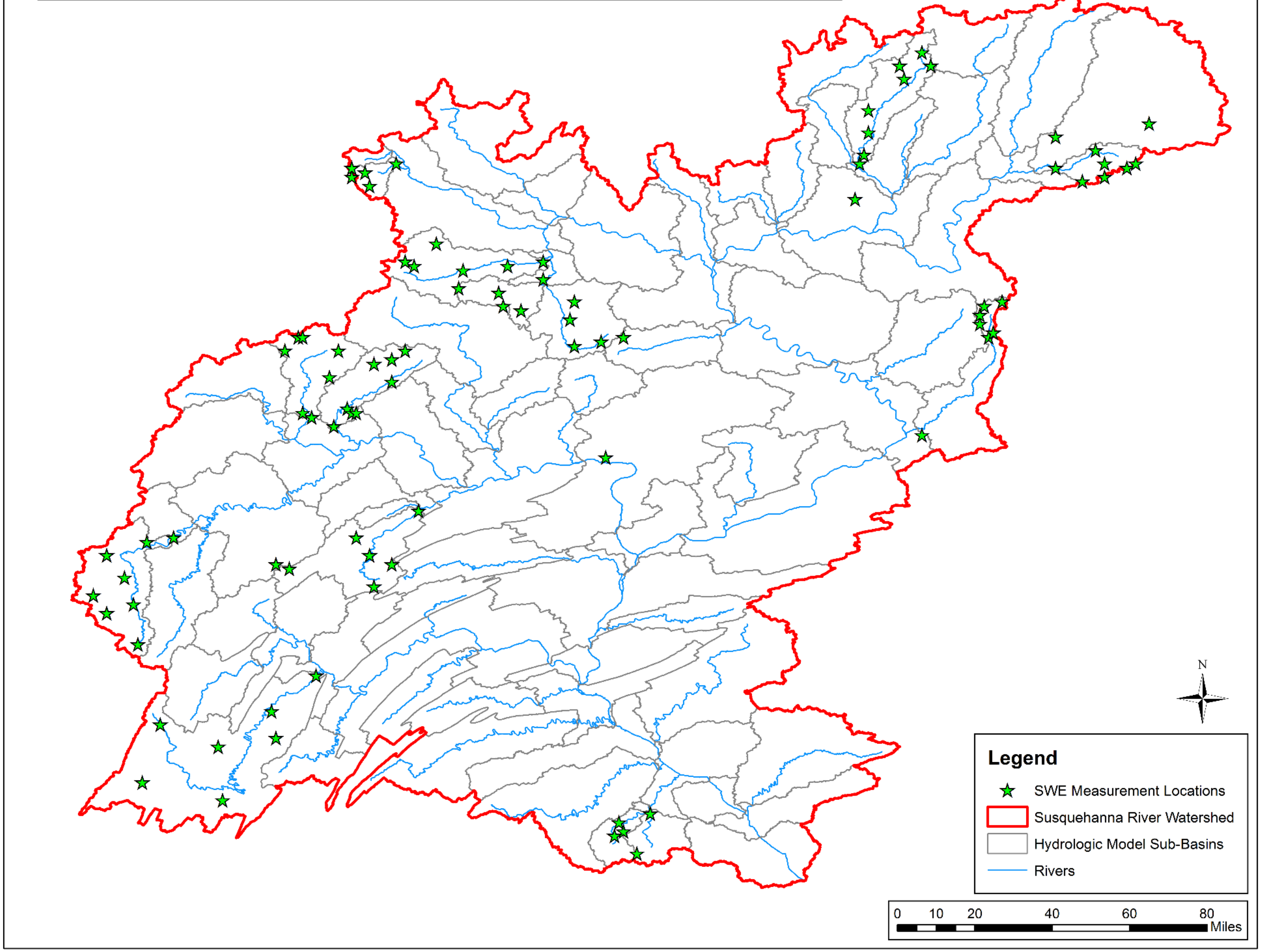
## Data Collection

Development of the hydrologic model and evaluation of the two PMF scenarios required a wide variety of data for input and evaluation of model results. The data sets collected for this study included meteorological inputs such as precipitation, snowpack, temperature, wind speed and dewpoint; stream flow and reservoir operations under the historic events and per flood operating guidelines.

Collection of these data sets for calibration was a very time intensive effort for a basin of this size, therefore selection of calibration events was an important part of minimizing the effort required to compile the input data needed for calibration of the snowmelt and hydrologic models. For each calibration scenario, several events were considered in order to find events that would provide a good basis for the selection of model parameters throughout the basin based on the relative size of flows at various locations, amount of precipitation, availability of precipitation and streamflow data, and in the case of rain-on-snow calibration; snowpack depth, amount of snowmelt and availability of snow water equivalent data, temperature, wind speed and dewpoint. Events which did not produce significant flows throughout much of the basin, had poor data coverage, or rain-on-snow events which did not have significant initial snowpack in parts of the basin were eliminated from consideration.

Even after culling potential calibration events to focus on those with the best available data, the selected events had significant variations in quality and availability of data. Most notably, data on the depth of snow and water content of the snowpack, for use in calibrating the snowmelt model, had significant gaps in temporal and spatial coverage. Only a few locations within the basin make daily measurements of the snow water content. There are, however, several locations at which snow water content measurements are taken less frequently (approximately every two weeks), however these location are clustered in and around the 13 sub-basins containing USACE flood control reservoirs, as shown in Figure 1. The dataset which provides the most complete coverage of the basin was obtained from the NOAA co-operative observer network (COOP), which take daily measurements of snow depths at over one hundred locations in and around the basin. In order to develop a snow water content dataset which covered the entire drainage basin, locations where measurements of snow water equivalent and snow depth were used to develop an estimate of the spatial pattern of snow pack density (i.e. inches of water equivalent per inch of snow depth) for each date on which snow water equivalent measurements were taken. These estimates of snow pack density were used in conjunction with the measurements of snow pack depth taken at NOAA COOP sites to estimate the snow water equivalent at all of the sites at which snow depth measurements were made. These snow water equivalent estimates were combined with actual measurements of water equivalent in order to estimate the spatial distribution of snow water equivalent throughout the basin. However, because measurements of snow water equivalent were not taken on the same dates for all locations in the basin, estimates of the spatial distribution of water equivalent were only considered to be reliable in areas near to the actual snow water equivalent measurements. Therefore, the estimates were applied to basins only on the dates when the nearest snow water equivalent measurements were taken. Subsequently, the dates on which reliable estimates of snow water equivalent could be made varied from basin to basin, resulting in varying date ranges for which the snowmelt model was calibrated. Generally, the measurements of water equivalent were made over a two day period.

Figure 1: Location of Snow Water Equivalent Measurement Sites



Streamflow data from 68 USGS stream gages was the primary source of hydrograph data used in the calibration of the hydrologic model. In locations with significant hydraulic structures (i.e. USACE flood control reservoirs or dams on the Lower Susquehanna River), additional data on flood flows was used to either augment or validate the USGS gage records. In the case of the Lower Susquehanna River dams, data on operations during the calibration events allowed for independent calculation of either peak flows or discharge hydrographs at the dams. At the USACE flood control reservoirs, data on operations was used to compute reverse-routed inflow hydrographs for use in calibrating the basins upstream of the reservoir, without attempting to replicate specific storm operations of the dam. Although there were a significant number of USGS stream gages throughout the basin, not all of the sub-basins could be calibrated directly to a stream gage for all of the calibration events, either due to the delineation of a sub-basin to a point without a stream gage or due to missing or unavailability of hydrograph data. Several strategies were used to overcome the lack of streamflow data, depending on the situation. Overall, the calibration was approached in such a way as to maximize the use of available data. Therefore, sub-basins were categorized by their location within the stream network and availability of flow data, and calibrations were prioritized based on the classification of the sub-basin. Generally, headwater basins (those without inflows from upstream sub-basins) with available hydrograph records were calibrated first, as these calibrations would have the highest level of confidence. Calibration would proceed downstream to other sub-basins where the local sub-basin flow could be isolated (i.e. hydrographs were available for all inflows and at the outlet of the basin). The results of these calibrations were used to develop regional estimates of parameters for sub-basins without gage data that were then refined through group calibrations to the next downstream gage location. For group calibrations, adjustments were made proportionally in the sub-basins being calibrated based on measurable characteristics of the sub-basin which are expected to affect the hydrologic model parameter being adjusted.

Even in sub-basins with stream gages at their outlets, the stream gage records did not always provide sufficient information to complete an accurate calibration of the hydrologic model. Several common issues were encountered with the streamflow data for the USGS gage, including completely missing gage records, missing hourly or 15-minute data, washed out gages or estimated peak flows, and inconsistent hydrograph records. In performing a calibration for a smaller basin, such issues might exclude an event from use in calibration. However, for a large basin it is inevitable that any potential calibration event will have some data issues, therefore strategies for best utilizing the available data were employed. In cases where either the gage was not in place or the gage record is not available for a specific event, calibration was performed for the remaining events and the peak flow weighted average values from those events were used for the sub-basin with initial baseflow and loss rates calibrated based on a group calibration to the next downstream gage with data for the event. For gages with missing hourly or 15-minute data, but for which daily flows were available, a similar strategy was employed where the unit hydrograph and baseflow recession parameters were selected based on the other events and initial baseflow and loss rates selected to match the runoff volume from the daily flow records.

In some cases, hourly or 15-minute data were only missing for a portion of the calibration event (generally around the peak), in these cases the partial hydrograph and daily flow data were utilized both to select initial baseflow and loss parameters and adjust the unit hydrograph and baseflow recession parameters as appropriate for the available portion of the hydrograph. For locations where the gage was washed out or the peak stage exceeded the capacity of the gage measurements, peak flows were often estimated using information from nearby gages and other observations. These estimates were evaluated for bias in the peak flows and compared against other estimates of flows such as at the Lower Susquehanna dams. These evaluations indicated that the peak flow estimates were generally reasonable, and were the best available data for calibration of the hydrologic model. However, it was found that some of the flow estimates at stream gages were inconsistent (i.e. one gage hydrograph could not possibly be correct if the other is) resulting in an inability to make up the difference in flows in the intervening drainage area either due to too little precipitation or too much flow from upstream. In these cases, when no data could be obtained to verify a particular gage record as more accurate, the approach was to split the difference and produce an average fit to several gages in series. This average fit was achieved by adjusting loss rates in the overall model after the best fit calibration was achieved for the isolated sub-basins or groups of sub-basins. This process of combining the isolated calibration models also allowed an evaluation of whether individual calibration errors were offsetting or cumulative.

## Development of PMF Design Storm

Early on in the study, it was noted that some limitations of the typical methods for evaluating the PMP and developing design storms (i.e. HMR's 51 and 52) could result in a design storm which is not critical for the basin. Based on the size of the drainage basin, it was postulated that the largest storm which could be produced using the existing HMR52 methodology (i.e. 20,000 square miles) may not be critical for the basin. While a storm of that area would produce residual precipitation over the remainder of the basin, it was believed that a larger area storm with a more uniform distribution of rainfall could be more critical for the basin. Additionally, it was believed that the length of drainage course for the basin, and subsequently the overall lag time of the basin could result in a critical storm which is longer than that which could be produced by the existing HMR52 methodology (i.e. 72 hours).

Further complicating this issue was the existence of HMR40, which is essentially a site-specific PMP study for the Susquehanna River Basin above Harrisburg, PA produced by the Weather Bureau (now National Weather Service) in 1965. This study provided a specific storm pattern for the basin, based on locations which commonly receive the highest intensity precipitation during large rainfall events. This report had several apparent drawbacks for the updated PMF study. The provided storm pattern did not cover the entire drainage basin being considered and did not allow for the evaluation of different storm centers, sizes and orientation. This PMP evaluation does not include large storms which have occurred since 1965 (including Hurricane Agnes, the flood of record for the site), does not include PMP for areas larger than the basin size, is limited to a 72-hour duration and does not include the evaluation of the cool-season PMP. Based on the apparent limitations of the existing HMR for the basin, a site-specific PMP analysis was performed by Applied Weather Associates (AWA) for the basin, which evaluated both the all-season and cool-season PMP's for durations as long as 120 hours and area sizes up to 100,000 square miles, in order to bound the critical design storm for the basin. In order to spatially and temporally distribute the site-specific PMP on the basin, an extension of the HMR52 methodology was developed which allowed the input of a customized depth-area-duration table, development of design storms of any duration, and development of design storms with areas up to 60,000 square miles. Development of longer duration storms could have been accomplished relatively simply outside of the HMR52 program, as the HMR52 methodology utilizes the same spatial pattern of rainfall for all time periods outside of the highest 18 hours of the storm. However, because of the other changes which needed to be implemented in the methodology and other desired improvements, the decision was made to re-program the methodology using the Python scripting language. This updated program allowed basins and sub-basins to be fed into the program using GIS shapefiles, customization of inputs and outputs and alternative methodologies which could more easily deal with the potential differences between site-specific and HMR51 based PMP values. In order to enable the development of storm sizes larger than 20,000 square miles, the so-called Within-Storm/Without-Storm relationship from HMR52 was extended to storm sizes up to 60,000 square miles. The Within-Storm/Without-Storm relationship defines the depth of precipitation at standard area isohyets such that a design storm will produce the PMP depth at the area of the storm but at larger and smaller areas will produce a depth of precipitation which is less than the PMP for that specific area. The relationship recognizes that the PMP for different areas may be produced by different storm types and therefore it is unreasonable to assume that the PMP depth would be produced at several area sizes within the same design storm. The HMR52 relationship was based on the average of depth ratios for several storms which when maximized would approach the PMP for one or more area sizes. Unfortunately, the data upon which the relationship is based is not contained in the HMR52 documentation. Additionally, many of the storms which were utilized in the original analysis do not contain data for area sizes larger than 20,000 square miles. Therefore, it was decided to extrapolate the curves mathematically, maintaining the trends which were apparent in the HMR52 curves.

One additional issue, which was considered in the development of design storms for the basin, was the idea of a moving design storm. Due to the long lag time of the basin, it is possible for flows from downstream basins to flush out well before the overall basin peak flow arrives at the dam, if only a stationary storm is considered. Hypothetically, a storm which moved south or southwest through the basin could result in a more critical flow at the dam. Prior to Hurricane Agnes, storms of tropical origin had generally moved northward through the basin. In fact HMR40 discusses the movement of storms through the basin, and a southward moving storm was ruled out as a possibility in the basin. However, Hurricane Agnes violated that assumption, with the storm initially moving northeast through the basin, stalling, and then looping back southwestward. Various alternatives were considered for evaluating a moving design storm, including utilizing a hypothetical track for the storm center, moving the center of the isohyetal pattern every so many hours. This approach could have been achieved by combining different portions of the results of a series of HMR 52 runs and utilizing a pre-determined storm size and orientation. However, since Hurricane Agnes had occurred within the basin, with what appeared to be a near critical track, it was decided that a spatial and temporal pattern matching that storm, and scaled up to PMP magnitude would provide an adequate sensitivity analysis on the effect of a moving storm.

## Hydrologic Modeling Methods

Initially, the National Resource Conservation Service (NRCS, formerly SCS) curve number method was selected for modeling of infiltration in the hydrologic model. The method was selected for its relatability to measurable characteristics of the sub-basins and variation in antecedent storm conditions, as well as its ability to replicate the hypothetical decrease in infiltration capacity of soils with rainfall. Calibration of the hydrologic model provided good replication of the observed events, even with long duration and high intensity precipitation events (several sub-basins had precipitation depths exceeding nine inches and durations of 48 hours or more during Hurricane Agnes). However, applying the methodology to the long duration, high intensity storm resulting from the PMP appeared to cause a breakdown in the methodology. As noted previously, it was believed that the critical duration of storm for the basin may be longer than the standard 72-hour storm produced by the HMR51/52 methodologies. In order to evaluate this hypothesis, a sensitivity analysis was performed comparing the flows produced by 72-hour and 120-hour PMP storms. The results showed a marked increase in the peak flow due to the longer duration storm. However, as the results were scrutinized and compared to the differences in precipitation depth, the significant difference in peak flows did not appear to make sense. While review of historical data and the development of the hydrologic model had led to the conclusion that the peak flow would largely be driven by the runoff volume, the incremental precipitation between the 72- and 120-hour PMP, and associated precipitation intensity did not justify the increase in flow. Reviewing the basin average precipitation and infiltration hyetographs revealed that during the 120-hour event, computed infiltration essentially ceased at approximately 84 hours into the event, and had dropped off considerably by approximately 66 hours into the event, while the rainfall was still of considerable intensity. Reviewing the computation of runoff using the curve number method, this makes sense, as total rainfall is increased, the total infiltration approaches an upper limit, which is determined by the curve number and initial abstraction. By adding 24 hours of low intensity rainfall to either end of the PMP event, much of the computed infiltration capacity was being used up by the low intensity rainfall. However, it was not expected that such an effect would be observed in real life; what was essentially a light mist (average rainfall rates on the order of 0.02 inches/hour) should not significantly affect the infiltration capacity of a soil, even over a relatively long period. Considering the discrepancy between the expected impact of the longer duration PMP and the computed results, various alternative infiltration methods were considered.  In the end, the initial and constant loss method was selected for use in simulating the PMF for its ease of calibration and applicability to long duration/high volume events.

As noted previously, it is not intuitive that the controlling PMF scenario in a basin which extends as far south as southern Pennsylvania and northern Maryland would be a rain-on-snow scenario. Several of the large flood events on the Susquehanna River, including the second highest peak flow included a rain-on-snow component.  Additionally, with increasing size of the basin, and subsequently the storm area necessary to produce the PMF, the average depth of precipitation over the basin becomes lower.  Therefore, for larger basins even a relatively small amount of snowpack combined with a seasonal PMP can potentially produce a critical PMF scenario.  In order to evaluate the potential for the rain-on-snow scenario to control the PMF for the basin, a series of conservative screening type analyses were performed.  These analyses failed to rule out the rain-on-snow PMF as the potentially controlling scenario for the basin.  Therefore, a full calibration of snowmelt models and rain-on-snow hydrologic model was performed and several rain-on-snow PMF scenarios were evaluated.  For this basin, the rain-on-snow scenario was found to be the controlling scenario for the PMF.

## Data Management

Calibration of the hydrologic model, and simulation of the PMF scenarios for this study required a significant amount of input data and generated a lot of output as well.  Tracking and organizing the data, developing model inputs that could easily be fed into the model, and generating meaningful summaries of model output became a task in and of itself.  Further complicating the issue, were the snowmelt model and a pair of interconnected flood control dams, which all had to be modeled outside of the hydrologic model.

The USACE Hydrologic Engineering Center’s Hydrologic Modeling System (HEC-HMS) can handle the modeling of snowmelt using the degree-day method.  In our experience, the rate of snowmelt tends to be as dependent on wind speed, solar radiation, dewpoint and rate of rainfall as it is on the temperature.  Therefore, the energy budget method for evaluating snowmelt is preferred for the estimation of snowmelt due to its inclusion of these factors.  Additionally, the Federal Energy Regulatory Commission (FERC), the review agency for this study, prefers the use of the energy budget method for its incorporation of other parameters in the estimation of snowmelt, including wind speed, rainfall rate, dewpoint and solar radiation.  In order to utilize the energy budget snowmelt method, spreadsheet models were developed for each of the 80 sub-basins, which pulled in meteorological data and physical parameters of the basin in order to compute hourly potential snowmelt and perform an accounting of the average snow water equivalent within the basin and the spatial extent of snowpack, resulting in an hourly estimate of total effective precipitation (rainfall plus snowmelt) which was input to the hydrologic model.  In order to allow easier updates to the models, a few spreadsheets were used for data input to all 80 of the sub-basin models, and a single spreadsheet was used to gather the output of the individual snowmelt models for input to the hydrologic model.

Two flood control reservoirs (Tioga and Hammond) on two branches of the Tioga River are located on either side of a ridge and are interconnected via a spillway and gate structure on a connecting channel. Tioga reservoir has a low-level outlet but no emergency spillway, its only high flow discharge is through the connecting channel into Hammond Reservoir. Hammond Reservoir typically does not discharge low flows directly to the Tioga River, rather flow is diverted into Tioga Reservoir under such conditions. However, Hammond Reservoir does have an emergency spillway through which extreme inflows to both reservoirs are ultimately discharged. The interconnection of the reservoirs, resulting in flow moving in either direction in the connecting channel, depending on other conditions, made the reservoir system impossible to model within the HEC-HMS hydrologic model, without losing some of the potential function of the system. Again, a spreadsheet model was employed to compute the interflow between the reservoirs and the discharges through each of the dams. Input to the reservoir model came from a sub-section of the hydrologic model which only handled the two sub-basins upstream of the reservoirs. Computed outflows from the reservoirs were input to the overall hydrologic model as specified flows into the next downstream river reach.

With all of the movement of data between the HEC-HMS hydrologic model and various spreadsheets, it was important to have an efficient and reliable method for transferring data. The HEC-DSS add-in for Excel was an invaluable tool for transferring data back and forth between the hydrologic model and the spreadsheet models for snowmelt and the Tioga-Hammond reservoir system, as well as inputting precipitation data for the various design storm scenarios. As noted previously, the extension of the HMR52 methodology, developed for this study, allowed for customization of the output. This allowed the results of the HMR52 runs to be transferred directly to the DSS file or the snowmelt models without a lot of re-formatting of the data, as would be required with the USACE’s HMR52 program. Customizing the output of the HMR52 program to fit directly with the input to the other models allowed for multiple storm sizes, centers and orientations to be efficiently run through the other models in order to evaluate the critical storm for the PMF.

## Conclusions and Lessons Learned

Although modeling of such a large basin presents some unique challenges, workable solutions were found for all of the issues which arose in this study. Having a good overall vision of the study helped in alleviating many of the issues that could have arisen. By understanding what role each piece of the project would play, how everything would work together and what information was needed to make each of those pieces work, a good overall strategy was formed for the study allowing individual engineers to focus on their piece of the puzzle knowing that it would work with the other parts of the project. The overall strategy also helped to prioritize what issues were important to the overall results of the study and those that could be ignored.

For instance, lack of complete gage data for a calibration event in a small basin might mean that the event would have to be scrapped, but in a large basin it is unreasonable to expect to have a 100% complete dataset for nearly 70 stream gages during any event. By developing strategies to leverage the stream gage data in other sub-basins and/or partial gage records (partial hydrographs or daily data), it was possible to limit the total number of events used in calibration, and subsequently the level of effort required for data collection, while still maintaining a high quality model calibration. In some respects, the large size of the basin had some advantages with regard to data availability. When one sub-basin did not have a gage record at its outlet, there was always a gage downstream that could be utilized. If some of the sub-basins upstream of that point were also gaged, an even greater level of confidence could be placed in the results of the sub-basins calibrated through group methods.

The issue with the NRCS curve number method for infiltration was not anticipated going into the project, or even immediately obvious when it was first applied to the model runs for the PMF. Only after examining the results of the PMF runs for the 72- and 120-hour storms was it apparent that the infiltration method was breaking down under the long duration, high intensity events. This issued highlighted the need to know the limitations of the models and methodologies being used for a study and to critically evaluate whether the methods are appropriate for the intended study. The curve number method has been used for many PMF studies, and its application to PMF evaluation is discussed extensively in the FERC Engineering Guidelines on the Determination of the Probable Maximum Flood. Therefore, it seemed that the method was appropriate for application to this study. Including an evaluation of the potential limitations of modeling methods in the overall vision for the study could have highlighted this issue up front and is an important lesson for future projects. Also, a rain-on-snow event may produce the controlling PMF scenario even in drainage basins which are not subject to very high accumulation of snow water equivalent.

## About the Author

Damian Gomez is a Water Resources/Dam Safety Engineer with Gomez and Sullivan Engineers, P.C. in Utica, NY.  He has 13 years of professional experience focusing in hydrologic and hydraulic modeling, performing Probable Maximum Flood, Dambreak and floodplain mapping studies.  He is a licensed Professional Engineer and a Certified Floodplain Manager.  He has a B.S. in Civil Engineering from Penn State and a M.S. in Civil and Environmental Engineering from the University of Buffalo.