Technical Review Documentation

Flooding Hazard Reevaluation of

Quad Cities Nuclear Power Station, Units 1 and 2

Prepared by
Oak Ridge National Laboratory

October 31, 2016

INTRODUCTION

This document supplements the input to the Nuclear Regulatory Commission (NRC) Office of Nuclear Reactor Regulation Staff Assessment of the Flooding Hazard Reevaluation Report for the Quad Cities Nuclear Power Station (Quad Cities), Units 1 and 2. This document provides a summary of ORNL's technical review of the development, application, and effect of flooding hazards on water levels at the Quad Cities site as provided by the licensee in its Flood Hazard Reevaluation Report (FHRR). The review process undertaken by the ORNL staff included a review of the information submitted by the licensee; examination and evaluation for appropriateness and conservatism of the licensee's conceptual models and assumptions; checking of the licensee's information (including input files for computer models) for completeness, internal consistency and consistency with technical sources; and examination of the electronic files that document the licensee's analysis for indications of errors or computational problems that might compromise the results. The flooding hazards that were the focus of ORNL's analysis were (1) local intense precipitation and associated drainage (LIP), and (2) flooding in streams and rivers.

CONTENTS **page**

1. LOCAL INTENSE PRECIPITATION AND ASSOCIATED SITE DRAINAGE

1.1 Background

The licensee reported in the FHRR (Exelon, 2013; Exelon, 2015) that the reevaluated flood hazard for LIP is based on a stillwater surface elevation that ranges from 595.81 to 597.69 feet (ft), North American Vertical Datum of 1988 (NAVD88). This flood-causing mechanism is not described in the licensee's current design basis. Site drainage was not considered as part of the initial licensing.

The site grade at the Quad Cities powerblock is given in the FHHR as elevation 594.5 ft above mean sea level (MSL), 1912 Datum. The licensee states that the datum shift between the MSL 1912 Datum and NAVD88 is 0.70 ft at River Mile 506.9 (corresponding to the location of Quad Cities); furthermore, the licensee has provided information on the mathematical relationship between these two datums at the QCNPS as follows (Exelon, 2014a):

NAVD88 (in feet) + 0.70 ft = MSL 1912 Datum (in feet)

Therefore, the site grade at the QCNPS powerblock is at elevation 593.8 ft NAVD88. The licensee's LIP analysis used the NAVD88 datum, primarily because field survey data and other data available for topographical elevations at the site were available in the NAVD88 datum.

To provide additional information in support of the summaries and conclusions presented in the FHRR, the licensee provided for staff's review several calculation packages via an electronic reading room. These calculation packages supplement the information provided in the FHRR. In regard to the licensee's LIP analysis, the staff requested two sets of additional information from the licensee to supplement the FHRR (NRC, 2014a; NRC, 2014b). The licensee's responses to these requests (Exelon, 2014a; Exelon, 2014b; Exelon, 2015) provided the additional information used in the staff's evaluation, which is discussed below.[1]

1.2 Evaluation

For the LIP analysis, the licensee used the FLO-2D model Version 2009.06 (FLO-2D, 2009) with inputs consisting of topographical information and Manning's roughness coefficient (*n*) based on the proportions of different land covers at the site and their effects on flow depths and velocities. The licensee's LIP analysis assumed that all passive and active drainage system components were non-functional or blocked during the event, and ignored all runoff infiltration losses (Exelon, 2015). The licensee stated that impervious cover around the power block buildings coupled with the short-duration (1-hr precipitation) of the LIP will limit infiltration of precipitation and groundwater seepage to a minimum (Exelon, 2015). The staff agrees with this assumption, which is reasonable and conservative.

The licensee created a Digital Elevation Model (DEM) produced from publicly-available LiDAR data, with field surveys performed to further refine grading, slopes, drainage divides and elevation of the site that were not identified by the LiDAR survey (Exelon, 2015). The "spray canal" which runs along the north, east, and south sides of the Quad Cities site is included in the DEM, with a bottom elevation represented by the water surface elevation at the time of the LiDAR survey (Exelon, 2015). Orthoimagery was also used to determine the proportion of various land cover types and to estimate Manning's roughness coefficient using guidance in the

[1] Note that the licensee's response (Enclosure 2) (Exelon, 2015) to the third set of NRC requests provided an update of the LIP analysis in the original FHRR (Exelon, 2013c).

FLO-2D reference manual (FLO-2D, 2009). The licensee performed a sensitivity analysis to determine the effect of using the upper and lower range of Manning's roughness coefficients for a 20-ft grid size, which resulted in a maximum water surface elevation variation of ±0.1 ft (Exelon, 2015). Staff finds the licensee's use of DEM data and orthoimagery to be appropriate, and the assumed spray canal elevation, Manning's roughness coefficients, and grid size to be reasonable, with some apparent conservatism applied.

The 1-hr 1-mi^2 probable maximum precipitation (PMP) event was developed using a site-specific analysis approach described in a calculation package supplied in the electronic reading room. The PMP was derived following approaches similar to those used in developing Hydrometeorological Reports (HMR) 51 and 52 (NOAA, 1980; NOAA, 1982); however, various updates to the methodology were used. The NRC conducted a generic audit of the Applied Weather Associates' approach to conducting site-specific PMP (ssPMP) analyses and produced an audit report (NRC, 2015) documenting the findings relevant to the review of the licensee's analyses.

The licensee obtained a 1-hr 1-mi^2 PMP value of 13.6 inches (in.) through a ssPMP analysis after analyzing a short list of 21 historical LIP-type storms. Compared to the 1-hr, 1-mi^2 PMP derived from HMR-51 and HMR-52 (17.78 in.), the ssPMP value is 23.5 percent smaller (13.6 in.) and stems from transposition and maximization of the 1940 Hallett, Oklahoma storm (Exelon, 2015).

1.3 ORNL Staff Analysis

The ORNL staff reviewed the flooding hazard from LIP, including associated effects, against the relevant regulatory criteria based on present-day methodologies and regulatory guidance. The ORNL staff's review of the licensee's LIP ss PMP estimate includes sensitivity analysis related to two key points of expert judgment that had been identified in NRC's generic audit (NRC, 2015). As discussed in the paragraphs below—and as described in greater detailed in Appendix A of this current report—the ORNL staff investigated these two key points.

The <u>first issue</u> relates to a heuristic for storm representative dew point adjustment used to harmonize historical storms for which only 12-hr dew point data were available with more recent storms in a single database. While the original heuristic used by the licensee for converting maximum 12-hr persisting dew point values to maximum average dew point values for LIP-type storms consists of a +7 degree F adjustment (NRC, 2015), staff analysis of 11 short list LIP storms indicated that a +2 degree F adjustment was more appropriate. Consequently, ORNL's sensitivity analysis of LIP considered this difference.

The <u>second issue</u> relates to the use of climatological averages for spatially interpolating 100-year (yr) dew point values rather than a more gauge-based approach (NRC, 2015). When incorporating this gauge-based approach, the ORNL staff's analysis typically produced higher individual storm PMP adjustment factors than the licensee's analysis and resulted in a 10% increase to the 1-hr 1-mi^2 PMP value from 13.6 in. to 14.92 in., with the Hallett, Oklahoma storm remaining the bounding storm. The combination of this gauge-based approach with revision to the storm representative dew point heuristic further increased the 1-hr 1-mi^2 PMP value to 15.59 in. (i.e., 15% increase), with the 1926 Boyden, Iowa storm representing the bounding storm. Although the combination of both issues as used by the licensee caused an increase in the PMP rainfall depth estimate, sensitivity of water surface elevations using the FLO-2D model was within a reasonable margin of modeling error.

The sub-hourly PMP depths for the 5-minute (min), 15-min, and 30-min time intervals were calculated using the ratios obtained from Figures 36, 37, and 38 of HMR-52 (Exelon, 2015). The rainfall hyetograph was arranged using a front-loaded distribution, with the highest rainfall intensity occurring at the event onset (Exelon, 2015). The licensee concluded that the type of storm indicative of an LIP would likely be a mesoscale convective system, which is associated with a zone of convergence and very intense initial precipitation and would maintain "a decrease in the precipitation after the initial burst as the rear trailing stratiform region with the cold pool moves over the area," thus fitting with a front loaded distribution (Exelon, 2015). While this statement is true for some historical LIP-scale storms, alternative rainfall distributions have also frequently occurred. The ORNL staff performed sensitivity analysis relative to temporal rainfall distributions to ensure a conservative, realistic approach is used. ORNL noted a small increase in water surface elevations when a center weighted temporal distribution, which is within a reasonable margin of modeling error. The rainfall hyetograph for the LIP event is shown in Figure 1.

The licensee used the 2009 version of FLO-2D (Build No. 09-13.1.12) to calculate site flooding from the 1-hour (h) PMP. In the original FHRR submittal, the licensee simulated rainfall onto building roofs as being allowed to pond due to roof parapets and blocked roof drains (Exelon, 2013). A request for additional information (RAI) was issued (RAI Item #7a) (NRC, 2014b) to request that the licensee use a more conservative approach by allowing rainfall runoff from building roofs to be conveyed to the site ground.

In order to address this issue, the licensee simulated building flow blockage while transporting rainfall to the adjacent ground by raising the elevation of FLO-2D grid elements representing buildings above maximum flooding elevation (Exelon, 2015), which is a reasonable method for simulating flow obstruction around and runoff from these structures. Due to the potential for the elevated building elements to result in model instability in the form of rapidly varying flow, staff reviewed velocity distributions and noticed only a few abnormalities along building perimeters. These abnormalities were limited, and therefore had no impact on the reevaluated flood hazard results.

In addition, the concrete security barriers along the north, east, and south sides of the site were modeled with FLO-2D as a levee to account for the effects on local drainage patterns (Exelon, 2015). In the original FHRR submittal, the licensee simulated various 1- to 2-ft-wide openings in the security barriers but did not appear to capture various larger opening at other key locations (Exelon, 2013). As a result, an RAI was issued (RAI Item #9a) (NRC, 2014b) to request that the licensee capture the additional barrier gaps through revised FLO-2D modeling. For the multiple adjacent gaps along the east side of the plant, a single 20-ft gap was used (Exelon, 2015). This particular model configuration conservatively enables higher flow rates onto the site than would occur through the modeling of ten 2-ft gaps. The ORNL staff reviewed the location and sizing of the revised security barrier gaps to ensure the application was accurate and appropriate.

1.4 Conclusions

The licensee reported that the reevaluated flood hazard for LIP would range from 595.81 to 597.69 ft NAVD88 (i.e., 596.51 to 598.39 ft MSL). The licensee stated that although LIP is "a beyond design basis event, additional interim actions have been evaluated to mitigate risk to the site from a LIP event" (Exelon, 2015). ORNL confirmed the process used to estimate these reevaluated elevations were reasonable for the purposes of the 50.54(f) request.

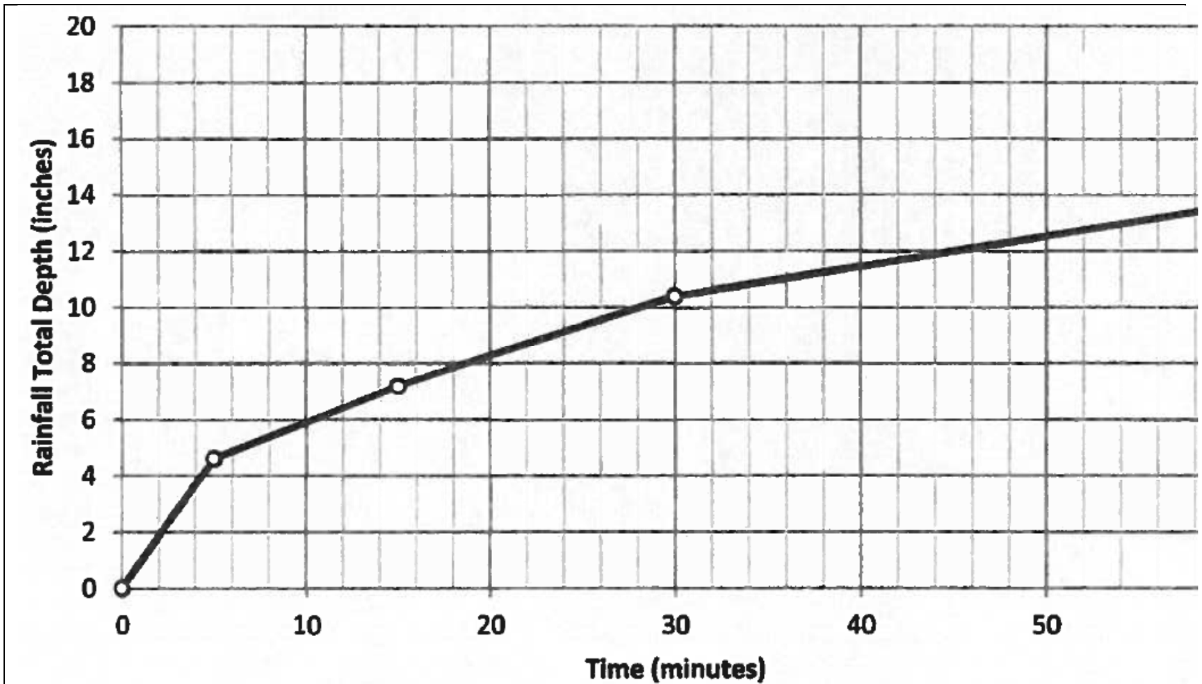

Figure 1. 1-h Probable Maximum Precipitation (PMP) distribution at Quad Cities Nuclear Power Station.
Source: Exelon, 2015

1.5 References[2]

Exelon (Exelon Generation Company, LLC), 2013, "Flood Hazard Reevaluation Report in Response to the 50.54(f) Information Request Regarding Near-Term Task Force Recommendation 2.1, Flooding, for the Quad Cities Nuclear Power Station," Exelon Generation Company, Chicago, IL, March 1, 2013, ADAMS Accession No. ML13081A039.

Exelon (Exelon Generation Company, LLC), 2014a, "Response to Request for Additional Information Regarding Fukushima Lessons Learned - Flood Hazard Reevaluation Report," RS-14-173, letter to NRC from Glen T. Kaegi, Exelon Generation Company, LLC, July 3, 2014, ADAMS Accession No. ML14238A384.

Exelon (Exelon Generation Company, LLC), 2014b, "Response to Request for Additional Information Regarding Fukushima Lessons Learned - Flood Hazard Reevaluation Report," RS-14-276, letter to NRC from Glen T. Kaegi, Exelon Generation Company, LLC, October 6, 2014, ADAMS Accession No. ML14300A169.

Exelon (Exelon Generation Company, LLC), 2015, "Response to Request for Additional Information Regarding Fukushima Lessons Learned - Flood Hazard Reevaluation Report," RS-15-001, letter to NRC from Glen T. Kaegi, Exelon Generation Company, LLC, January 13, 2015, ADAMS Accession No. ML15021A179.

FLO-2D, 2009, *Reference Manual–Version 2009*, Version 2009.06 Build No. 09-13.1.12, FLO-2D Software, Inc., Nutrioso, Ariz. Company website http://www.flo-2d.com/.

NOAA (National Oceanic and Atmospheric Administration), 1980, "Hydrometeorological Report No. 51 (HMR-51); Probable Maximum Precipitation Estimates, United States East of the 105th Meridian," prepared by L.C. Schreiner and J.L. Riedel, Hydrometeorological Branch, Office of Hydrology, National Weather Service, Washington, D.C., originally published July 1978, reprinted August 1980.

NOAA (National Oceanic and Atmospheric Administration) 1982, "Hydrometeorological Report No. 52 (HMR-52), Application of Probable Maximum Precipitation Estimates - United States East of the 105th Meridian," prepared by E.M. Hansen, L.C. Schreiner and J.F. Miller, Hydrometeorological Branch, Office of Hydrology, National Weather Service, Washington, D.C., August.

NRC (U.S. Nuclear Regulatory Commission), 2014a, letter from Brenda M. Mozafari, Office of Nuclear Reactor Regulation, to Michael J. Pacilio, Exelon Generation Company, LLC, regarding "Quad Cities Nuclear Power Station, Units 1 and 2–Request for Additional Information Regarding Fukushima Lessons Learned Flood Hazard Reevaluation Report (TAC Nos. MF1108 and MF1109)," June 25, 2014, ADAMS Accession No. ML14120A441.

NRC (U.S. Nuclear Regulatory Commission), 2014b, e-mail from Victor Hall, Office of Nuclear Reactor Regulation, to David Distel, Exelon Generation Company, LLC, regarding "Quad Cities Flood Hazard Reevaluation Report RAI," October 17, 2014, ADAMS Accession No. ML14293A224.

[2] ADAMS Accession Nos. refer to documents available through NRC's Agencywide Document Access and Management System (ADAMS). Publicly-available ADAMS documents may be accessed through http://www.nrc.gov/reading-rm/adams.html.

NRC (U.S. Nuclear Regulatory Commission), 2015 "Report for the Audit of Applied Weather Associates, LLC, Regarding Site Specific Probable Maximum Precipitation Development in Support of Near-Term Task Force Recommendation 2.1 Flood Hazard Reevaluations," May 19, 2015, ADAMS Accession No. ML15113A029.

2. FLOODING IN STREAMS AND RIVERS

2.1 Background

This section presents a summary of the technical review of the development, application, and effect of the flooding resulting from the probable maximum flood (PMF) on the water levels in the Mississippi River as provided by the licensee in the FHRR for the Quad Cities site (Exelon, 2013). The ORNL staff reviewed and verified hydrologic and hydraulic parameter selection, the licensee's modeling approach and assumptions, and overall methodological approach to modeling with respect to conservatism.

The licensee reported in the FHRR that the reevaluated flood hazard, including associated effects, for streams and rivers is based on a stillwater surface elevation of 600.5 ft MSL (Exelon, 2013). This flood-causing mechanism is described in the licensee's current design basis. According to the FHRR, the current design basis hazard for site flooding from streams and rivers is 603 ft MSL, while the Updated Final Safety Analysis Report (UFSAR) Section 2.4.3 identifies probable maximum flood as [redacted] ft MSL, and while UFSAR Figure 2.4-1 suggests a probable maximal flood elevation of [redacted] ft MSL (Exelon, 2012).

2.2 Evaluation and ORNL Staff Analysis

To provide additional information in support of the summaries and conclusions presented in the FHRR, the licensee provided for staff's review several calculation packages via an electronic reading room. These calculation packages supplement the information provided in the FHRR.

In regard to flooding on streams and rivers, the NRC staff requested additional information from the licensee to supplement the FHRR (NRC, 2014b). The licensee's response to these requests (Exelon, 2014a; Exelon, 2014b) provided this additional information which is discussed below. The ORNL staff describes its evaluation of site flooding from streams and rivers, including associated effects, against the relevant regulatory criteria based on present-day methodologies and regulatory guidance below.

Since HMR-51 (NOAA 1980) does not provide PMP values for drainage areas greater than 20,000 square miles (mi^2), the licensee conducted a ssPMP analysis to estimate the watershed-scale PMP for the upper Mississippi River drainage basin upstream of the Quad Cities site, a total area of approximately 88,000 mi^2. Both all-season and cool-season (rain on snow event) PMP were estimated in the licensee's ssPMP study. The ssPMP methodology is generally consistent with the HMRs, with variations on the inclusion of more recent storms (since the date of publication of the HMRs) and other adjustments (e.g., definition of storm representative dew point and maximum dew point climatology) as discussed in the NRC generic ssPMP audit report (NRC, 2015). By reviewing multiple historical extreme storms that were observed in the neighboring regions of the Quad Cities watershed, the licensee selected a short list of 31 major storms for the ssPMP calculation (Exelon, 2013). For each of the storms evaluated, the licensee considered transposition limits which could prevent historical storm events from having occurred at the basin centroid and each of the 20 grid point locations within the Quad Cities drainage basin for which the ssPMP was evaluated (Exelon, 2013). Various procedures for adjusting historical rainfall events as documented in the ssPMP audit report (NRC, 2015) were followed. Using storm adjusted rainfall at each grid point, the licensee constructed depth-duration plots to provide the PMP values at each grid point and the basin centroid. The licensee also allowed for movement of the design storm during the PMF calculations, which is different from the stationary storm method used in HMR-52 (NOAA, 1982; NRC, 2015). The ORNL staff

observed that the ssPMP values are consistently less than HMR values across various storm durations and drainage areas.

To quantify the snowmelt contributions to the cool-season PMP, the licensee developed a meteorological parameter time series for each of the 10 major sub-watersheds within the basin, and the licensee calculated a 100-yr area-weighted snowpack at a sub-watershed level from weather gages throughout each watershed (Exelon, 2013).

As discussed in the following paragraphs, the licensee identified three alternatives in the FHRR (Exelon, 2013) for the investigation of the PMF is a function of the combined events defined in NUREG/CR-7046 (NRC, 2011a) for floods caused by precipitation events.

Alternative 1 involved mean monthly base flow, median soil moisture, an antecedent of the subsequent rain which is the lesser of (a) rainfall equal to 40 percent of PMP or (b) a 500-yr rainfall, followed by a 72-h dry period and then the full PMP, and waves induced by 2-yr wind speed applied along the critical direction. Alternative 1 resulted in a maximum water surface elevation of 595.2 ft MSL with a corresponding flow of 551,800 ft^3/s; however, this alternative was not the controlling PMF scenario (Exelon, 2013).

Alternative 2 involved mean monthly base flow, probable maximum snowpack and a 100-yr cool-season rainfall, and waves induced by 2-yr wind speed applied along the critical direction. Alternative 2 was not the controlling PMF scenario; hence, the licensee did not provide a numerical estimate of the surface water elevation for this alternative (Exelon, 2013).

Alternative 3, which was the controlling PMF scenario, involved mean monthly base flow, 100-yr snowpack, cool-season PMP, and waves induced by 2-yr wind speed applied along the critical direction (Exelon, 2013). The licensee used the USACE Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) software Version 3.5 (USACE, 2010b) and the PMP values to determine the watershed runoff using the Clark unit hydrograph and flow routing to the Mississippi River using the Muskingum method (Chow et al., 1988; USACE 2010b). U.S. Geological Survey daily stream flow data for historical extreme storms were used to calibrate and verify the HEC-HMS model. Baseflow was obtained using gage data averaged within each month, with the highest monthly averaged flow from May to November used for the all season PMF and the March average monthly flow used for cool-season PMF. The licensee considered modifying the calibrated hydrographs to account for nonlinear basin response in accordance with NUREG/CR-7046, by increasing the peak by one-fifth and decreasing the time-to-peak by one-third. However, because these adjustments resulted in lower flows, in the interest of conservatism, the licensee did not use the nonlinear adjustments in the PMF analysis.

The hydrological response of the watershed is accomplished using the HEC-HMS model. The ORNL staff agrees with the licensee's specification of hydrological inputs and assessment of the response of the watershed. The licensee calibrated the HEC-HMS model to flow observations by [redacted]. Estimation for parameters for ungaged watersheds was assessed based on [redacted]. The model was calibrated using [redacted] storm events and verified using [redacted] different storm events (Exelon, 2014a). The model calibration results are very good and the verification results are also very good with the exception of a storm event (smallest resulting flood of the verification set) for which the model conservatively over predicts observed flow levels. The ORNL staff's review of the calibration and verification results confirms that the model is accurately predicting flood events based on the calibrated parameters, and the staff agrees that the model is valid for assessing such events.

The routing of the PMF resulting from the watershed runoff to the Quad Cities site is accomplished using the unsteady flow module of Hydrologic Engineering Center–River Analysis System (HEC-RAS) Version 4.1.0 (USACE, 2010a), for both Alternative 1 and Alternative 3. The geometry of the hydraulic model is based on a truncated section of the USACE's UNET model (Version 4.0) (USACE, 2001) for the reach of the Mississippi River that extends from upstream River Mile 614.9 to the downstream River Mile 457.2 (i.e., at Lock and Dam No. 16), which bounds the Quad Cities site at River Mile 506.9 (Exelon, 2013). The licensee calibrated the model using extreme historical flow data from river gaging stations by refining the input parameters in HEC-RAS to match the data to within 0.5 ft. Manning's roughness coefficient (*n*) is the main adjustable parameter. The maximum PMF peak elevation at the Quad Cities site is 600.5 ft MSL with a corresponding flow of 744,700 ft^3/s, and the maximum duration of flooding above elevation 595 ft MSL for this scenario is 10 days (Exelon, 2013).

The ORNL staff agrees with the licensee's use of the hydraulic inputs and assessment of the routing response of the river using HEC-RAS. The licensee's calibration of the model is performed using sensitivity runs for Manning's roughness coefficient adjustments for five flood events (Exelon, 2013). The ORNL staff's review of the calibration results indicates the differences in simulated and observed elevations are within 0.5 ft, with the exception of one flood for which the model conservatively over predicts by 0.7 ft. The ORNL staff agrees that these calibration results are acceptable and the model set-up demonstrates predictive performance for assessing the PMF.

The ORNL staff's review of the licensee's ssPMP estimate included sensitivity analysis related to a key point of expert judgment that had been identified in NRC's generic audit (NRC, 2015). The licensee's use of climatological averages for spatially interpolating 100-yr dew point values resulted in a lowering of the PMP rainfall depth relative to a more gauge-based approach; however, sensitivity of modeled water surface elevations at the site were within a reasonable margin of modeling error.

The ORNL staff performed sensitivity studies in HEC-RAS to investigate the effect of an increased PMP specification in support of the study conducted by staff to evaluate the appropriateness of the licensee PMP determination. The sensitivity study involved determination of water surface elevations at Quad Cities with respect to an 8.7% increase in the licensee's originally specified ssPMP and variation on Manning's roughness coefficient values. All hydrological parameters except the rainfall amounts are held constant. Adjustments to Manning's roughness coefficient values were applied to the entire Mississippi and Wapsipinicon Rivers.[3] The increase in ssPMP resulted in an approximate 2.5 ft increase in water surface elevation at the site. This is equivalent to a roughly 15% increase in Manning's roughness coefficient values using the licensee's originally defined ssPMP. The study revealed stronger sensitivity to changes in elevation with Manning's roughness coefficient as compared to flow. Additional information related to the ORNL staff's review of the ssPMP used for Quad Cities is provided in Appendix A.

During staff evaluation of the ssPMP, it was observed that the Alley Spring, Missouri storm (the bounding storm for nearly all cool-season PMP area-durations) was transpositioned to only the southern portions of the watershed, and was not transpositioned to the basin centroid or to the northern half of the watershed. At the basin centroid, the exclusion of Alley Spring resulted in a large reduction of cool-season ssPMP for durations above 12-h, which would have the largest

[3] Note that this refers to the licensee's approach for calibrating the HEC-RAS model for variations in Manning's roughness coefficient only between cross-sections 522.5 and 493.4 and again between cross-sections 493.2 and 482.9.

impact on riverine flooding. While the exclusion of the Alley Spring storm may be attributed to distance (i.e., the original storm occurred in a location too far south to be considered transpositionable based on latitudinal meteorological differences), the decision made for Alley Spring was not consistent with other cool-season short list storms; however, it was determined that the potential for the licensee's ssPMP evaluation to underpredict ssPMP was not significant enough to warrant further review.

2.3 Conclusions

The licensee reported that the reevaluated flood hazard for streams and rivers was 600.5 ft MSL which is bounded by the current design basis flood hazard of 603 ft MSL. ORNL confirmed the process used to estimate the reevaluated elevation was reasonable for the purposes of the 50.54(f) request.

2.4 References

Chow, V.T., Maidment, D.R., and Mays, L.W., 1988, *Applied Hydrology*, Tata McGraw-Hill Education (reprint edition).

Exelon (Exelon Generation Company, LLC), 2012, "Exelon Generation Company, LLC's 180-day Response to NRC Request for Information Pursuant to 10 CFR 50.54(f) Regarding the Flooding Aspects of Recommendation 2.3 of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident," RS-12-170, letter to NRC from Glen T. Kaegi, Exelon Generation Company, LLC, November 27, 2012, ADAMS Accession No. ML12332A307.

Exelon (Exelon Generation Company, LLC), 2013, "Flood Hazard Reevaluation Report in Response to the 50.54(f) Information Request Regarding Near-Term Task Force Recommendation 2.1, Flooding, for the Quad Cities Nuclear Power Station," Exelon Generation Company, Chicago, IL, March 1, 2013, ADAMS Accession No. ML13081A039.

Exelon (Exelon Generation Company, LLC), 2014a, "Response to Request for Additional Information Regarding Fukushima Lessons Learned - Flood Hazard Reevaluation Report," RS-14-173, letter to NRC from Glen T. Kaegi, Exelon Generation Company, LLC,July 3, 2014, ADAMS Accession No. ML14238A446 (Non-publicly available).

Exelon (Exelon Generation Company, LLC), 2014b, "Response to Request for Additional Information Regarding Fukushima Lessons Learned - Flood Hazard Reevaluation Report," RS-14-276, letter to NRC from Glen T. Kaegi, Exelon Generation Company, LLC, October 6, 2014, ADAMS Accession No. ML14300A169.

NOAA (National Oceanic and Atmospheric Administration), 1980, "Hydrometeorological Report No. 51 (HMR-51); Probable Maximum Precipitation Estimates, United States East of the 105th Meridian," prepared by L.C. Schreiner and J.L. Riedel, Hydrometeorological Branch, Office of Hydrology, National Weather Service, Washington, D.C., originally published July 1978, reprinted August 1980.

NOAA (National Oceanic and Atmospheric Administration), 1982, "Hydrometeorological Report No. 52 (HMR-52), Application of Probable Maximum Precipitation Estimates - United States East of the 105th Meridian," prepared by E.M. Hansen, L.C. Schreiner and J.F. Miller, Hydrometeorological Branch, Office of Hydrology, National Weather Service, Washington, D.C., August.

NRC (U.S. Nuclear Regulatory Commission), 2011a, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United State of America," NUREG/CR-7046, November 2011, ADAMS Accession No. ML11321A195.

NRC (U.S. Nuclear Regulatory Commission), 2014b, letter from Brenda M. Mozafari, Office of Nuclear Reactor Regulation, to Michael J. Pacilio, Exelon Generation Company, LLC, "Quad Cities Nuclear Power Station, Units 1 and 2–Request for Additional Information Regarding Fukushima Lessons Learned Flood Hazard Reevaluation Report," June 25, 2014, ADAMS Accession No. ML14120A441.

NRC (U.S. Nuclear Regulatory Commission), 2015 "Report for the Audit of Applied Weather Associates, LLC, Regarding Site Specific Probable Maximum Precipitation Development in Support of Near-Term Task Force Recommendation 2.1 Flood Hazard Reevaluations," May 19, 2015, ADAMS Accession No. ML15113A029.

USACE (U.S. Army Corps of Engineers), 2001, *UNET One-Dimensional Unsteady Flow through a Full Network of Open Channels*, User's Manual CPD-66, Version 4.0, USACE Hydrologic Engineering Center, April.

USACE (U.S. Army Corps of Engineers), 2010a, *HEC-RAS River Analysis System*, Hydraulic Reference Manual CPD-69, Version 4.1.0, USACE Institute of Water Resources–Hydrologic Engineering Center, January 2010.

USACE (U.S. Army Corps of Engineers), 2010b, *HEC-HMS Hydrologic Modeling System*, User's Manual, Version 3.5/Build 1417, USACE Institute of Water Resources–Hydrologic Engineering Center, August 2010.

Appendix A

Quad Cities FHRR Review Summary

Site-specific Probable Maximum Precipitation (ssPMP)

Table of Contents

Executive Summary

This Appendix contains the staff's evaluation of the site-specific probable maximum precipitation (ssPMP) at Quad Cities Nuclear Power Station (Quad Cities), including description of the licensee's submittal, staff's independent review, and staff's sensitivity analysis. The staff performed independent sensitivity analysis of both the ssPMP itself as well as the flooding impacts associated with ssPMP to illustrate key technical issues that may affect the conservativeness of the licensee's submitted results. The licensee's submitted ssPMP was developed by Applied Weather Associates (AWA) and is documented in Beyond Design Basis Site-Specific Local Intense Precipitation Analysis (Fukushima) for Exelon's IL Sites, including Quad Cities (Exelon, 2014). This evaluation of ssPMP was conducted by staff at Oak Ridge National Laboratory with support from Nuclear Regulatory Commission staff. Given the complexity associated with ssPMP estimation, this document is not intended to describe every aspect of ssPMP development. Rather this document focuses on several key areas of concern which could impact PMP estimation and, in turn, flooding at the Quad Cities site. While the results contained herein are specific to Quad Cities, the key areas of concern may apply to other ssPMP studies following AWA's methodology, with the technical issues warranting consideration for all evaluations.

1. BACKGROUND

The Nuclear Regulatory Commission (NRC), with support from Oak Ridge National Laboratory (ORNL), conducted a site audit on the Applied Weather Associates' (AWA) site-specific probable maximum precipitation (ssPMP) analysis from February 23–25, 2015 in Rockville, MD, with a subsequent follow-up conference call and webinar held on March 11, 2015. During the audit, the staff acknowledged that several technical issues remained unresolved, and these areas were highlighted in the NRC's AWA ssPMP audit report (ADAMS Accession No. ML15113A029) issued on May 19, 2015 (NRC, 2015). For more information on the AWA ssPMP methodology and staff's observations, refer to the audit report.

Key areas of concern applicable to ssPMP estimates at Quad Cities Nuclear Power Station (Quad Cities) include: 1) Storm Representative Dew Point (abbreviated Td) Selection and Adjustment, 2) Maximum Dew Point Climatology, and 3) Storm Selection and Exclusion during Envelopment. As a result, ORNL independently evaluated these ssPMP components by following AWA's stated procedures with a few modifications made to address areas in which staff felt further sensitivity analysis is required.

PMP estimation is inherently uncertain, yet the impacts from slight changes to PMP could significantly impact both Local Intense Precipitation (LIP or LIP-PMP) flooding and Watershed Scale PMP (WS-PMP) flooding. In order to better assess the level of uncertainty associated with the ssPMP and the corresponding impacts on flooding, a flood sensitivity analysis is conducted using 1) the licensee's ssPMP estimate, 2) ORNL's adjusted estimate, and 3) HMR's original values. These sensitivity analyses are compared with sensitivity resulting from other hydrologic/hydraulic model-input parameters: 1) Manning's roughness coefficient and 2) temporal rainfall distribution (LIP only).

2. STAFF'S ssPMP EVALUATION – KEY TECHNICAL ISSUES AND APPROACH

To evaluate the reasonableness and conservatism of the Quad Cities ssPMP estimates, ORNL conducted a sensitivity analysis for both WS-PMP and LIP-PMP. The current analysis focuses on testing the sensitivities of:

(1) Storm Representative Dew Point,
(2) Dew Point Climatology, and
(3) Storm Selection and Exclusion during Envelopment.

Using hourly dew point data collected from the National Climatic Data Center's Integrated Surface Database (NCDC-ISD, http://www.ncdc.noaa.gov/isd), both storm representative dew point and dew point climatology values are computed independently for all the Quad Cities short list storms (20 for warm season WS-PMP, 11 for cool season WS-PMP, and 21 for LIP-PMP). These dew point values are applied on all short list storms to generate PMP envelope curves for comparison with AWA's ssPMP estimates. Except for updating dew point values, all other AWA steps were remained unchanged in the ORNL analysis.

2.1. Storm Representative Dew Point – Recent Storms

Recent storms refer to storms with available historic hourly dew point observation. These storms are mostly analyzed by AWA using the Storm Precipitation Analysis System (SPAS) (NRC, 2015). For each storm, AWA used NOAA's HYSPLIT[4] to help determine the storm moisture source and to select storm representative dew point values from surface weather stations. For most short list storms, AWA documented the exact NCDC stations (e.g., KPRN, KCEW) and the exact time (e.g., 6AM–6PM CDT) that they selected. However, for a few storms (e.g., 9W-Edgerton-Missouri, 5W-Aurira College-Illinois), some of the information was missing (NRC, 2015).

[4] http://www.arl.noaa.gov/HYSPLIT_info.php

Using the storm dew point time and stations reported by AWA, ORNL looked up the storm representative dew point independently (including adjustment to 1000 millibar level based on station elevation). For those storms with missing dew point station info, dew point data from several stations nearby the moisture source (identified by AWA) was looked up. A comparison is shown in Figure A-1 below. In general, the values between AWA and ORNL are consistent in this comparison. For the purpose of sensitivity analysis, ORNL used the storm representative dew point values identified by staff rather than those provided by AWA.

[Redacted]

Figure A-1 – Comparison of storm representative dew point for the recent storms (ORNL vs AWA)

2.2. Storm Representative Dew Point Adjustment – Past Storms

Past storms refer to storms without available historic hourly dew point observation. These storms were mostly analyzed by the National Weather Service (NWS) or USACE or in the NOAA HMRs, in which the depth-area-duration table and storm representative dew point have been developed (NRC, 2015). In such cases, since the storm representative dew point is in the form of 12-hour (h) persisting dew point, instead of the 6-, 12-, and 24-hour (h) average dew point preferred by AWA, a conversion factor developed by AWA is used. For WS-PMP, 2 degree Fahrenheit (F) is added on the 12-h persisting dew point to approximate 12- or 24-hour average dew point. A larger 7 degree F conversion factor is used for LIP-PMP to approximate 6- or 12-h average dew point. The Electric Power Research Institute (EPRI) Michigan-Wisconsin report is cited by AWA as a justification for this conversion. The NRC's AWA ssPMP Audit Report describes this storm representative dew point adjustment (also referred to as "EPRI Heuristic") and documents a demonstration that was requested by staff and performed by AWA during the site-audit. This demonstration was made specifically for the Boyden, Iowa storm, a historical LIP-type rainfall event which occurred on September 17, 1926 and is a part of the Quad Cities short list of LIP storms (NRC, 2015).

By adjusting the EPRI Heuristic for this particular storm from 7 degree F to 2 degree F, a significant difference was noted for the in-place moisture maximization value and, in turn, the PMP value for the storm. As a result, the Boyden, Iowa LIP-PMP value exceeded the original value proposed for Quad Cities (resulting from the Hallett, Oklahoma storm). This sensitivity demonstrated the importance of this parameter.

To examine the reasonableness of this conversion for the Quad Cities study area, an analysis was performed by ORNL staff using the hourly dew point data from recent storms in the Quad Cities' short list (for both WS-PMP and LIP-PMP). The storms included in this analysis are listed in Table A-1.

Table A-1 – List of storms included in ORNL's storm representative dew point adjustment evaluation

Storm	AWA No	Precipitation Source
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

For the surface weather stations reported by AWA in the short list storm calculation sheets, the original hourly dew point data was downloaded from the NCDC-ISD database. The hourly dew point data was then used to calculate the maximum 12-h persisting dew point, and the maximum 6-, 12-, and 24-h average dew point. Using this information, a direct comparison can then be made between the maximum average dew point (used by AWA) and the 12-h persisting dew point (used by the HMRs). For each storm, the difference between the maximum averge dew point (using the same -6, -12, -24-h dew point duration specified by AWA) and 12-h persisting dew point was calcualted and is summarized by storm type in Figure A-2.

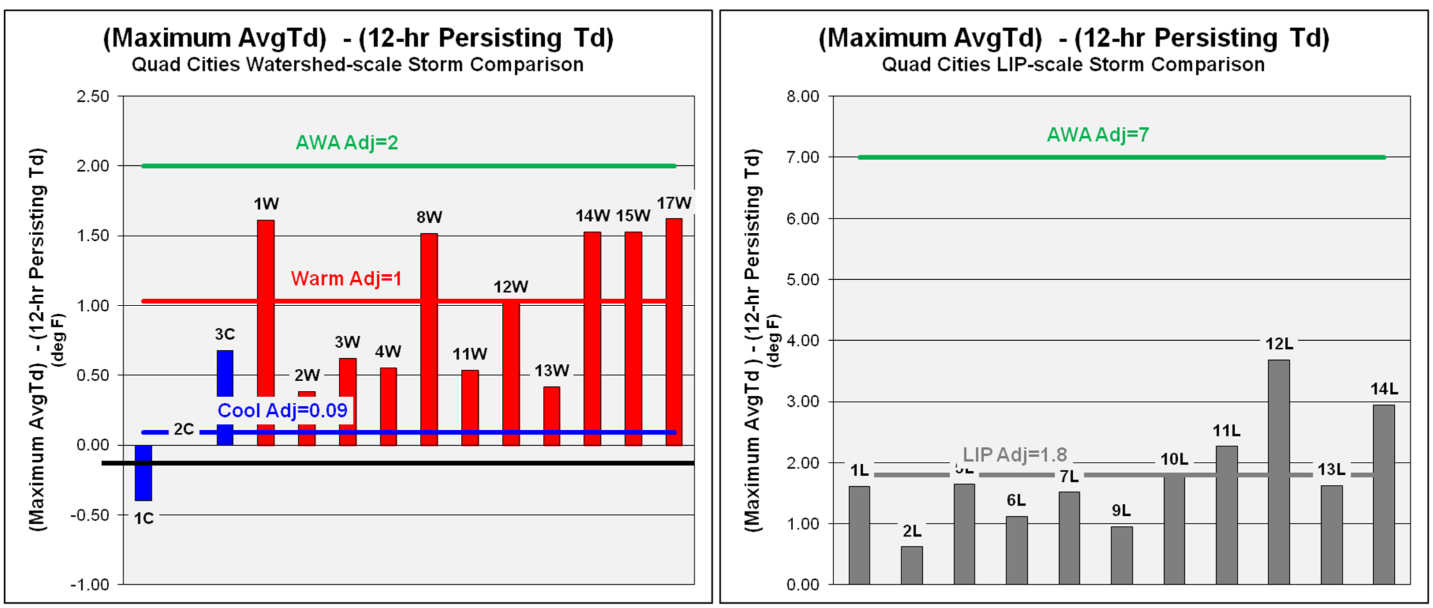

Figure A-2 – ORNL evaluation of storm representative dew point conversion factor

Compared with AWA's selected observational dew point adjustment factor of 2 degrees F, the computed adjustment factor for cool-season storms ranges from -0.4 degree F to +0.7 degree F, with an average of +0.09 degree F. For warm-season storms, the adjustment range is +0.3 degree F to +1.6 degree F, with an average of +1.0 degree F. These values are significantly lower than the values purposed by AWA and would typically result in sizable increases in PMP for the storms for which this adjustment was needed. For LIP storms, the adjustment ranges from +0.6 to +3.7 degree F, with an average of +1.8 degree F. Compared with the AWA adjustment values for LIP-type storms (7 degree F), these adjustment values are significantly lower and would typically result in sizable increases in PMP for those storms (note: 1 degree F difference is approxiately a 4-5% change in PMP).

The staff noted that while the 7 degree difference between maximum 12-h persisting and 6-h average dew point is possible, it is only observed in few individual weather stations and does not seem to be spatially consistent with other neighboring stations. When selecting storm representative dew point, it is preferred to use the spatially averaged hourly dew point data (from multiple stations in the moisture source region, HMR approach) and after this process, the large difference is usually reduced further. Therefore, the largest adjustment factor in this analysis is only 4.0 degree F (the Stanton_Nebraska 12L LIP storm listed in Table A-1) instead of 7.0 degree F.

For the purpose of sensitivity analysis, ORNL recommended keeping the 2 degree F adjustment factors for all past WS-PMP storms, but lowering the adjustment factor from 7 degree F to 2 degree F for all LIP-PMP storms. For warm season WS-PMP, the difference between AWA and the ORNL sensitivity analysis was only 1 degree F. For cool season WS-PMP, while the difference is larger (2 degree F), there are only 3 storms so it may not be sufficient to draw conclusion. Therefore, the 2 degree F adjustment factor is maintained for WS-PMP. On the contrary, for LIP-PMP, a major distinction is noticeable in comparing the results of staff's sensitivity analysis with the averaged adjustment value used by AWA. Based on the ORNL's independent analysis of 11 LIP-scale storms, a 2 degree F adjustment factor was suggested for LIP-PMP storms[5].

2.3. Maximum Dew Point Climatology

The NRC's AWA ssPMP Audit Report describes AWA's maximum dew point climatology methodology (NRC, 2015). One observation from the audit was that AWA's method of spatially interpolating 100-yr dew point values via manual smoothing may not be appropriate and may provide significant differences when evaluating in-place and transpositioned maximum dew point values. Additional technical issues were also identified which may contribute to inaccurate or misrepresented results (NRC, 2015). The NRC concluded that staff may request or conduct sensitivity analysis to assess how alternative methods may impact results.

In order to assess how various AWA assumptions may affect results, ORNL developed an alternative ssPMP methodology that is similar to AWA's method in many respects but has several distinctions. Throughout this document, ORNL's methodology for maximum dew point climatology evaluation is referred to as a "gauge-based approach" since one of the primary distinctions between ORNL's and AWA's methods is that ORNL relied upon gauge-based data for final determination, whereas AWA used data from in-house manually smoothed maps.

The differences between AWA and ORNL approaches included (from the most important to the least important factors):

(1) ORNL did not spatially smooth the dew point climatology values. In most of cases, the spatial variability is small, so sophisticated spatial interpolation method may not be required.
(2) The Kolmogorov–Smirnov goodness-of-fit test (under 5% significance level) is used to filter out ill-fitted results.
(3) Another widely-used parameter estimation method, maximum likelihood, is used to estimate the parameters of generalized extreme value (GEV) distributions.
(4) Depending on data processing procedures, the annual maximum dew point series used for GEV fitting could be different.

To understand the uncertainty of AWA's dew point climatology values, a gauge-based analysis was performed independently by ORNL. Using the NCDC-ISD database and following most of AWA's dew point climatology assessment steps, the 100-yr, 6-, 12-, and 24-hr duration maximum dew points are calculated for all stations with sufficiently long records (greater than 30-yr). The April 1st values (averaged between March 15th and April

[5] Note that subsequent analysis by ORNL to better replicate the data processing used by AWA resulted in a recommended 4 degree F adjustment factor for LIP-PMP rather than a 2 degree F adjustment factor. This change is supported by ORNL's analysis for storms evaluated for the Quad Cities site and the Perry Nuclear Power Plant ssPMP studies. The higher adjustment factor would result in decreases in the LIP-PMP.

15th maps) are illustrated in Figure A-3 as an example. The maps are constructed for all Quad Cities short list storms to help look up the dew point climatology values.

For the purpose of sensitivity analysis, ORNL updated dew point climatology values using the gauge-based results. The selection of dew point climatology value was made directly by considering various stations in the moisture region.

2.4. Storm Selection and Exclusion during Envelopment

During the staff evaluation, it was observed that the 1C-Alley Spring-Missouri storm, which is the bounding storm for nearly all cool-season WS-PMP area-durations, was transpositioned to only the southern portions of the watershed, and was not transpositioned to the basin centroid or to the northern half of the watershed (NRC, 2015). At the basin centroid, the exclusion of Alley Spring resulted in a large reduction of cool-season ssPMP for durations above 12-h (see Figure A-4). AWA's envelopment curves (black lines) slightly exceed maximum individual storm values at all points, while the Alley Spring values (green lines) are raw values without smoothing or enveloping.

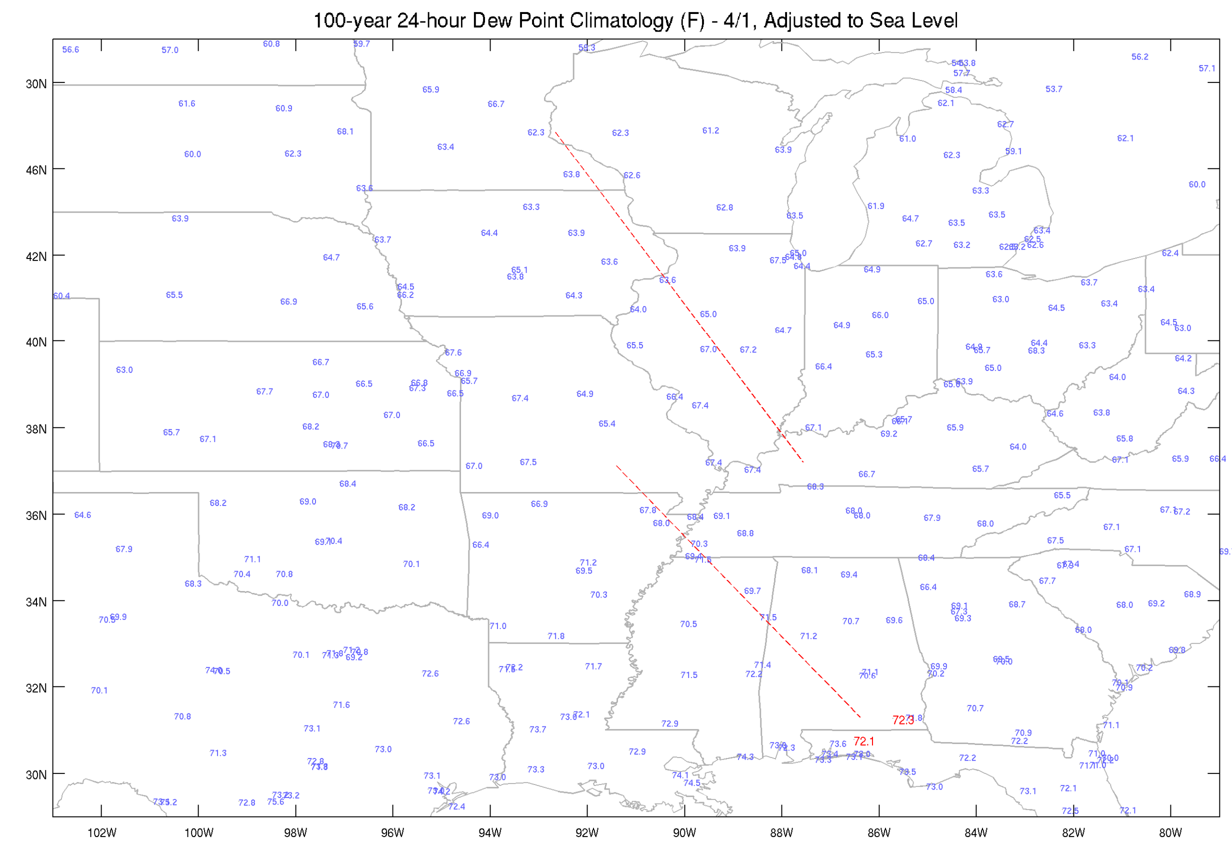

Figure A-3 – Example of gauge-based dew point climatology

[Redacted]

Figure A-4 – Comparison of AWA cool-season WS-PMP envelopment with adjusted PMP for Alley Spring

While this exclusion may be attributed to distance, the decision made for Alley Spring was not consistent with other cool-season short list storms. For instance, staff observed that the 8C-Willow Spring-Missouri storm, which occurred near Alley Spring, was transpositioned by AWA to all Quad Cities grid points. Another example, the 3C-Louisville-Kentuky storm where storm moisture source was also near the Georgia-Florida boarder (similar to Alley Spring), was also transpositioned to all Quad Cities grid points. The objective criteria beyond this decision were not clearly documented. Given the significant influence of this particular storm, Alley Spring is included in the following staff sensitivity analysis.

3. STAFF'S SSPMP EVALUATION – SENSITIVITY ANALYSIS RESULTS

ORNL staff conducted a sensitivity analysis to understand how the various factors described in Section 2 of this Appendix may impact both WS-PMP and LIP-PMP estimates. In evaluating the all-season and cool-season WS-PMP values, ORNL staff compared results for the watershed basin centroid only. ORNL's approach considered all short list storms as being transpositionable to the watershed basin centroid, which differs from AWA's approach which limits the transposition of some storms. This approach by AWA is inconsistent with idea of the short storm list, which has supposedly excluded storms considered non-transpositionable to the basin. In addition, AWA's approach inconsistently selects which storms are limited from transposition and which are allowed to be transpositioned. The issue of short list storm transposition was carefully reviewed by ORNL as described in Sections 3.1 and 3.2 below.

3.1. All-Season Watershed PMP Sensitivity Analysis and Results

For all short list WS-PMP storms, the storm representative dew point (using 2 degree F conversion factor for all past storms, consistent with AWA), in-place maximum, and transpositioned maximum dew point values were evaluated using ORNL's gauge-based approach. While storm representative dew point values were similar between the AWA and ORNL evaluations (Figure A-1), both in-place and transpositioned 100-yr dew point values show large differences. The resulting data (including the resulting total adjustment factor) are shown in Figure A-5 and indicate a tendency for ORNL's PMP values to be higher than AWA's PMP values.

[Redacted]

Figure A-5 – WS-PMP Dew Point Comparison (AWA vs ORNL)

As shown in Figure A-5, the total adjustment factor was based on values of storm representative dew Td, in-place maximum Td, and transpositioned maximum Td. The majority of WS-PMP storms show higher total adjustment factors under ORNL's approach compared to AWA's results. Once computed, the total adjustment factor is used to modify observed PMP data to derive depth-area-duration PMP values for the watershed basin centroid.

Figure A-6 shows the depth-area envelopment curves at various durations for all-season WS-PMP storms. These envelopment curves are composite curves based upon multiple historic storms and capture the maximum rainfall depth for each area-duration combination. AWA's envelopment curves (black lines) slightly exceeded maximum individual storm values at all points, while the ORNL envelopment curves (red lines) are raw values without smoothing or enveloping. For all-season WS-PMP, the AWA and ORNL curves are in approximate agreement, especially for long durations and large areas (which are of most importance when evaluating watershed flooding in streams and rivers). Figure A-7 shows the individual storm depth-area curves used in compiling the ORNL envelopment curves, with related information reported in Table A-2. While the ORNL envelopment curves do exceed the AWA envelopment curves for various area-duration combinations, these increases would have very minor impacts on all-season WS-PMP flooding.

[Redacted]

Figure A-6 – All-season WS-PMP Envelopment[6]

[Redacted]

Figure A-7 – All-season WS-PMP Envelopment with Controlling Storms Identified[7]

Table A-2 – Summary of all-season WS-PMP controlling storms

Storm	Storm Num	Included in Td Adj Analysis?	Critical Bounding Duration(s)				
[redacted]	[redacted]		[redacted]	[redacted]	[redacted]		
[redacted]	[redacted]				[redacted]	[redacted]	[redacted]
[redacted]	[redacted]			[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]			[redacted]
[redacted]	[redacted]			[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]		[redacted]			
[redacted]	[redacted]		[redacted]	[redacted]			
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]			

It is important to note that in AWA's approach, several all-season short list storms were transpositioned to only portions of the watershed, including limitations to the basin centroid (NRC, 2015). The distinction that staff compared depth-area-duration values for the watershed basin centroid would be important if ORNL values sizably bounded AWA values for critical area-durations, which is not the case for all-season WS-PMP. Many of the differences between the ORNL envelopment and AWA envelopment for all-season WS-PMP are likely due to several all-season storms which AWA did not transposition to the basin centroid. The impacts of limiting transposition of some key storms could be non-conservative. However, since the licensee concluded that cool-season WS-PMP flooding effects bound all-season WS-PMP flooding effects and the impacts of potentially different transposition are not expected to outweigh differences for cool-season WS-PMP, the staff determined that its sensitivity analysis on all-season WS-PMP flooding was complete.

3.2. Cool-Season Watershed PMP Sensitivity Analysis and Results

For all short list WS-PMP storms, the storm representative dew point (using 2 degree F conversion factor for all past storms, consistent with AWA), in-place maximum, and transpositioned maximum dew point values were evaluated using ORNL's gauge-based approach. While storm representative dew point values were similar between the AWA and ORNL evaluations (Figure A-1), both in-place and transpositioned 100-yr dew point values show large differences. The resulting data (including the resulting total adjustment factor) are shown in

[6] Note: some anomalies may be noticeable at various area sizes since some storms do not contain observed data for every area size plotted.

[7] Note: some anomalies may be noticeable at various area sizes since some storms do not contain observed data for every area size plotted.

Figure A-5 and indicate a tendency for ORNL's PMP values to be higher than AWA's PMP values, especially for Cool-season WS-PMP.

As shown in Figure A-5, the total adjustment factor is based on values of storm representative dew Td, in-place maximum Td, and transpositioned maximum Td. The majority of WS-PMP storms show higher total adjustment factors under ORNL's approach compared to AWA's results. Once computed, the total adjustment factor is used to modify observed PMP data to derive depth-area-duration PMP values for the watershed basin centroid.

Figure A-8 shows the depth-area envelopment curves at various durations for cool-season WS-PMP storms. These envelopment curves are composite curves based upon multiple historic storms and capture the maximum rainfall depth for each area-duration combination. AWA's envelopment curves (black lines) slightly exceed maximum individual storm values at all points, while the ORNL envelopment curves (blue lines) are raw values without smoothing or enveloping. For cool-season WS-PMP, the AWA and ORNL curves are in approximate agreement for the 6-hr duration PMP but deviate substantially for longer duration events at both small and large area sizes. These significant differences could have significant impacts on cool-season WS-PMP flooding. Figure A-9 shows the individual storm depth-area curves used in compiling the ORNL envelopment curves, with related information reported in Table A-3.

For cool-season WS-PMP, the critical bounding storm for nearly all area-duration combinations is the Alley Spring, Missouri storm. For the Alley Spring, Missouri storm, the ORNL ssPMP values is 10% higher than the AWA ssPMP value due to the following differences:

- ORNL ssPMP storm representative dew point is 0.5 degree F lower than AWA's. The storm representative dew point is looked up independently from the NCDC-ISD dataset (Section 2.1).
- ORNL ssPMP in-place maximum dew point is 0.5 degree F lower than AWA's due to ORNL's gauge-based approach (has no impact on total adjustment factor)
- ORNL ssPMP transpositioned maximum dew point is 1.5 degree F higher due to ORNL's gauge-based approach (contributes to a higher total adjustment factor)

Since the ORNL envelopment curves exceeded the AWA Envelopment curves for various area-duration combinations (including those that would impact flooding), staff decided to evaluate how different ssPMP results could impact cool-season WS-PMP flooding at Quad Cities.

[Redacted]

Figure A-8 – Cool-season WS-PMP Envelopment[8]

[Redacted]

Figure A-9 – Cool-season WS-PMP Envelopment with Controlling Storms Identified[9]

[8] Note: some anomalies may be noticeable at various area sizes since some storms do not contain observed data for every area size plotted.
[9] Note: some anomalies may be noticeable at various area sizes since some storms do not contain observed data for every area size plotted.

Table A-3 – Summary of cool-season WS-PMP controlling storms

Storm	Storm Num	Included in Td Adj Analysis?	Critical Bounding Duration(s)				
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Since the applying a moving PMP (used by the licensee) to an entire watershed requires substantial implementation efforts to simulate spatial and temporal rainfall impacts, the staff sought a way to effectively conduct a sensitivity analysis. To achieve this, the staff identified an interpolated 72-h, 88,000-mi^2 PMP value of 8.7% higher compared to AWA's approach and increased precipitation by 8.7% across all time steps for each precipitation gauge in HEC-HMS. The staff reasoned that this increased would produce a noticeable impact on flooding but would also underestimate a more precise implementation of ORNL's ssPMP results. This observation is demonstrated in Table A-4, which indicates that this discrepancy increases for smaller area sizes or for shorter durations. The staff conducted a detailed sensitivity analysis of cool-season WS-PMP flooding using ORNL ssPMP adjustment described in Section 4.1.

Table A-4 – PMP % Differences between ORNL and AWA SSPMP Results ($\frac{ORNL-AWA}{AWA}$)

• +8.7% for 88,000-mi^2 (@72-hr)	• +8.7% for 72-hr (@88,000-mi^2)
• +12.9% for 50,000-mi^2 (@72-hr)	• +13.9% for 48-hr (@88,000-mi^2)
• +18.9% for 20,000-mi^2 (@72-hr)	• +32.2% for 24-hr (@88,000-mi^2)

It is important to note that in AWA's approach, the Alley Spring, Missouri storm, which is the bounding storm for nearly all cool-season WS-PMP area-durations, was transpositioned to only the southern portions of the watershed, and was not transpositioned to the basin centroid or for the northern half of the watershed (NRC, 2015). This important observation explains why, despite ORNL's total adjustment factor for Alley Spring being 10% higher than AWA's, the envelopment curves shown in Figure A-8 are not equally offset (i.e., Alley Spring dictates the ORNL envelopment but is not included in the AWA envelopment).

The distinction that staff compared depth-area-duration values for the watershed basin centroid would be important if AWA values were sizably bounded by ORNL values for critical area-durations, which is the case for cool-season WS-PMP. Many of the differences between the ORNL envelopment and AWA envelopment for cool-season WS-PMP was due to AWA's decision to not transposition the Alley Spring storm to the basin centroid. The impact of limiting this transposition is non-conservative; however staff determined that the potential for the licensee's ssPMP evaluation to underpredict ssPMP was not significant enough to warrant further review.

3.3. Local Intense Precipitation PMP Sensitivity Analysis and Results

For all short list LIP storms, the storm representative dew point, in-place maximum, and transpositioned maximum dew point values were evaluated using ORNL's gauge-based approach. The storm representative dew point was evaluated under two different scenarios for all past storms:

- ORNL ssPMP1 – Uses AWA's 7 degree F conversion factor, and
- ORNL ssPMP2 – Uses ORNL's 2 degree F conversion factor.

While storm representative dew point values were similar between the AWA and ORNL evaluations (Figure A-1), both in-place and transpositioned 100-yr dew point values show large differences, especially for all past storms due to the differing conversion factor. The resulting data (including the resulting total adjustment factor) are shown in Figure A-10 and Figure A-11 and indicate a tendency for ORNL's PMP values to be higher than AWA's PMP values for nearly all short list storms.

As shown in Figure A-10 and Figure A-11, the total adjustment factor is based on values of storm representative dew Td, in-place maximum Td, and transpositioned maximum Td. The majority of WS-PMP storms show higher total adjustment factors under ORNL's approach compared to AWA's results. Once computed, the total adjustment factor is used to modify observed 1-hr, 1-mi^2 PMP.

Figure A-12 shows the adjusted LIP-PMP values for three different scenarios: 1) AWA ssPMP, 2) ORNL ssPMP1, and 3) ORNL ssPMP2. In addition, this figure indicates which storms were included in the storm representative dew point adjustment analysis (see Section 2.2) and which storms require use of the EPRI Heuristic for storm representative dew point adjustment.

For AWA's evaluation, the Hallett, OK storm is the bounding storm, with a 1-hr, 1-mi^2 LIP-PMP of [redacted] inches (in.) (Exelon, 2014). Using ORNL's gauge-based approach and a 7 degree F EPRI Heuristic, ORNL ssPMP1 resulted in a bounding 1-hr, 1-mi^2 LIP-PMP of 14.92 inches associated with the Hallett, Oklahoma storm. Using ORNL's gauge-based approach and a 2 degree F EPRI Heuristic, ORNL ssPMP2 resulted in a bounding 1-hr, 1-mi^2 LIP-PMP of 15.59 inches associated with the Boyden, Iowa storm.

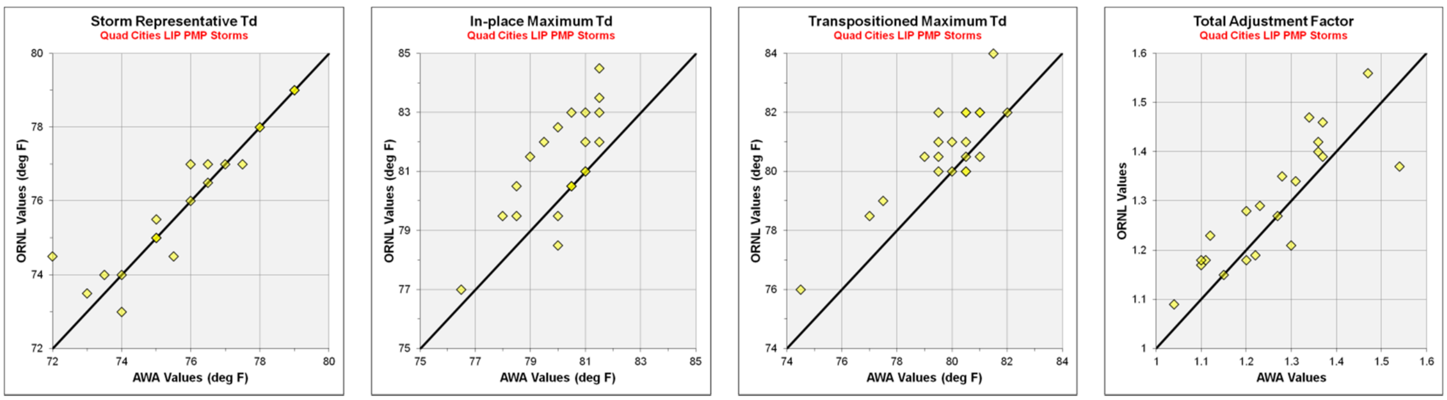

Figure A-10 – LIP-PMP Dew Point Comparison Using AWA +7 degree F adjustment

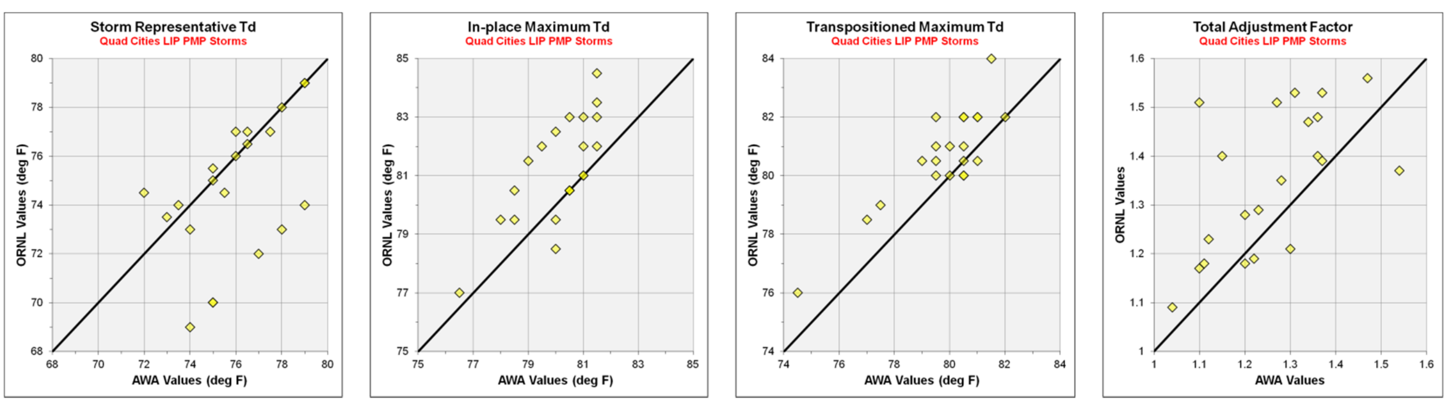

Figure A-11 – LIP-PMP Dew Point Comparison Using AWA +2 degree F adjustment

[Redacted]

Figure A-12 – Summary of LIP-PMP results

For the Hallett, Oklahoma storm, the ORNL ssPMP1 value is 10% higher than the AWA ssPMP value due to the following differences:

- ORNL ssPMP1 storm representative dew point is 0.5 degree F lower than AWA's due to ORNL's gauge-based approach (contributes to a higher total adjustment factor)
- ORNL ssPMP1 in-place maximum dew point is 0.5 degree F lower than AWA's due to ORNL's gauge-based approach (has no impact on total adjustment factor)
- ORNL ssPMP1 transpositioned maximum dew point is 1.5 degree F higher due to ORNL's gauge-based approach (contributes to a higher total adjustment factor)

For the Boyden, Iowa storm, the ORNL ssPMP2 value is 37% higher than the AWA ssPMP value due to the following differences:

- ORNL ssPMP2 storm representative dew point is 5 degree F lower than AWA's due to a differing EPRI Heuristic (contributes to a higher total adjustment factor)
- ORNL ssPMP2 in-place maximum dew point is 1.0 degree F higher than AWA's due to ORNL's gauge-based approach (has no impact on total adjustment factor)
- ORNL ssPMP2 transpositioned maximum dew point is 1.5 degree F higher due to ORNL's gauge-based approach (contributes to a higher total adjustment factor)

While ORNL's PMP values generally exceed AWA's value regardless of the EPRI Heuristic value used, the differebce is much more noticeable when using the reevaluated adjustment value of +2 degree F. When applied to the short list storms, the results reveal a 1-h, 1-mi^2 PMP value of:

- 14.92 in. (+9.8%) when using +7 degree F EPRI Heuristic (ORNL ssPMP1)
- 15.59 in. (+14.7%) when using +2 degree F EPRI Heuristic (ORNL ssPMP2)

Given the significant differences between AWA's LIP-PMP, ORNL ssPMP1, and ORNL ssPMP2, staff conducted detailed sensitivity analysis of LIP-PMP flooding as described in Section 4.2.

4. STAFF'S FLOODING EVALUATION – SENSITIVITY ANALYSIS RESULTS

Based on the staff's ssPMP sensitivity analysis results (Section 3), detailed sensitivity analyses were performed to evaluate flooding impacts resulting from changes in cool-season WS-PMP, as well LIP-PMP.

4.1. Flooding in Rivers and Streams – Cool-Season Watershed PMP Flooding Sensitivity

Various HEC-HMS and HEC-RAS model sensitivity runs were conducted to evaluate how uncertainty of model input variables could influence the Probable Maximum Flood (PMF) maximum flooding elevations. The following ten cases were evaluated:

<u>Base Case: Licensee ssPMP</u>

The Base Case is ORNL's re-run of the licensee's model to establish the basis of their results such that subsequent sensitivity runs and comparisons can be made with respect to those results. This utilizes an ssPMP approach developed by AWA, with rainfall spatially and temporally distributed across the Quad Cities watershed. The Cool-Season HEC-RAS Model run with the storm center at McGregor is the licensee's most conservative case and serves as the base case in this sensitivity study. Please note that the results of ORNL's reproducible run of the licensee's model is within 0.008% and 0.05% of the licensee's results for the maximum elevation and flow at the site.

<u>Case 1: 8.7% ssPMP Increase</u>

This case utilized HEC-HMS to increase all rainfall gauge values by 8.7% and subsequently routes the resulting flood to the site using HEC-RAS by updating the inflow hydrographs for the Mississippi and Wapsipinicon Rivers. The rainfall augmentation value was determined based on updated analysis

performed by ORNL which uses a gauge-based approach for identifying storm representative, in-place maximum, and transpositioned maximum dew point values. This approach also considered whether any change was needed in how 12-h persisting dew point values are converted to maximum average dew point values for PMF-scale storms. ORNL determined that no change in AWA's adjustment value of +2 degrees F was needed.

Case 2: Base Case with 5% Increase in the Manning's *n* Values

This case utilized HEC-RAS to obtain results for elevation and flow at the site due to a 5% increase in the values for Manning's *n* for all reaches on the Mississippi and Wapsipinicon Rivers using the licensee's ssPMP values.

Case 3: Case 1 (8.7% ssPMP Increase) with 5% Increase in the Manning's *n* Values

This case utilized HEC-RAS to obtain results for elevation and flow at the site due to a 5% increase in the values for Manning's *n* for all reaches on the Mississippi and Wapsipinicon Rivers using the 8.7% increase of the ssPMP values.

Case 4: Base Case with 10% Increase in the Manning's *n* Values

This case utilized HEC-RAS to obtain results for elevation and flow at the site due to a 10% increase in the values for Manning's *n* for all reaches on the Mississippi and Wapsipinicon Rivers using the licensee's ssPMP values.

Case 5: Case 1 (8.7% ssPMP Increase) with 10% Increase in the Manning's *n* Values

This case utilized HEC-RAS to obtain results for elevation and flow at the site due to a 10% increase in the values for Manning's n for all reaches on the Mississippi and Wapsipinicon Rivers using the 8.7% increase of the ssPMP values.

Case 6: Base Case with 5% Decrease in the Manning's *n* Values

This case utilized HEC-RAS to obtain results for elevation and flow at the site due to a 5% decrease in the values for Manning's *n* for all reaches on the Mississippi and Wapsipinicon Rivers using the licensee's ssPMP values.

Case 7: Case 1 (8.7% ssPMP Increase) with 5% Decrease in the Manning's *n* Values

This case utilized HEC-RAS to obtain results for elevation and flow at the site due to a 5% decrease in the values for Manning's n for all reaches on the Mississippi and Wapsipinicon Rivers using the 8.7% increase of the ssPMP values.

Case 8: Base Case with 10% Decrease in the Manning's *n* Values

This case utilized HEC-RAS to obtain results for elevation and flow at the site due to a 10% decrease in the values for Manning's *n* for all reaches on the Mississippi and Wapsipinicon Rivers using the licensee's ssPMP values.

Case 9: Case 1 (8.7% ssPMP Increase) with 10% Decrease in the Manning's *n* Values

This case utilized HEC-RAS to obtain results for elevation and flow at the site due to a 10% decrease in the values for Manning's *n* for all reaches on the Mississippi and Wapsipinicon Rivers using the 8.7% increase of the ssPMP values.

Case 10: Base Case with 15% Increase in the Manning's *n* Values

This case utilized HEC-RAS to obtain results for elevation and flow at the site due to a 15% increase in the values for Manning's *n* for all reaches on the Mississippi and Wapsipinicon Rivers using the licensee's ssPMP values.

Results:

Based on the results for the elevation and flow at the Quad Cities site in Table A-5 and Figure A-13, the 8.7% increase in the ssPMP values result in a roughly 2.5-feet (ft) increase in flood water elevation accompanied by a 12% gain in peak flow of 836,465 ft^3/s or roughly 92,000 ft^3/s more flow. This increase in elevation due to the scenario of an 8.7% increase in the ssPMP was roughly equivalent to a 15% increase in the value for Manning's *n* using the licensee's ssPMP. A 15% increase of the value Manning's *n* for the main channel of the Mississippi was still within acceptable ranges for the type of channel given that the licensee's choice of the main channel value corresponds to the normal value on a range from minimum to maximum.

Flows at the site are not as sensitive to changes in Manning's *n* values as elevation changes are. Therefore, an equivalent scenario involving respective Manning's *n* value changes applied to the licensee's ssPMP to obtain similar flows at the site based on an 8.7% increase in ssPMP would result in Manning's *n* values much different than those currently used and may not be representative of the site.

Table A-5 – Cool-season PMF flooding sensitivity results

Input			Output			
Case	**Manning's n Values With Respect to Base Case**	**PMP Difference With Respect to Base Case**	**Elevation***	**Flow***	**Elevation Deviation From Base Case**	**Flow Difference With Respect To Base Case**
	(%)	(%)	(ft MSL)	(cfs)	(ft)	(%)
Base Case	0	0	600.55	744,302	0	0
Case 1	0	+8.7%	603.00	836,465	+2.45 ft	+12.4%
Case 2	+5%	0	601.34	742,040	+0.79 ft	(-0.3)%
Case 3	+5%	+8.7%	603.85	835,232	+3.30 ft	+12.2%
Case 4	+10%	0	602.08	739,209	+1.53 ft	(-0.6)%
Case 5	+10%	+8.7%	604.65	832,560	+4.10 ft	+11.9%
Case 6	(-5%)	0	599.65	746,350	(-0.90) ft	+0.3%
Case 7	(-5%)	+8.7%	602.06	838,800	+1.51 ft	+12.7%
Case 8	(-10%)	0	598.84	748,678	(-1.71) ft	+0.6%
Case 9	(-10%)	+8.7%	601.21	841,846	+0.66 ft	+13.1%
Case 10	+15%	0	602.9	738,000	+2.35 ft	(-0.8)%

* Elevation and Flow are noted at site in HEC-RAS tables for maximum values at Mississippi River Reach 13 at RM 506.9. Elevations are presented in Mean Sea Level (MSL).

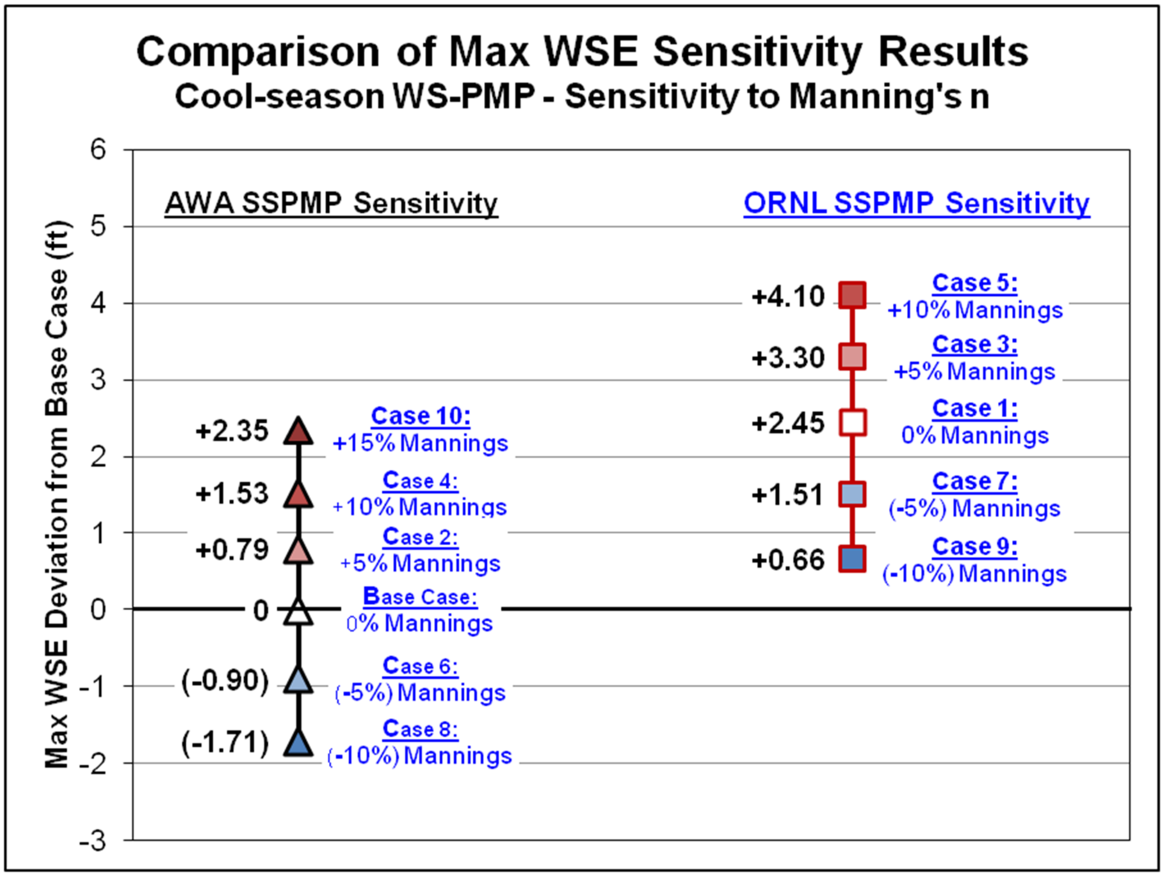

Figure A-13 – Comparison of maximum water-surface elevation (WSE) from various cool-season WS-PMP cases

While not explicitly evaluated, uncertainty in both infiltration and cross-sectional geometry were considered by staff. It is the staff's opinion that any changes in infiltration or upstream/downstream cross-sectional geometry (such as modeling of bridges) would have minimal impact compared to the uncertainties reported with ssPMP. In addition, since the Manning's *n* values, infiltration rates, and cross-sectional geometry were all included in a well-calibrated model, staff believe that the true uncertainties in these parameters are even further reduced, thus highlighting the importance of ssPMP estimation.

4.2. Local Intense Precipitation Flooding Sensitivity

Various FLO-2D model sensitivity runs were conducted to evaluate how uncertainty of model input variables could influence LIP maximum flooding elevations. The following six cases were evaluated:

LIP Run 1: Licensee ssPMP

This run used a 1-hr, 1-mi^2 ssPMP of 13.59 in. developed by AWA, arranged with a front-loaded distribution. Uses roof elevation to represent buildings in order to block flow paths and convey water to the ground. The vehicle barrier system was represented with various openings. In areas adjacent to site buildings, Manning's *n* values were typically 0.02 to 0.035, which is the middle of the range for asphalt/concrete (0.02-0.05).

LIP Run 2: HMR PMP

This run was the same as #1, except the 1-hr, 1-mi^2 PMP value was 17.78 in., per HMR-52.

LIP Run 3: ORNL ssPMP1

This run was the same as #1, except the 1-hr, 1-mi^2 PMP value was 14.92 in., which is based on ORNL's reassessment of the ssPMP using a gauge-based approach for identifying storm representative, in-place maximum, and transpositioned maximum dew point values (note: this methodology does not capture any change in methodology for historical storms for which 12-h persisting dew point values were converted to maximum average dew point values).

LIP Run 4: ORNL ssPMP2

This run was the same as #3, except the 1-h, 1-mi^2 PMP value was 15.59 in., which reflects the changes noted in #3 in addition to a reevaluated dew point. While the licensee's approach, uses a +7 degree F adjustment in converting 12-h persisting dew point values to maximum average dew point values for LIP-type storms, ORNL's reanalysis using data from the Quad Cities short storm list found an average adjustment of approximately +2 degrees F, which was used instead for this analysis.

LIP Run 5: ORNL Manning's *n*

This run was the same as #1, except values for Manning's *n* were adjusted (generally increased) to a value of 0.05 in areas immediately adjacent to site buildings. This slightly higher value was selected to demonstrate slightly higher roughness and likely capture higher peak flooding conditions.

LIP Run 6: ORNL Centered

This run was the same as #1, except the sub-hourly PMP increments were arranged following a centered distribution as opposed to a front-loaded distribution (Figure A-14).

LIP Run 7: ORNL Combined (Centered SSPMP2)

This run was a combination of LIP Run 6 and LIP Run 4 and combined a reevaluated ssPMP (including dew point adjustment) with a centered rainfall distribution.

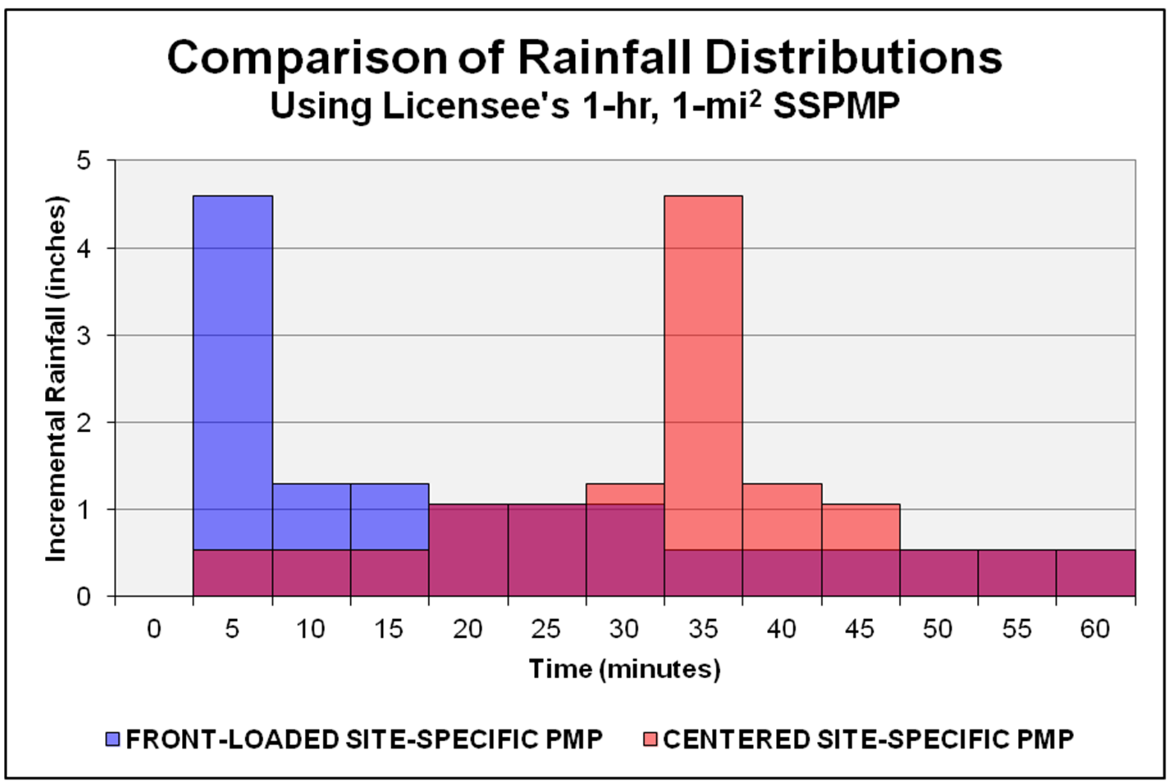

Figure A-14 – Comparison of front-loaded and centered ssPMP temporal rainfall distribution

Results:

The maximum WSE at 7 doors of interest were compared across each of the sensitivity runs. The results indicated that, as expected, WSE's increase with increasing rainfall input to the model. The HMR rainfall values (LIP Run 2) were the highest of any scenario evaluated and resulted in the highest predicted flooding on site. The ORNL reanalysis results (LIP Runs 3 and 4) were lower than the HMR results, but still notably higher than the licensee's results. In comparison to sensitivity of total rainfall, the sensitivity conducted on varying Manning's *n* values (LIP Run 5) was lower, while sensitivity to rainfall distribution (LIP Run 6) was slightly lower than ssPMP2. These results clearly demonstrate that total rainfall and rainfall distribution are the key parameters influencing maximum WSE. For Manning's *n* values, the licensee had previously stated that when using the upper and lower range of Manning's *n* values resulted in maximum WSE variation of ±0.1 ft, which is outweighed by variation in maximum WSE due to total rainfall and rainfall distribution.

The results are graphically represented in Figure A-15 below and are summarized in Table A-6.

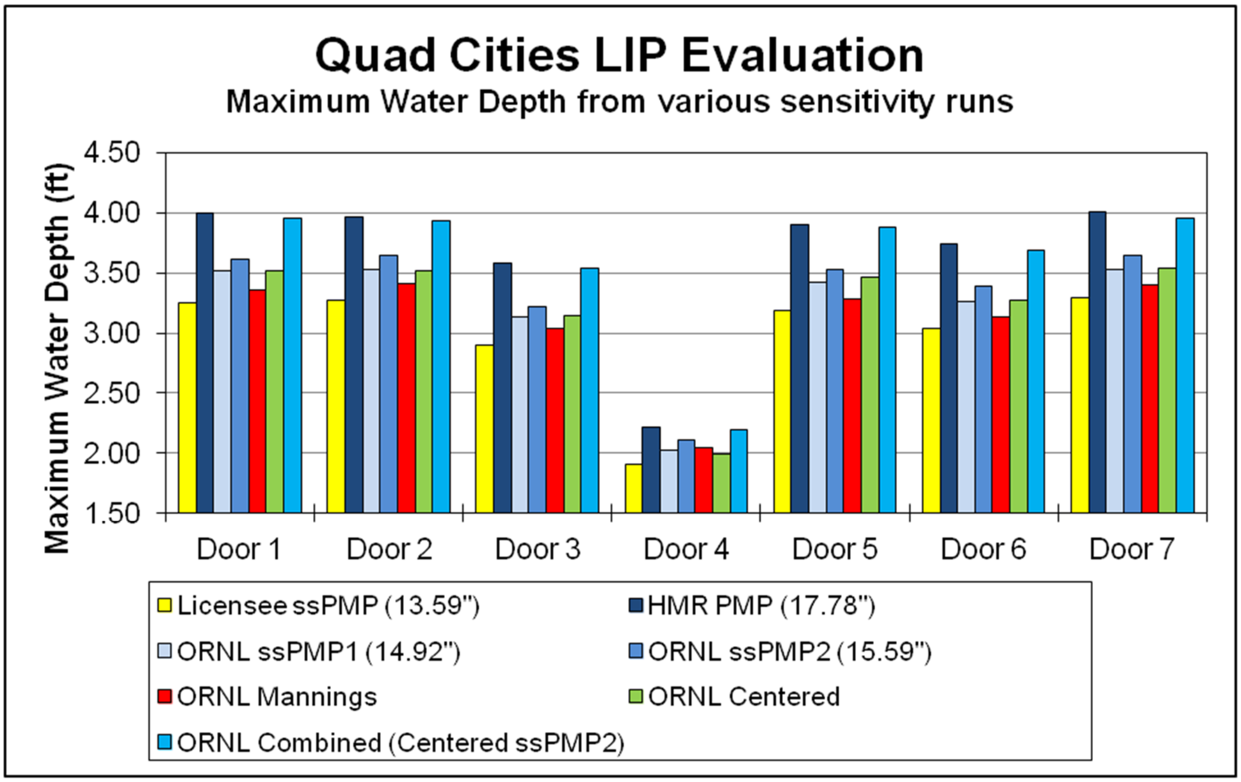

Figure A-15 – Comparison of maximum water depth from various LIP flooding sensitivity analyses

Table A-6 – LIP Flooding Sensitivity Results

Input				Output
Sensitivity Run	**Description**	**1-hr, 1-mi^2 PMP**	**Temporal Rainfall Distribution**	**Maximum WSE Results**
Run 1	Use licensee's ssPMP values	13.59 in.	Front-loaded	Maximum flood depth of 1.98 ft to 3.32 ft at Doors
Run 2	Use HMR PMP values	17.78 in.	Front-loaded	0.31 ft to 0.74 ft higher than the licensee's analysis
Run 3	Use reevaluated dew point values	14.92 in.	Front-loaded	0.12 ft to 0.26 ft higher than the licensee's analysis
Run 4	Use reevaluated dew point values and updated dew point adjustment	15.59 in.	Front-loaded	0.2 ft to 0.37 ft higher than the licensee's analysis
Run 5	Use higher Manning's *n* values adjacent to buildings	13.59 in.	Front-loaded	0.1 ft to 0.14 ft higher than the licensee's analysis
Run 6	Use a centered rainfall distribution with the licensee's ssPMP	13.59 in.	Center-loaded	0.09 ft to 0.28 ft higher than the licensee's analysis
Run 7	Use a centered rainfall distribution with ORNL ssPMP2	15.59 in.	Center-loaded	Max WSE ranges from 0.29 ft to 0.7 ft higher than the licensee's analysis

5. CONCLUSIONS

ORNL, in consultation with NRC staff, evaluated the Quad Cities ssPMP for several areas of concern including: 1) Storm Representative Dew Point Selection and Adjustment, 2) Maximum Dew Point Climatology, and 3) Storm Selection and Exclusion during Envelopment. ORNL independently evaluated these ssPMP components by following AWA's stated procedures with a few modifications made to address areas in which staff felt further sensitivity analysis was required. The major differences between the AWA and ORNL approach included:

1) Revised EPRI Heuristic for adjusting 12-h persisting dew point values to 6-h maximum average dew point values (used for past storms without adequate data coverage). No change was made for WS-PMP, but the LIP-PMP value was changed from +7 degree F to +2 degree F. The adjustment was based on the evaluation of hourly dew point observation from other recent short list storms in the Quad Cities study.

2) Used a gauge-based approach to evaluate maximum dew point climatology. Differences were identified between AWA's maximum dew points and ORNL's gauged-based values. The differences could be due AWA's manual smoothing during climatology map development.

3) Given the significant influence of 1C-Alley Spring-Missouri storm on cool-season ssPMP, it was included for all Quad Cities grid points in the sensitivity analysis. The decision made for Alley Spring by AWA was not consistent with other cool-season short list storms.

The differences in the ssPMP considered in this report indicated that both WS-PMP and LIP-PMP may be considerably underestimated in the ssPMP submitted by the licensee. WS-PMP flooding sensitivity results indicated that variation in ssPMP far outweigh uncertainties in other model inputs parameters, with the associated maximum flooding elevations exceeding the licensee's values by 2.45 ft when the ssPMP is increased by 8.7%. This increase corresponds to a maximum water surface elevation of 603 ft MSL, which is equivalent to Quad Cities's current protection level.

LIP-PMP flooding sensitivity results indicated that variation in the ssPMP outweigh uncertainties in Manning's *n* values, with the associated maximum flooding elevations exceeding the licensee's values by up to 0.37 ft when

incorporating ORNL's gauge-based approach with adjusted EPRI Heuristic (ORNL ssPMP2). When this ORNL ssPMP2 was combined with a center-weighted rainfall distribution, the maximum flooding elevations are up to 0.70 ft higher than the licensee's values. It is important to note that these results are for a 1-hr duration PMP only and that higher flooding may result from longer duration LIP events.

6. REFERENCES

Exelon (Exelon Generation Company, LLC), 2013, "Probable Maximum Precipitation (PMP) for the Upper Mississippi River Watershed: Contributory to QCNPS," Calculation Package QDC-0085-S-1989, Revision 0, January 2013, ADAMS Accession Nos ML14238A387, ML14238A389, ML14238A390, ML14238A391, and ML14238A392 (Non-publicly available).

Exelon (Exelon Generation Company, LLC), 2014, "Beyond Design Basis Site-Specific Local Intense Precipitation Analysis (Fukushima) for Exelon's IL Sites, including Quad Cities," Calculation Package QDC-0000-S-2131, Revision 0, October 2014, ADAMS Accession No. ML15307A248 (Non-publicly available).

NRC (U.S. Nuclear Regulatory Commission), 2015 "Report for the Audit of Applied Weather Associates, LLC, Regarding Site Specific Probable Maximum Precipitation Development in Support of Near-Term Task Force Recommendation 2.1 Flood Hazard Reevaluations," May 19, 2015, ADAMS Accession No. ML15113A029.