2.4.5 PROBABLE MAXIMUM SURGE AND SEICHE FLOODING

In this subsection, the hydrometeorological design basis is developed to ensure that potential hazards to the safety-related structures, systems and components (SSC) at the new plant location, due to the effects of probable maximum hurricane (PMH) surge and seiche, are considered in the design of the new plant. The new plant is located on the eastern shore of the Delaware River estuary. The existing topography at the new plant location ranges from 5 to 15 feet (ft.) NAVD (Reference 2.4.5-11). Consequently, the new plant may be affected by hurricane storm surge.

The approach used to determine the PMH surge, seiche flooding, and wave runup are presented. The methodologies used to determine storm surge from the PMH are in accordance with American National Standards Institute/American Nuclear Society (ANSI/ANS)-2.8-1992 (Reference 2.4.5-1) and RG 1.59.

Methods used to determine maximum surge and seiche flooding include:

- Bodine storm surge model (Reference 2.4.5-2), coupled with the HEC-RAS model (Reference 2.4.5-28) and the wind setup model of Kamphuis (Reference 2.4.5-10)
- NOAA, *Sea, Lake, and Overland Surges from Hurricanes* (SLOSH) model (References 2.4.5-22 and 2.4.5-23)
- RG 1.59
- ADCIRC+SWAN Model (Reference 2.4.5-41)

The design basis flood level established in this subsection is conservatively based on the ADCIRC+SWAN model's simulation of the storm surge due to the PMH. Initially, the Bodine storm surge model is used to screen storm surge water levels based on varying PMH parameters in combination with HEC-RAS and the Kamphuis wind setup model. The Bodine model calculates storm surge at the open coast. HEC-RAS determines the PMH surge water level as the surge propagates through Delaware Bay to the new plant location. The Kamphuis method calculates additional effects on water levels at the new plant caused by wind blowing over the Delaware Bay.

The alternative methods listed above (SLOSH and RG 1.59) are investigated, and results are discussed in this subsection, but the alternative methods are determined to have limitations for determining the PMH surge at the site. Those limitations are discussed in Subsection 2.4.5.2.

The overall approach and sequence of steps are as follows. Subsection 2.4.5.1 documents that the PMH, as defined by NOAA's *Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Windfields* National Weather Service Technical Report NWS 23 (NWS 23) (Reference 2.4.5-18), represents the Probable Maximum Wind Storm (PMWS) at the new plant location. As defined by NOAA, the PMH may exhibit a range of meteorological characteristics, so preliminary screening level calculations are performed that identify the PMH characteristics that produce the PMH surge at the new plant location. The PMH with these specific characteristics is used to specify the PMWS.

Determination of the maximum still water level (SWL) of the PMH surge based on the Bodine, HEC-RAS and Kamphuis method is presented in Subsection 2.4.5.2. The analysis commences with the effects of the hurricane over the continental shelf, producing a surge at the mouth of Delaware Bay, which is determined using the Bodine model. The surge is superimposed on a coincident 10% exceedance high tide. Outputs of the Bodine model are used as input to HEC-RAS, defining the surge at the mouth of the bay as a stage boundary condition. The upstream boundary of HEC-RAS is the head of tide at Trenton, NJ, where the discharge hydrograph reflects the effects of hurricane-associated precipitation. The additional effects of wind blowing over Delaware Bay, not simulated by HEC-RAS, are calculated using a formula for wind setup in semi-enclosed bodies of water as presented by Kamphuis (Reference 2.4.5-10).

Wave heights and wave runup coincident with the maximum SWL are determined in Subsection 2.4.5.3, using the hurricane wind field specified by NWS 23. Wave runup is calculated in accordance with USACE's *Coastal Engineering Manual* (CEM) (Reference 2.4.5-27). Wave runup is added to the maximum SWL of the PMH surge.

In Subsection 2.4.5.4, the potential future effects of sea level rise are evaluated and added to the maximum WSEL from the PMH surge, which includes coincident wind wave activity, to determine the future maximum WSEL through the projected life of the new plant in Subsection 2.4.5.5.

Subsection 2.4.5.6 presents the final design basis flood WSEL due to the PMH surge using a conservative, current practice approach predicted by a two-dimensional storm surge model. The ADCIRC+SWAN model is used in conjunction with the CEM wave runup equations to determine the design basis flood level for the PSEG Site.

Subsection 2.4.5.7 addresses sediment erosion and deposition associated with the PMH and their potential effects on the safety-related intake structure. Subsection 2.4.5.8 demonstrates that Delaware Bay does not resonate with meteorological or seismic forcing, providing further confirmation that the PMH surge as calculated in this section represents the most severe flooding that could occur at the new plant.

2.4.5.1 Probable Maximum Winds (PMW) and Associated Meteorological Parameters

This subsection identifies the meteorological characteristics of the PMH that causes the PMH surge and demonstrates that the PMH wind field represents the PMWS at the new plant location. The basic meteorological parameters that define the PMH are varied within limits given by NOAA (Reference 2.4.5-18) to determine the most severe combination that results. The detailed analysis of surge (in Subsection 2.4.5.2) is based on the most severe combination of these parameters.

The meteorological parameters associated with the PMH at the mouth of Delaware Bay are based on NWS 23. The mouth of Delaware Bay is defined as a point bisecting the line from Cape May, New Jersey (NJ) to Cape Henlopen, Delaware (DE), at latitude 38°51'30"N, longitude 75°01'30"W. At this location, NOAA provides the following meteorological parameters for the PMH:

- Central pressure, p_0 = 26.65 inches of mercury [in. of Mercury (Hg)].
- Pressure drop, Δp = 3.5 in. of Hg.
- Radius of maximum winds, R = from 11 to 28 nautical miles (NM).
- Forward speed, T = from 26 to 42 knots (kt).
- Coefficient related to density of air, K = 68 (when parameters are in units of in. of Hg and kt)
- Track direction, from 138 degrees (moving northwest).

The northwest track direction is perpendicular to bathymetric contours of the continental shelf offshore of the mouth of Delaware Bay (Reference 2.4.5-20). The track of this storm is illustrated in Figure 2.4.5-1. This track direction is within the range of directions that NOAA specifies for the PMH at the mouth of Delaware Bay. The inflow angle, which varies with distance from the storm center, is as specified by NOAA (Reference 2.4.5-18). From these parameters, the maximum winds range from 128 to 135 kt, as shown in Table 2.4.5-2. Thus, the PMH is a relatively strong Category 4 hurricane by the Saffir-Simpson hurricane scale. Category 4 hurricanes have maximum sustained winds ranging from 114 to 135 kt.

NOAA specifies that the PMH may occur within a range of radius of maximum winds (R) and forward speed (T) (Reference 2.4.5-18). The method described in Subsection 2.4.5.2.2.2 is used to calculate the maximum storm surge at the open coast for nine possible combinations of R (11, 20, and 28 NM) with T (26, 34, and 42 kt) spanning the ranges of these parameters specified by NOAA. This analysis follows methodology described in ANSI/ANS-2.8-1992 Section 7.2.1.4. In these preliminary simulations, designed to identify the PMH producing the maximum storm surge, a static high tide condition is specified. This tide condition differs from the dynamic tidal input used in Subsection 2.4.5.2.2. These preliminary screening level analyses (presented in Table 2.4.5-3) show that the surge at the mouth of Delaware Bay increases with R and T, with a maximum surge at the mouth of the bay when both R and T are high, specifically for the PMH with R = 28 NM, and T = 42 kt. This result is consistent with modeling performed in support of RG 1.59, which determined that the maximum surge at the coast consistently resulted from the PMH with high R and T.

The hurricane producing the maximum surge at the open coast may not produce maximum WSEL in bays and estuaries. A storm that progresses at approximately the same speed as the tide propagates is expected to produce maximum surges within Delaware Bay (Reference 2.4.5-3). The speed of propagation of the tide in Delaware Bay is approximately 14 kt (References 2.4.5-3 and 2.4.5-8). Therefore, it may be expected that a PMH with a high forward speed (42 kt) may not produce the highest storm surge at the new plant location, even though it produces the highest surge at the mouth of Delaware Bay. A fast-moving storm moves ahead of the storm surge wave, while a slower moving storm tends to reinforce the surge. Since the surge at the mouth of Delaware Bay is strongly dependent on the radius of maximum winds, R, but weakly dependent on the forward speed, (T), the three storms with R = 28 are further investigated using HEC-RAS and the Kamphuis wind setup method to determine the potential effects of these storms on SWLs at the new plant location. This analysis (presented in Table 2.4.5-3) shows that the PMH with R = 28 NM, and T = 26 kt produces the maximum surge at the new plant location consistent with Bretschneider's evaluation.

A PMH with R = 28 NM, and T = 26 kt produces the PMH surge at the new plant location. The PMH with R = 28 NM and T = 26 kt, is simulated in more detail in Subsections 2.4.5.2 and 2.4.5.3. Specifically, the storm is simulated with a fluctuating tide at the mouth of Delaware Bay, which produces the 10 percent exceedance high tide at the new plant location. The phase of the tide is established in relation to the development of the storm surge such that the 10 percent exceedance high tide coincides with the peak storm surge at the new plant location.

The pressure distribution and wind field associated with this storm are determined as specified by NOAA (Reference 2.4.5-18) for a PMH. Wind speed and direction at any point depend on Δp, T and R; the distance and angular orientation of the specified point relative to the center of the storm and the direction of storm movement. Wind speed varies with time at a point as the storm moves along its track relative to that point. Latitude and the density of air also affect the wind speed calculations. The maximum sustained winds over the ocean are calculated to be 128 kt; while the maximum winds over Delaware Bay are 126 kt, and maximum winds at the new plant location are 116 kt.

The HEC-RAS hydraulic simulation does not account for wind stress acting on water within Delaware Bay, therefore, the effect of wind stress within the bay is determined using the steady state wind setup method described by Kamphuis (Reference 2.4.5-10). Wind setup refers to the response of water surface elevations in enclosed or semi-enclosed bodies of water to winds blowing across the water surface. The method presented by Kamphuis assumes wind setup in Delaware Bay to be a steady state response to steady, uniform wind over the bay. This simplification is appropriate because Delaware Bay is less extensive in area than the continental shelf, and winds are more uniform. The assumption that the bay exhibits a steady state response to winds that change with time is a conservative assumption (Reference 2.4.5-4) because the bay would not reach a steady state condition instantaneously.

ANSI/ANS-2.8-1992 (Reference 2.4.5-1), recommends use of the parameterization of the wind stress, k, as discussed in Bodine (Reference 2.4.5-2), unless other values can be justified using better observational data. Recent research shows that the Bodine parameterization overestimates the wind stress coefficient at hurricane force winds. Recent observations of the wind stress coefficient at hurricane force winds have been made possible by the development of observational devices not available in 1971 when the Bodine technical memorandum was published (References 2.4.5-26 and 2.4.5-7). Observations, utilizing advanced devices, have determined k values at hurricane force winds ranging from 1.4×10^{-6} to 3.0×10^{-6} (References 2.4.5-4, 2.4.5-26, and 2.4.5-7). Above the threshold of hurricane force winds, k does not increase with wind speed (Reference 2.4.5-7). Therefore, the Bodine relationship for the wind stress coefficient is modified at high wind speeds so that the wind stress coefficient does not exceed 3.0×10^{-6}, the highest observed value reported at hurricane force winds (References 2.4.5-4, 2.4.5-26, and 2.4.5-7). Use of a maximum value of k of 3.0×10^{-6} is conservative based on measured values at hurricane force winds.

2.4.5.1.1 Probable Maximum Wind Storm (PMWS)

The PMH represents the PMWS that could cause flooding at the new plant location. A 31-year record (1978 through 2008) of wind speed and direction data from Dover, DE

(11 miles west of the center of Delaware Bay) was analyzed. The Dover weather station is the closest to the center of Delaware Bay, and thus the most appropriate location for evaluating winds over the bay that could cause wind setup or seiche activity. Setup of Delaware Bay has been observed when strong winds parallel to its long axis (i.e., northwest-southeast) persist for durations of 2 to 12 hours (Subsection 2.4.11). Winds at Dover were averaged over 4 hours, a sufficient duration to cause wind setup of Delaware Bay, based on the observations summarized in Subsection 2.4.11. The analysis shows that 4 hour average winds parallel to the long axis of Delaware Bay did not exceed 35 mph (30 kt) at Dover. Overwater winds are expected to be 50 kt when overland winds are 30kt (Reference 2.4.5-18). Therefore winds of sufficient duration to cause wind setup or seiche did not exceed 50 kt over Delaware Bay during the period 1978 through 2008. By comparison, the wind speeds associated with the PMH exceed 125 kt over Delaware Bay. Therefore, the PMH represents the PMWS for the new plant location.

2.4.5.1.2 Appropriateness of PMH Determination

The probable maximum storm surge water level estimation described in Subsection 2.4.5.5 uses the PMH parameters defined by NWS 23 for coastal locations on the United States (U.S.) Gulf and East coasts. NWS 23 is recognized as a reliable source of information to characterize the PMH (Reference 2.4.5-1). The PMH parameters in NWS 23 are based on historical data for hurricanes making landfall on the U.S. coasts between 1851 and 1975. Comparisons of hurricane climatology during the period evaluated in NWS 23 with hurricanes making landfall after 1975 indicate that the NWS 23 parameters for the PMH are still applicable.

NOAA (Reference 2.4.5-15) has summarized variations in the frequency of major hurricanes that relate to variations in climatologic conditions. The Atlantic Multi-decadal Oscillation, which refers to cyclic fluctuations in oceanic surface temperature over periods that last as long as several decades, appears to affect the frequency of hurricanes; resulting in periods of 20 years or more with a high frequency of major hurricanes, which may be followed by a similar period with lower hurricane frequency. Atlantic Ocean hurricanes were significantly more active from 1995 to 2005 than in the previous two decades (1970 to 1985). Prior to that, the period 1945 through 1970 was relatively active, as active as the 1995 to 2005 period. NOAA published a technical memorandum (Reference 2.4.5-24) analyzing the number and strength of hurricane strikes by decade and location in the U.S. According to this publication, on average, a Category 4 or stronger hurricane hits the U.S. once every 7 years. However, in the 35 years from 1970 to 2005, only three Category 4 or larger hurricanes have reached the U.S., which is less than the expected number of 5 in 35 years. Based on this information, it is reasonable to conclude that the number and strength of hurricanes since NWS 23 was published are not greater than hurricanes prior to 1975. The NWS 23 climatological data set includes the relatively active period of 1945 through 1970. Therefore, meteorological criteria for hurricanes affecting the gulf and east coasts of the U.S., described in NWS 23, are conservative even considering potential future climatic variability.

2.4.5.2 Surge and Seiche Water Levels

Assessment of the PMH meteorolgical parameters that produce the maximum SWL surge at the PSEG Site is presented in this subsection. The most severe hurricane storm surges historically reported for the site and surrounding area are characterized in Subsection 2.4.5.2.1. The PMH surge SWL calculations are presented in Subsection 2.4.5.2.2. Analysis of the PMH surge begins with the effects of the hurricane as it moves over the continental shelf, producing a surge at the mouth of Delaware Bay, determined using the Bodine model. The surge is superimposed on a coincident 10% exceedance high tide. Outputs of the Bodine model are used as input to HEC-RAS, defining the surge at the mouth of the bay as a stage boundary condition. The upstream boundary of HEC-RAS is the head of tide at Trenton, NJ, where the discharge reflects a historical rainfall event that conservatively represents the effects of hurricane-associated precipitation. The additional effects of wind blowing over the Delaware Bay are calculated using a formula for wind setup in semi-enclosed bodies of water as presented by Kamphuis (Reference 2.4.5-10).

Results are compared with results from alternative methods. The methodology used to determine the PMH surge SWL are validated by reproducing the storm surge observed in Delaware Bay from one of the historical hurricanes summarized in Subsection 2.4.5.2.1.

2.4.5.2.1 Historical Surges

Delaware, New Jersey, and Pennsylvania did not experience a direct hit from a major hurricane during the period 1851-2006 (Reference 2.4.5-24). Although storms that create substantial surges in Delaware Bay are rare, the bathymetry and shape of Delaware Bay can produce storm surge in response to hurricanes that make landfall to the west of the bay while traveling in a northward direction. Hurricanes producing severe storm surge at Philadelphia, PA (on the Delaware River estuary 30 miles northeast of the PSEG Site) include the Chesapeake-Potomac hurricane (1933), Hazel (1954), Connie (1955), Floyd (1999), and Isabel (2003). Tracks of these storms are shown in Figure 2.4.5-2, based on data accessed from NOAA's Coastal Services Center (Reference 2.4.5-12). This list of storms is assembled from published descriptions of hurricanes producing significant surges in Delaware Bay and from review of hurricane tracks passing within 100 NM of the new plant location, while making landfall to the west of the mouth of Delaware Bay.

The Chesapeake-Potomac hurricane made landfall as a Category 1 hurricane near Currituck, North Carolina (NC). Traveling northwest, its track paralleled the western shore of Chesapeake Bay. It then turned northeasterly, bringing the storm center within 80 NM of the new plant location (Reference 2.4.5-12). It produced a maximum storm surge of 3.8 ft. near the mouth of Delaware Bay; 7.7 ft. at Reedy Point, DE (nearest tidal gage to the new plant location), and 7.1 ft. at Philadelphia (Reference 2.4.5-3).

Hazel made landfall as a Category 4 hurricane near the border of NC and South Carolina (SC). It moved north, with Category 1 status at its nearest approach to the new plant location, when the storm center was 98 NM west of the new plant location (Reference 2.4.5-12). Hazel produced a maximum storm surge at Philadelphia of 9.4 ft. (Reference 2.4.5-31).

Connie made landfall near Cape Charles, Virginia, as a tropical storm, and its inland track generally followed the eastern shore of Chesapeake Bay. At its nearest point, the storm center was within 43 NM of the new plant location (Reference 2.4.5-12). It produced a maximum surge at Philadelphia of 5.0 ft. (Reference 2.4.5-31).

The storm center of Floyd bypassed Delaware Bay to the south and east, 70 NM from the new plant location, moving northeast as a Category 1 hurricane (Reference 2.4.5-12). It produced a storm surge (after correcting for astronomical tide) of 3.0 ft. at Cape May, NJ (mouth of Delaware Bay); 2.9 ft. at Reedy Point; and 4.0 ft. at Philadelphia (Reference 2.4.5-13).

Traveling northwest, Isabel made landfall as a Category 1 hurricane near Beaufort, NC. The storm center was closest to the new plant location at 163 NM to the southwest. At this point, it was a tropical storm (Reference 2.4.5-12). Isabel produced a storm surge of 3.1 ft. at Lewes, DE; 5.0 ft. at Reedy Point; and 5.4 ft. at Philadelphia (Reference 2.4.5-14).

Hurricane Hazel and the Chesapeake-Potomac hurricane produced the maximum historical storm surges recorded in Delaware Bay. Of these, the Chesapeake-Potomac hurricane storm center passed closer to the new plant location, exhibiting a northwesterly track most similar to the hypothetical storm track of the PMH (References 2.4.5-18 and 2.4.5-17). Based on the storm track and adequate available data related to this storm, the Chesapeake-Potomac hurricane of August 1933 is selected to validate the storm surge model used to determine the PMH surge.

2.4.5.2.2 Estimation of Probable Maximum Storm Surge

In order to satisfy the combined events criteria specified in Section 9.2.2 of ANSI/ANS-2.8-1992, (Reference 2.4.5-1) storm surge at the new plant is evaluated combining probable maximum surge and seiche with wind wave activity concurrent with the 10 percent exceedance high tide, and effects of hurricane-associated precipitation. This subsection outlines the sequence of steps taken to calculate the maximum surge SWL due to PMH. Subsequent subsections describe wave runup and sea level rise estimates.

Surge at the open coast results from meteorological and oceanographic processes occurring offshore over a scale of 500 NM. Between the mouth of the bay and the new plant location, a distance of 50 NM, the propagation of the surge is controlled by the geometry and hydraulics of the estuary. Water levels further increase due to wind blowing directly over the bay. Wave runup addresses processes occurring upwind of the new plant location on spatial scales (fetch lines) of less than 10 NM which are discussed in Subsection 2.4.5.3. The analysis proceeds from the large, offshore spatial scales to smaller spatial scales proximal to the new plant location near the head of Delaware Bay. Details of the storm surge analysis are presented in the remainder of this subsection.

The PMH surge SWL is determined by combining the effects of surge at the open Atlantic coast coincident with the 10 percent exceedance high tide. That surge plus tide is propagated through Delaware Bay to the new plant location; and the effects of wind setup resulting from wind stress over Delaware Bay are superimposed, by addition, on the propagated surge. The overall approach uses:

- Bodine method to determine storm surge at the open coast
- HEC-RAS analysis to propagate that surge through Delaware Bay to the site
- Kamphuis method to determine wind setup at the site caused by winds blowing over the Delaware Bay

The storm surge water levels determined by the Bodine method are used as a stage boundary condition at the mouth of Delaware Bay for the HEC-RAS simulation within the Delaware River estuary. The upstream boundary conditions input into the HEC-RAS model, consisting of discharge of the Delaware River at Trenton, and discharge of tributaries downstream of Trenton, are based on a 2006 event to account for hurricane-related precipitation. The water levels determined by HEC-RAS, and winds defined by NOAA (Reference 2.4.5-18) for the PMH, are used to determine wind setup at the new plant location. The combination of HEC-RAS surge, which includes the 10 percent exceedance high tide, and Kamphuis wind setup determines the PMH surge SWL at the new plant location.

The Bodine model was used by the NRC to develop default storm surge estimates at the open coast in support of RG 1.59 and is cited as an acceptable methodology for such analyses by ANSI/ANS-2.8-1992 (Reference 2.4.5-1).

HEC-RAS is a widely accepted model for dynamic flood routing in rivers developed by the U.S. Army Corps of Engineers. It incorporates the ability to simulate hydraulics of estuaries by using a stage hydrograph as a downstream (tailwater) boundary condition. According to ANSI/ANS 2.8-1992, Section 7.3.2.1, a transient one-dimensional model can be used to compute resonance effects for a narrow body of water with a bay entrance. HEC-RAS is one-dimensional, and does not account for flow perpendicular to the primary longitudinal axis of the Delaware Bay and estuary. This model simplification does not have a significant effect on HEC-RAS ability to simulate either the tide or storm surge at the new plant.

Flow in Delaware Bay and near the new plant is predominantly longitudinal (References 2.4.5-36 and 2.4.5-37). Bretschneider determined that cross-wind effects on storm surge are virtually negligible (less than 3 percent) upstream of the head of Delaware Bay (upstream of RM 48), and reduces surge on the east side of the estuary at the new plant location (Reference 2.4.5-3), therefore neglecting cross-wind effects is conservative at the new plant location. The wind setup algorithm of Kamphuis is a steady-state analytical solution of the fundamental equations governing hydrodynamics, which can be found in reference texts (References 2.4.5-27 and 2.4.5-4). Its primary assumption, that water levels exhibit a steady state response to varying winds, is conservative because the bay does not respond to the winds instantaneously. The combination of these methods is demonstrated to be valid by reproducing the storm surge of an actual historical hurricane as described in the remaining paragraphs of this subsection.

These methods are validated by reproducing the surge observed during the Chesapeake-Potomac hurricane of 1933. The pressure distribution and winds associated with this storm are specified as described by Bretschneider (Reference 2.4.5-3) and NOAA (Reference 2.4.5-18). Bretschneider reports a pressure drop of 0.85 in. of Hg. This value is used with NOAA (Reference 2.4.5-18) formulas for the Standard

Project Hurricane to determine the pressure distribution and wind field throughout the storm. Bretschneider reports maximum sustained winds over the ocean of 58 mph (50 kt), and maximum sustained winds over Delaware Bay of 50 mph (43 kt). The simulated storm exhibits maximum winds of 64 mph (56 kt) over the ocean, and 47 mph (41 kt) over Delaware Bay, similar to the wind speeds reported for the Chesapeake-Potomac hurricane.

Coincident astronomical tides are specified at the mouth of Delaware Bay. Comparison of model results with the actual response to the Chesapeake-Potomac hurricane is expressed as storm surge, the difference between actual water levels and the predicted astronomical tide level. The storm surge calculated at the mouth of Delaware Bay, using the Bodine method, reproduces the observed surge as described by Bretschneider (Reference 2.4.5-3). Comparison of observed and simulated surge at the mouth of the bay is illustrated in Figure 2.4.5-3. The peak storm surge at Reedy Point, DE, is calculated to be 7.9 ft., while the observed surge at Reedy Point was 7.7 ft. Water surface elevations (surge plus tide) at Reedy Point are illustrated in Figure 2.4.5-4. The Delaware Bay storm surge model described here is demonstrated to be conservative. The margin of error is consistent with comparable models, such as NOAA's SLOSH model which has a stated margin of error of +/- 20 percent (Reference 2.4.5-23).

2.4.5.2.2.1 Estimation of 10 Percent Exceedance High Tide

Maximum monthly high tide values from 1987 through 2008 are analyzed at NOAA tidal gage stations upstream and downstream from the new plant location to determine the 10 percent exceedance high tide at the site (Reference 2.4.5-16). This analysis calculates a 10 percent exceedance high tide of 4.2 ft. NAVD at the Lewes, DE, NOAA tidal gage (8557380) at river mile (RM) 0, and 4.6 ft. NAVD for the Reedy Point, DE, NOAA tidal gage (8551910) at RM 59 as illustrated in Figure 2.4.5-5. Based on these values, the 10 percent exceedance high tide at the new plant location at RM 52 is determined by linear interpolation to be 4.5 ft. NAVD.

This approach for estimating 10 percent exceedance high tide, based on recorded tides, intrinsically includes the effects of sea level anomaly (also known as initial rise). ANSI/ANS-2.8-1992, Section 7.3.1.1.2, concludes sea level anomaly need not be included when 10-percent exceedance high tide is based on recorded tides. Sea level anomaly is not included in this analysis because recorded tide data is used to calculate the 10-percent exceedance high tide.

2.4.5.2.2.2 Storm Surge at the Open Coast

Calculations presented by Bodine are verified by reproducing a sample problem provided by Bodine (Reference 2.4.5-2). The model reproduced Bodine's results for maximum surge to four significant figures.

Inputting the PMH identified in Subsection 2.4.5.1 into the Bodine calculations, a maximum surge elevation of 20.9 ft. NAVD is calculated at the mouth of Delaware Bay. This value includes a fluctuating tide at the mouth of the bay that generates the 10 percent exceedance high tide at the new plant coincident with the peak storm surge (Figure 2.4.5-6).

As a point of comparison, other methodologies available from NOAA and NRC to determine storm surge at the open coast are NOAA's SLOSH program and RG 1.59 Appendix C. SLOSH results are accessed using the SLOSH Display Program v. 1.61g (Reference 2.4.5-22) and adjusted to account for the 10 percent exceedance high tide and NAVD datum. NOAA uses SLOSH to determine hurricane surge levels for a large number of potential hurricanes and provides access to the results via the SLOSH Display Program. The storms presented in the Display Program include a Category 4 storm on the Saffir-Simpson scale, but the Delaware Basin v3 SLOSH dataset does not include a storm with the same parameters as the PMH determined for the PSEG Site. Using the SLOSH Display Program, the highest surge elevation at the mouth of Delaware Bay is 17.6 ft. NAVD. Accounting for the 10 percent exceedance high tide indicates a Category 4 storm elevation of 19.8 ft. NAVD.

RG 1.59 is applicable to determine PMH surge levels on open coast sites on the Atlantic Ocean and Gulf of Mexico. Therefore, it is appropriate to use this methodology for estimating storm surge up to the mouth of Delaware Bay, but it is not appropriate to use it beyond the area where a hurricane makes initial landfall. As such, it is not an acceptable method for estimating surge at the new plant. RG 1.59, Appendix C, results for the mouth of Delaware Bay are based on interpolating results from Atlantic City, NJ, and Ocean City, MD, and then adjusting to NAVD. Including the 10 percent exceedance high tide, RG 1.59 estimates a maximum storm surge of 21.7 ft., NAVD at the mouth of the Delaware Bay.

While the three methods do not compare the exact same hurricane parameters, the three models produce similar storm surge estimates at the mouth of Delaware Bay for Category 4 hurricanes. The Delaware Basin v3 SLOSH dataset does not include a storm with the same parameters as the PMH determined for the PSEG Site. Therefore, SLOSH is not used to determine the peak surge at the mouth of the Bay. RG 1.59 cannot be used to determine surge at the new plant location, and cannot be used as a substitute for the Bodine method because it does not provide a stage hydrograph for the simulated hurricane to input into HEC-RAS. Further, RG 1.59 does not simulate the PMH as defined by NWS 23 (References 2.4.5-32 and 2.4.5-18). The Bodine method produces a more conservative result than SLOSH, and can specifically simulate the response to the PMH. Therefore, the Bodine model is selected as the basis for determining the PMH surge. The stage hydrograph, including the peak surge at the mouth of the bay calculated using the Bodine method, is input to the HEC-RAS model which propagates the storm surge through Delaware Bay.

2.4.5.2.2.3 Propagation of Surge through Delaware Bay

The propagation of surge through Delaware Bay is calculated using the HEC-RAS computer program. The HEC-RAS model is developed using channel geometry and floodplain elevations for the Delaware River between Trenton, NJ, and the head of Delaware Bay determined from the Triangular Irregular Network (TIN) terrain model developed from the U.S. Geological Survey (USGS) National Elevation Dataset (NED) (Reference 2.4.5-30) digital elevation model (DEM), and the NOAA Estuarine Bathymetry DEM (Reference 2.4.5-19). The HEC-RAS model is calibrated using observed tidal data. The calibrated model is then used to simulate the propagation of the surge from the mouth of Delaware Bay to the new plant.

In order to simulate the propagation of the PMH surge, the surge hydrograph generated by the Bodine calculations for the PMH is used as the stage boundary condition at RM 0. Discharge hydrographs generated by the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) for the Delaware River at Trenton and its major tributaries downstream of Trenton are used to simulate flow conditions in the Delaware River resulting from a historical rainfall event that conservatively represents the effects of hurricane-associated precipitation. Specifically, the HEC-RAS model uses a historical rainfall event that occurred in June 2006 that produced a basin average rainfall of 6 inches in the Delaware River Basin.

A discharge boundary condition at Trenton, defined by the HEC-HMS model response to the June 2006 rainfall event is input into the HEC-RAS model (Reference 2.4.5-29). Discharges from tributaries downstream of Trenton are also based on the HEC-HMS hydrographs for the June 2006 event, representing hurricane-associated precipitation. The output from the Bodine method describing the surge at the open coast is specified as the stage boundary condition at RM 0.

The effect of winds blowing over Delaware Bay, referred to as wind setup, is calculated using a standard method presented by Kamphuis (Reference 2.4.5-10), and is added to the HEC-RAS simulated water levels. Wind setup depends on wind speed and direction over the center of Delaware Bay; a coefficient accounting for wind and bottom stress; and water depth. The winds over the center of Delaware Bay at model time step 20.5 hours are 120 kt from the south-southeast, determined in accordance with NWS 23 (Reference 2.4.5-18). The stress coefficient is 3.3×10^{-6} (Reference 2.4.5-3). The cross-section average depth of water varies with RM and time, and is determined from the HEC-RAS water levels and channel geometry. The calculated wind setup at time 20.5 hours is 14.0 ft. at the new plant location. The wind setup is added to the HEC-RAS water level to determine the SWL, 26.86 ft. at t = 20.5 hours (Table 2.4.5-1).

Using the methods described in this subsection, the PMH surge SWL at the new plant location is 26.9 ft. NAVD (Table 2.4.5-1 and Figure 2.4.5-6). This maximum still water surface elevation combines the coincident effects of the 10 percent exceedance high tide, the propagation of the open coast surge through Delaware Bay, hurricane-associated precipitation, and the effect of winds over Delaware Bay.

The maximum SWL may be compared with maximum surge levels calculated by the NOAA SLOSH model, accessed using the SLOSH Display Program v. 1.61g (Reference 2.4.5-22). However, the Delaware Basin v3 SLOSH dataset does not include a storm with the same parameters as the PMH determined for the PSEG Site, nor do results include the 10 percent exceedance high tide, or effects of river flow. The maximum surge level reported by the SLOSH Display Program at the new plant location is 22.8 ft. NAVD. Adjusting to include the 10 percent exceedance high tide indicates a Category 4 storm elevation of 25.3 ft. NAVD using the SLOSH Display Program.

Based on the analyses described in Subsection 2.4.5.2, the PMH surge SWL at the new plant location is 26.9 ft. NAVD. The maximum WSEL, including wave runup, occurs one-half hour later, when the SWL is 26.7 ft. NAVD (Subsection 2.4.5.5 and Table 2.4.5-1).

2.4.5.3 Coincident Wave Runup

Subsection 2.4.5.3.1 presents the methodology used to determine wave runup coincident with the PMH surge. Results of the analysis are provided in Subsection 2.4.5.3.2. The resultant wave runup is added to the maximum SWL.

2.4.5.3.1 Methodology

Coincident wave runup, in association with the PMH surge, is determined using the approach described by USACE (Reference 2.4.5-27). Winds are estimated at the new plant location in accordance with NOAA (Reference 2.4.5-18). Water depth is determined from the TIN terrain model, using coincident water levels determined by the Delaware Bay storm surge model, as defined in Subsection 2.4.5.2. The wave field is fetch- and duration-limited, as defined by USACE. Wind vectors are averaged over time consistent with the fetch and duration limitations, as specified by USACE. The significant wave height and period are calculated using the straight line fetch and the friction velocity. A check is made to validate the use of deep water equations, comparing the calculated significant wave period with the limiting spectral peak period. If the calculated period is less than the limiting spectral peak period, then the deep water equations are valid. Otherwise, the wave heights are limited by breaking. The maximum breaker height is determined using the Miche criterion (Reference 2.4.5-27).

The SWL and wave data (significant wave height, period and direction) over the course of the PMH storm surge event are shown in Table 2.4.5-5. The wave runup calculations described below are performed at each half hour interval.

Wave runup calculations for the new plant are based upon the latest design guidance found in the USACE CEM, Chapter VI-5 (Reference 2.4.5-27). The new plant's powerblock will be constructed on engineered fill with riprap protection, with facing slopes of 3:1 (horizontal:vertical), as shown on Figure 2.5.4.5-2.

Although the CEM prescribes the use of significant wave height to calculate wave runup, one alteration from the methodology presented in the CEM is the use of the lesser of (a) the maximum wave height, or (b) the "breaker height" (0.78 times depth of water) for computation of wave runup as required by Reference 2.4.5-1. Per Reference 2.4.5-1, the maximum wave height, H_{max}, is defined as the 1 percent wave, $H_{1\%}$, and for deep water waves, H_{max} = 1.67 times the significant wave height, H_s. CEM Equation II-1-132 also defines $H_{1\%}$ as 1.67 times H_s (Reference 2.4.5-27). Consequently, H_s, is replaced by H_{max} (H_s times 1.67) in the CEM equations for both the surf similarity parameter and the wave runup for the PSEG Site. This alteration essentially yields the highest runup of any single wave running up the embankment.

CEM Equation VI-5-3 provides a general form for the wave runup equation for structures as (Reference 2.4.5-27):

$$R_{ui\%} / H_s = (A\ \xi + C)\ \gamma_r\ \gamma_b\ \gamma_h\ \gamma_\beta \qquad \text{(Equation 2.4.5-1)}$$

where:

$R_{ui\%}$ runup level exceeded by *i* percent of the incident waves

H_s	significant wave height of incident waves at the toe of the structure, in this case the maximum wave height ($H_{max} = 1.67H_s$)
ξ	surf similarity parameter, ξ_{om} or ξ_{op} (defined below)
A, C	coefficients dependent on ξ and i but related to the reference case of a smooth, straight impermeable slope, long-crested head-on waves and Rayleigh-distributed wave heights
γ_r	reduction factor for influence of surface roughness
γ_b	reduction factor for influence of a berm ($\gamma_b = 1$ for non-bermed profiles)
γ_h	reduction factor for influence of shallow-water conditions where the wave height distribution deviates from the Rayleigh distribution ($\gamma_r = 1$ for Rayleigh distributed waves)
γ_β	factor for influence of angle of incidence β of the waves ($\gamma_\beta = 1$ for head-on long-crested waves, i.e., $\beta = 0^o$). The influence of directional spreading in short-crested waves is included in γ_β as well.

The surf similarity parameter for random waves is defined as:

$$\xi_{om} = \frac{\tan\alpha}{\sqrt{s_{om}}} \quad \text{or} \quad \xi_{op} = \frac{\tan\alpha}{\sqrt{s_{op}}} \qquad \text{(Equation 2.4.5-2)}$$

where:

$$s_{om} = \frac{2\pi}{g}\frac{H_s}{T_m^2}$$

$$s_{op} = \frac{2\pi}{g}\frac{H_s}{T_p^2}$$

tan α is the structure slope
T_m is the mean wave period
T_p is the spectral peak wave period.

For the new plant an *i* value of 2 percent is adopted. This establishes values for *A* and *C* in Equation 2.4.5-1 depending on the surf similarity parameter as provided by CEM Equation VI-5-6:

A=1.5 ξ_{op} ; C=0 for 0.5< $\xi_{op} \leq 2$

A=0.0 ; C=3.0 for 2< $\xi_{op} \leq$ 3-4

In establishing the γ parameters to be used in the calculation of wave runup at the new plant, the berm factor γ_b is set equal to 1.0 because there is no berm in the design cross-section. The shallow water reduction factor is conservatively set to 1.0 as there will be storm surge conditions where the waves impinging on the new plant's slope will be non-

breaking (i.e., Rayleigh distributed). The roughness factor γ_r as provided by Table VI-5-3 of the CEM is between 0.5 and 0.6, dependent upon the number of layers of rock to be placed on the slope. As this design detail has yet to be determined, the least restrictive value of 0.6 is selected for conservatism. Finally, it is assumed that the waves are head-on; i.e., normally-incident to the slope, so that γ_β is set equal to 1.0.

2.4.5.3.2 Wave Runup at the New Plant Location

Wave runup is determined at a time coinciding with the maximum PMH surge SWL at the new plant location, as well as half-hour intervals immediately before and after that time. Calculations during the extended time are performed to ensure that the maximum PMH flood level, consisting of the SWL plus wave runup, is identified. Coincident wave runup in association with the PMH is determined using the methodology described in Subsection 2.4.5.3.1. Winds coincident with the maximum surge are determined at the new plant location using the methodology described by NOAA (Reference 2.4.5-18).

At the time when SWL plus wave runup peaks, the wind speed is 104 kt from the east-southeast. Due to the flood levels associated with the PMH surge, the inundated fetch line upwind to the east-southeast is 8.3 mi. The wave field reaches steady state along this fetch line if winds blow steadily along the fetch line for 1.5 hours (hr.). Therefore, wind speed is averaged over the prior 1.5 hr. to determine an appropriate wind speed and direction.

The significant deep water wave height is 14.7 ft., and its period is 5.6 seconds. The maximum wave height is 24.5 ft.; however, the average depth along the fetch line is 22.0 ft. Thus, the deepwater equations are not valid: waves of this height would break. The maximum breaker height is 14.5 ft. Wave runup is estimated from the maximum wave height or the maximum breaker height, whichever is less; in this case the maximum breaker height. The wave runup is calculated to be 14.3 ft. using the procedure described in Subsection 2.4.5.3.1. Table 2.4.5-5 presents the wave runup results at each time step calculated.

2.4.5.4 Potential Sea Level Rise

NOAA has evaluated the trend of sea level at the NOAA Reedy Point tidal gage station. Measurements at any given tide station include both global sea level rise and vertical land motion, such as subsidence, glacial rebound, or large-scale tectonic motion. The monthly sea level trend based on monthly mean sea level data from 1956 through 2006 is 1.14 ft./century, with an upper 95 percent confidence limit of 1.35 ft./century (Reference 2.4.5-21). The maximum flood level determined at the new plant location includes 1.35 ft. to conservatively account for sea level rise over the projected 60 year life of the new plant.

2.4.5.5 Maximum Water Surface Elevation Associated with the PMH

The PMH, defined in Subsection 2.4.5.1, is determined to produce the PMH surge, as defined in NRC RG 1.59. Specifically, the storm used to determine maximum WSEL is the PMH that causes the PMH surge as it approaches the site along a critical path at an optimum rate of movement. At the time when water levels including wave runup peak, the SWL at the new plant location is calculated to be 26.7 ft. NAVD using the Bodine,

HEC-RAS and Kamphuis method. The addition of wave runup, 14.3 ft., creates a water surface elevation of 41.0 ft. NAVD. Future sea level rise of 1.35 ft. per century is added to the effects of storm surge and wave runup for a maximum water surface elevation that could occur during the projected life of the new plant of 42.4 ft. NAVD at the new plant location. This result is illustrated in Figure 2.4.5-7, and water elevations from the combined events are presented in Table 2.4.5-1, which discusses rounding the result to tenths of ft.

Maximum wave runup does not occur simultaneously with maximum SWL (Table 2.4.5-1). When the SWL reaches its maximum at 26.9 ft. NAVD, wave runup is 12.8 ft, which combines to an elevation of 39.7 ft. NAVD. One half-hour later, SWL drops to 26.7 ft. NAVD and wave runup increases to 14.3 ft., which combines to 41.0 ft. NAVD (Figure 2.4.5-7), 0.3 ft. higher than the previous time step.

2.4.5.6 PMH Design Basis Flood Level

The maximum SWL results reported in Subsection 2.4.5.5 are based on a simplified modeling approach available at the time of the initial ESPA preparation. Subsequently, high-resolution storm surge modeling systems, and the computational resources required to run them, have become the standard for more accurate determination of flood levels due to hurricane storm surge. NUREG/CR-7046, *Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America*, supports use of these high-resolution models as they allow more detailed and accurate simulations of storm surges because they are based on more recent understanding of the physics of the hurricane-storm surge processes; resolve the spatial heterogeneity in bathymetry, topography, and hydrologic characteristics; and can explicitly account for coastal structures that may impede or enhance the movement of storm surge inland. NUREG/CR-7046 also introduces the hierarchical hazard assessment (HHA) process. The HHA is a progressively refined, stepwise estimation of site-specific hazards that evaluates the safety of SSCs with the most conservative plausible assumptions consistent with available data. Consistent with this process, this subsection presents a more site-specific storm surge hazard assessment using the high-resolution storm surge modeling system described below.

The design basis flood level for the PSEG Site is established by using the PMH meteorological parameters determined in Subsection 2.4.5.2 and simulating the surge response in a current day two-dimensional storm surge modeling system. This subsection presents information on the development of the modeling system, the PMH cases run in the model and the design basis flood level determined at the PSEG Site.

2.4.5.6.1 Modeling System

The modeling system used for the analysis of the PMH surge at the PSEG Site uses a suite of state-of-the-art numerical wind, wave, and surge models and methods to compute surge still and total WSELs at the points of interest. The model suite consists of the Oceanweather Planetary Boundary Layer (PBL) wind model for tropical storms, the wave-field model Simulating Waves Nearshore (SWAN), and the storm surge and tidal model ADCIRC. This wind, wave and surge modeling approach is very similar to the recent FEMA-sponsored Region III floodplain-mapping project (Reference 2.4.5-44). In addition to the numerical models, estimation of wave runup at the points of interest to

establish a maximum total WSEL is determined using the approach described by USACE (Reference 2.4.5-27). The input to the modeling system is a series of parameters that represent the synthetic storm (i.e., storm track, which consists of time, position, central pressure, Holland B parameter [which controls the shape of the pressure and wind fields], radius to maximum winds, and peripheral pressure). The output from the modeling system is the maximum SWL and total WSEL for the PSEG Site associated with each individual storm modeled.

2.4.5.6.1.1 Wind Model

The Oceanweather PBL model is used to develop wind and pressure fields for the synthetic storms (Reference 2.4.5-40). For each storm, defined by a track and time-varying wind field parameters, the Oceanweather PBL model is applied to construct wind and atmospheric pressure fields every 15 minutes for driving surge and wave models. Oceanweather generates wind and pressure fields with a highly refined meso-scale moving vortex formulation developed originally by Chow (Reference 2.4.5-39) and modified by Cardone et al. (Reference 2.4.5-38). The model is based on the equation of horizontal motion, vertically averaged through the depth of the planetary boundary layer.

2.4.5.6.1.2 ADCIRC+SWAN Model

Storm surge simulations are performed using the tightly coupled ADCIRC+SWAN state-of-the-art coastal circulation and wave model. ADCIRC is based on the two-dimensional, vertically-integrated shallow water equations that are solved in Generalized Wave Continuity Equation form (Reference 2.4.5-41). The equations are solved over complicated bathymetry encompassed by irregular seashore boundaries using an unstructured finite-element method. This algorithm allows for flexible spatial discretizations over the entire computational domain. The advantage of this flexibility in developing a computational mesh is that larger elements can be used in open-ocean regions where coarser resolution is needed, whereas smaller elements can be applied in the nearshore and estuary areas where finer resolution is required to resolve hydrodynamic details and more accurately simulate storm surge propagation onto a complex coastal landscape. (Reference 2.4.5-45)

The recent FEMA Region III storm surge study developed a high-resolution ADCIRC mesh that covers the entire Delaware Bay and PSEG Site region (see Figure 2.4.5-8). The ADCIRC mesh is comprised of a high-resolution grid covering FEMA Region III that was appended to a previously developed grid of the western North Atlantic, the Gulf of Mexico and the Caribbean Sea. Specifically, the grid covers the area from the 60 degrees west meridian to the US mainland. Within FEMA Region III, the grid extends inland to the 49.2 ft. NAVD (15 m) contour to allow for inland storm surge flooding. In this region, the grid was designed to resolve major bathymetric and topographic features such as: inlets; dunes; and river courses, as identifiable on the detailed FEMA digital elevation model (DEM), satellite images, and National Oceanic and Atmospheric Administration (NOAA) charts. (References 2.4.5-42 and 2.4.5-43)

After confirming the FEMA developed ADCIRC mesh was operating correctly on the project computing platform, the mesh is refined in the vicinity of the PSEG Site to more accurately represent the topographic features of the site. To properly describe the topographic features important to the hydrodynamic and wave characteristics at the

PSEG Site, high resolution, site-specific topographic data including the controlling vertical features important to surge conveyance and wave propagation were incorporated into the finite element mesh. The refined mesh for the PSEG Site area is shown on Figure 2.4.5-9. The refined PSEG Site mesh is inserted into the overall FEMA Region III mesh and the model is re-validated using the same Hurricane Isabel and Nor'easter Ida test storm input files as the FEMA Model validation report prepared by USACE (Reference 2.4.5-44). A graphical comparison of water levels from the Hurricane Isabel storm simulation on the refined PSEG Site mesh and unmodified FEMA Region III at locations around the PSEG Site is shown in Figure 2.4.5-10. This process confirms that the refined mesh produces results that are essentially the same as the unmodified FEMA Region III mesh in the vicinity of the PSEG Site.

2.4.5.6.1.3 Wave Runup Estimation

The ADCIRC+SWAN simulations of each storm produce SWL and wave data (significant wave height, period and direction) over the course of each storm surge event. Wave field data on each of the four sides of the site (see Figure 2.4.5-11) are provided at 15-minute intervals. The data is analyzed and captured for the subsequent wave runup calculations. The wave runup calculations described below are performed at each time step and at each of the four locations around the site. After the calculations are performed, the maximum total WSEL value, defined as the SWL plus wave runup, at any of the four points is captured as the maximum value for that storm event.

Wave runup calculations for the new plant are based upon the latest design guidance found in the USACE Coastal Engineering Manual (CEM), Chapter VI-5 (Reference 2.4.5-29). The new plant's powerblock will be constructed on engineered fill with riprap protection, with facing slopes of 3:1 (horizontal:vertical), as shown on Figure 2.5.4.5-2. The wave runup equations described in Subsection 2.4.5.3.1 are used for the analysis. Additionally, the angle of incidence factor is considered variable in this analysis because more detailed wave direction information is available from the ADCRIC+SWAN model.

Based upon Equation VI-5-11 from the CEM and the expectation that waves impinging on the slope will be short-crested, the angle reduction factor is given by:

$$\gamma_\beta = 1 - 0.0022\,\beta \qquad \text{(Equation 2.4.5-3)}$$

where:
β (in degrees) is computed based upon the mean wave direction produced by SWAN and the orientation of the new plant's embankment.

The angle, β, is oriented such that it is zero when the incident wave direction is normal to a particular side of the new plant's embankment and is valid up to +/- 90° from due perpendicular. For example, at the Western point of interest (see Figure 2.4.5-11) a wave would need to have an easterly direction component to be impinging on the site. If the wave is traveling due East, then the angle β is zero and no reduction factor for wave direction is included in the wave runup calculation. If the wave is traveling in an easterly direction with some north/south component to it, then the wave runup is reduced according to the factor determined using Equation 2.4.5-3. This reduction factor is

conservatively set to be very small and is only 20 percent when the wave is parallel to the shore (i.e., +/- 90 degrees).

2.4.5.6.2 PMH Storm Simulations

Using the modeling system described in Subsection 2.4.5.6.1, three PMH storm simulations are run with differing antecedent water level conditions to compare the sensitivity of the resultant WSEL at the PSEG Site to the effects of potential sea level rise and 10 percent exceedance high tides. The PMH parameters described in Subsection 2.4.5.2 are used as an input to the modeling system. Table 2.4.5-4 provides the input parameters for each PMH model simulation.

One additional parameter not identified by NOAA (Reference 2.4.5-18), but required by the Oceanweather PBL wind field model is the Holland B parameter. A Holland B parameter of 1.1 is selected for these simulations, as this represents the mean value for the region.

As described in Subsection 2.4.5.2.2, the combined events criteria specified in Section 9.2.2 of ANSI/ANS-2.8-1992, (Reference 2.4.5-1) for determining the storm surge at the new plant is evaluated by combining probable maximum surge and seiche with wind wave activity concurrent with the 10 percent exceedance high tide, and effects of hurricane-associated precipitation. The modeling system developed for the PMH analysis accounts for the surge with wind wave activity concurrent with the 10 percent exceedance high tide through the use of antecedent water levels. The effects of hurricane-associated precipitation are not included in the analysis.

Analysis of the effects of precipitation based flooding in the Delaware River Basin is discussed in Subsections 2.4.3 and 2.4.4. These subsections estimate the resultant WSEL at the PSEG Site from the 500 year flood and various probable maximum precipitation events. While the ANSI/ANS-2.8-1992 combined events criteria only requires assessment of hurricane-associated precipitation, even these extreme precipitation events do not significantly increase the WSEL at the PSEG Site due to the size of the Delaware River at this location. Based on the limited response in WSEL at the PSEG Site to extreme precipitation events and the significantly higher WSEL when the PMH storm is modeled in the ADCIRC+SWAN modeling system, effects of hurricane-associated precipitation are not expected to affect the peak WSEL identified in the analysis.

2.4.5.6.3 PMH Design Basis Flood Level

Table 2.4.5-4 presents the resulting maximum WSEL's at the PSEG Site for each PMH event modeled. The only difference between each of the ADCIRC+SWAN simulations of the PMH is the antecedent water levels. Varying the antecedent water levels of the model simulations from 0 ft. NAVD to 5.85 ft. NAVD to conservatively account for potential sea level rise and the 10 percent exceedance high tide results in an approximate 1 ft. difference in maximum WSEL at the PSEG Site. The PMH simulations in the ADCIRC+SWAN modeling system produce maximum WSELs approximately 10 ft. below the equivalent maximum WSEL of the Bodine, Kaphuis and HEC-RAS modeling approach.

The design basis flood level due to a PMH storm surge event at the PSEG Site is established using the results of Run No. 2 (Table 2.4.5-4). This simulation conservatively sets the antecedent water level of the entire model domain to the estimated sea level rise value at the end of the life of the new plant (see Subsection 2.4.5.4). Run No. 3 includes an antecedent water level that includes sea level rise and 10 percent exceedance high tide applied to the entire model domain. Raising the domain water level to reflect an increase in sea level rise is appropriate, due to the global effects of this phenomenon. Tidal variations are localized effects, and, therefore, it is more accurate to account for tides as a localized increase in the results of the model, rather than an antecedent water level increase. Therefore, Run No. 3 is considered unrealistic and not considered as the design basis level. The PMH maximum WSEL of 32.1 ft. NAVD using the high-resolution modeling system described in Subsection 2.4.5.6.1 represents the design basis flood for the new plant location.

2.4.5.7 Sediment Erosion and Deposition Associated with the PMH Surge

Tidal current velocities normally range from 2 to 3 ft/sec. Velocities determined by the HEC-RAS model's simulation of the PMH surge show that velocities throughout Delaware Bay exceed 4.9 ft/sec; while velocities in the river channel near the new plant exceed 8 ft/sec. These calculated current velocities are sufficient to cause resuspension of natural sediments and cause erosion (Reference 2.4.5-5). Safety-related SSC will be protected against erosion that could affect the integrity of those facilities.

Gross deposition is determined by conservatively assuming that all total suspended solids in the water column are deposited within a few days after passage of the hurricane. Observations of total suspended solids concentrations (TSS) in other bays and estuaries shortly after passage of hurricanes indicate that TSS increase approximately tenfold more than normal pre-storm levels (References 2.4.5-9, 2.4.5-34, and 2.4.5-35). TSS levels near the bottom of the Delaware Bay normally range between 450 and 525 mg/L during the flood and ebb periods in the tidal cycle (Reference 2.4.5-5). Therefore, TSS levels immediately after the storm could reach 5000 mg/L, ten times greater than the normal level of approximately 500 mg/L. Since current velocities are higher in the river channel near the new plant than would generally occur throughout Delaware Bay, net erosion is more likely to occur than net deposition. Since the intake structure would be protected from erosion, net deposition could occur immediately around the intake structure. Calculations based on the assumption that 5000 mg/L of total suspended solids deposit shortly after the passage of the hurricane indicate that deposition is not expected to exceed 2 in. of sediment.

The effect of the PMH surge on sediment deposition and erosion is not expected to adversely affect operation of safety-related SSC.

2.4.5.8 Seiche and Resonance

Seiche is an extreme sloshing of an enclosed or partially enclosed body of water excited by meteorological causes (e.g., barometric fluctuations, storm surges, and variable winds), interaction of wave trains with geometry and bathymetry of the water body (e.g., from tsunamis), and seismic causes (e.g., a local seismic displacement resulting in sloshing of the water body).

Seiche motion can be complex in water bodies with variable width and depth. The simplest seiche motion in an estuary like Delaware Bay causes the largest water level fluctuations at the head of tide (near Trenton, NJ) while water levels are relatively constant at the mouth of the bay. This type of seiche is called the fundamental mode (Reference 2.4.5-27). The free oscillation period of the fundamental mode seiche propagating along the length of the Delaware Estuary from its mouth at RM 0 to the head of tide at Trenton (RM 134) is 31 hrs.

Shorter length seiche waves (with shorter oscillation periods) are possible. The effect of winds blowing along the axis of Delaware Bay (northwest-southeast) may excite a seiche within Delaware Bay, but with little effect on the upper estuary, due to the change in orientation of the river in the upper estuary (more nearly northeast-southwest) and less surface area for the wind to act on. Therefore, winds from the northwest tend to excite a shorter length wave with greater effect in Delaware Bay and less effect in the upper estuary. Fluctuations in the strength of northwest winds could generate seiche waves of the second mode, which have a period of 10 hrs. (Reference 2.4.5-27).

Researchers have observed water level fluctuations in Delaware Bay that have lower frequency than tides, which are semidiurnal (indicating 12-hour periods). Water level fluctuations that have lower frequency than tides are referred to as subtidal. The magnitude of such subtidal oscillations observed by these researchers at the new plant location was less than 2 ft. Researchers further determined that these water level fluctuations are associated with wind forces of two types. The first type is direct wind stress on the surface of Delaware Bay, while the second is an indirect forcing associated with wind stress fluctuations over the Atlantic Ocean. The fluctuations in wind stress are associated with fluctuations in water levels in the Delaware Bay at periods of more than 3 days. Together, these direct and indirect wind stress fluctuations are associated with nearly all subtidal fluctuations of water surface elevations observed at Reedy Point, DE, 7 mi. from the new plant location. (References 2.4.5-36 and 2.4.5-37)

From the observations reported, it can be seen that the atmospheric forcing, associated with seiche motion in Delaware Bay, occurs with longer periods (more than 3 days) than the natural period of oscillation of the Delaware Estuary (30 hrs. or less). Therefore, Delaware Bay does not resonate with the meteorologically-induced wave periods. This lack of resonance contributes to the relatively small magnitude of seiche motion in Delaware Bay.

The Delaware Bay also would not resonate with seismic activity. Seismic waves have a period of 1 hr. or less (Reference 2.4.5-25). Subsection 2.4.6 documents the effect of tsunami-induced seiche motion in Delaware Bay, showing that the magnitudes of water level fluctuations are too small to affect safety-related SSC.

Due to the lack of resonance with identified forcing functions, as well as observational evidence of the relatively small magnitude of seiche motions, potential seiche waves produce much smaller flood levels than the PMH surge.

2.4.5.9 References

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Table 2.4.5-1
Resulting Water Elevations at the PSEG Site (RM 52)[(a)(b)(c)(d)]

Model Time Step (hr.)	Hurricane Surge Stillwater Level (ft. NAVD)	Wave Runup (ft.)	Hurricane Surge with Wave Runup (ft. NAVD)	Sea Level Rise (ft.)	PMH Surge Maximum Water Surface Elevation (ft. NAVD)
20.5	26.9	12.8	39.7	1.35	41.1
21.0	26.7	14.3	41.0	1.35	42.4

a) PMH surge results include coincident 10 percent exceedance high tide.
b) PMH surge SWL occurs one-half hour earlier than the PMH surge maximum water surface elevation, and is equal to 26.9 ft. NAVD.
c) Calculations are performed using more significant figures than shown in the Table, and the result is rounded to tenths of a ft. If intermediate results were rounded prior to addition the result would not be correct.
d) These results are based on the Bodine, HEC-RAS and Kamphuis model described in Subsection 2.4.5.2.

Table 2.4.5-2
Maximum Sustained Wind Speed (kt) for Multiple PMH Scenarios[a]

		Radius of Maximum Winds, R (NM)		
		11	**20**	**28**
Forward Speed, T (kt)	**42**	135	133	132
	34	133	131	130
	26	131	129	128

a) Each PMH evaluated in the above table exhibited a central pressure, p_0 = 26.65 inches of mercury; pressure drop, Δp = 3.5 inches of mercury; and track direction from 138 degrees (moving northwest). These parameters, and the ranges considered, represent the PMH that can affect the project site according to NOAA (Reference 2.4.5-18).

Table 2.4.5-3
Maximum Surge (ft. NAVD) for Multiple PMH Scenarios from Screening Simulations[a]

		Radius of Maximum Winds, R (NM)			
		11	**20**	**28**	**28**
		At Mouth of Delaware Bay (RM 0)			**At the Site (RM 52)**
Forward Speed, T (kt)	**42**	18.5	21.7	22.7	23.4
	34	18.4	21.2	22.1	25.3
	26	18.1	21.2	22.1	27.8

a) Each PMH evaluated in the above table exhibited a central pressure, p_0 = 26.65 inches of mercury; pressure drop, Δp = 3.5 inches of mercury; and track direction from 138 degrees (moving northwest). The tide is specified as static at the 10% exceedance high tide at the mouth of the Delaware Bay. Consequently these results cannot be compared with results presented in table 2.4.5-1 where a dynamic tide input is specified.

Table 2.4.5-4
PMH Storm Parameters and Maximum Total Water Surface Elevation

Storm Description	PMH Storm	ADCIRC Run #1	ADCIRC Run #2	ADCIRC Run #3
Modeling System	Bodine and HEC-RAS	ADCIRC	ADCIRC	ADCIRC
Central Pressure (mb)	902	902	902	902
Peripheral Pressure (mb)	1021	1021	1021	1021
Radius to Maximum Winds (NM)	28	28	28	28
Forward Speed (kt)	26	26	26	26
Storm Track Heading (deg. West of North)	42	42	42	42
Holland B Parameter	N/A[a]	1.1	1.1	1.1
Antecedent Water Level[b] (ft. NAVD)	Dynamic 10% Exceedance High Tide	0	1.35	5.85
Maximum SWL (ft. NAVD)	26.7	18.6	20.2	25.3
Wave Runup (ft.)	14.3	7.5	7.4	7.7
10% Exceedance High Tide (ft.)	N/A[d]	4.5	4.5	N/A[d]
Sea Level Rise (ft.)	1.35	1.35	N/A[d]	N/A[d]
Maximum Total Water Surface Elevation[c] (ft. NAVD)	42.4	32.0	32.1	33.0

a) The NOAA wind field model (Reference 2.4.5-18) does not use the Holland B parameter.
b) HEC-RAS is used to dynamically model the 10 percent exceedance high tide coincident with the PMH surge; whereas, the ADCIRC+SWAN model uses a static initial water surface elevation set to the elevations indicated in the table.
c) These values include the 10 percent exceedance high tide, wave runup and potential sea level rise.
d) This component of the maximum total WSEL is included in the antecedent water level for the corresponding simulation.

Table 2.4.5-5
Wave Runup Parameters and Results

Model Time Step (hr.)	Fetch Direction	Still WSEL (ft. NAVD)	Hs (ft.)	Wave Period (sec)	Hmax (ft.)	Surf Similarity Parameter	Wave Runup (ft.)
19.0	NE	9.3	7.2	4.0	4.6	1.40	5.8
19.5	ENE	15.4	9.5	4.7	7.9	1.25	8.8
20.0	ENE	23.3	11.7	5.1	11.8	1.11	11.7
20.5	E	26.9	13.1	5.3	12.8	1.11	12.8
21.0	ESE	26.7	14.7	5.6	14.4	1.10	14.3
21.5	ESE	25.7	14.0	5.5	14.1	1.10	13.9
22.0	ESE	24.4	13.3	5.4	13.1	1.12	13.2
22.5	ESE	22.9	11.5	5.1	12.1	1.11	12.1
23.0	ESE	21.5	9.9	4.9	11.2	1.10	11.1
23.5	ESE	19.5	8.6	4.7	9.8	1.12	9.9
24.0	S	17.0	9.0	4.5	12.8	0.95	11.0