Introduction

- Introductions

- Purpose of Meeting
  - Present methodology for performing ESP Flood Re-Analysis
    - RAI 67 Response Approach
    - JPM-OS Methodology
    - ADCIRC Storm Surge Model
  - Facilitate technical discussion with NRC staff
  - Discuss remaining actions for RAI #67 response
Agenda

- Background
- Discussion of JPM Approach
- Application of JPM at PSEG Site
- Selection of Storm Surge Model
  - FEMA Model Description
  - ADCIRC V&V Steps
  - Comparisons to FEMA Results
  - Refine FEMA ADCIRC Mesh
  - Validate Updated ADCIRC Model
RAI No. 67 Requested:

- PSEG provide an analysis of the PMH events using a conservative, current practice approach such as those predicted by a two-dimensional storm surge model (e.g., ADCIRC, FVCOM, SLOSH, other) with input from appropriate PMH scenarios and with resolution that captures the nuances of the bathymetry and topography near the project site. Note that, to account for wave-induced water level effects (wave setup), PSEG will likely need to couple a nearshore wave transformation model to a hydrodynamics model.
Background

- Original PSEG ESPA Storm Surge Analysis based on PMH Storm (NWS 23) modeled with Bodine storm surge model, coupled with HEC-RAS and the wind setup model of Kamphuis.

- JLD-ISG-12-06 states Bodine storm surge model recommended in RG 1.59 is not consistent with current state of knowledge.

- JLD-ISG-12-06 also provides the first NRC guidance on probabilistic storm surge analysis and points to NUREG/CR-7134.
JPM Approach and Application to the PSEG Site
Outline of JPM Development

- Approach to JPM for Tropical and Extratropical storms
  - Definition of Response Surface and storm probabilities
  - River discharge effects on surge probabilities
  - Analysis of the effects of tides on total depth probabilities

- Comparison to and consistency with extrapolated FEMA results

- Incorporation of Epistemic and Aleatory Uncertainties

- Wind field generation
  - Definition and V&V for tropical wind fields
  - Definition of Extratropical storm wind field characteristics and probabilities

- Independent Reviewer Selected (Dr. Jennifer L. Irish – Associate Professor, Virginia Tech)
For combined Extratropical and Tropical storms, we use the form:

\[ P_c(\eta) = 1 - (1 - P_{trop})(1 - P_{extrop}) \]

where \( P \) denotes an exceedance probability and the subscripts \( c \), \( trop \), and \( extrop \) refer to combined tropical and extratropical storm set.

Since, by definition \( P(\eta) = 1 - F(x) \) where \( F(\eta) \) is the cumulative distribution function, this is equal to

\[ 1 - F_c(\eta) = 1 - F_{trop}(\eta)F_{extrop}(\eta) \]
The cumulative distribution is defined via an integral over the storm parameters which influence surge generation (similar to Resio et al., 2012 – NUREG/CR-7134):

\[
F_c(\eta) = \int \cdots \int p(x_1, \ldots, x_n) H[\eta - \Lambda(x_1, \ldots, x_n)] dx_1 \cdots dx_2 \\
+ \int \cdots \int p(z_1, \ldots, z_m) H[\eta - \Lambda(z_1, \ldots, z_m)] dz_1 \cdots dz_2
\]

where the first integral represents contributions due to tropical storms and the second integral represents contributions due to extratropical storms, and

- \(x_1, \ldots, x_n\) are the \(n\) parameters influencing tropical surge generation;
- \(z_1, \ldots, z_m\) are the \(m\) parameters influencing extratropical surge generation;
- \(p\) is the multivariate probability function; and
- \(\Lambda\) is the model (system) which links the parameters to surge levels at each point of interest.
Our simulation domain will cover the probability range from $10^{-5}$ to $10^{-7}$.

Similar to earlier efforts, the primary parameters influencing extreme surges at this site include: landfall location, storm intensity and storm size.

The sensitivity to track angle is expected to be much larger than on the open coast.

Forward storm speed does not appear to have a pronounced influence on surge levels at the site.
Quantification of the Response Surface

- Relative Surge: Landfall

- Angle restricted to ±22.5 deg
- Size response similar to that of Resio et al., 2012.
- Surge increases monotonically with intensity
- Effects of tides and river discharge on water level probabilities are being investigated
Comparison to FEMA Region 3 Analysis

- FEMA analyses focused on 10 – 500 year range of return periods
- PSEG will focus on much longer return periods
- FEMA could neglect uncertainties in their analyses, given their range of applicability
- PSEG analyses cannot neglect uncertainty
- Modeling tools should be comparable

Figure 1.2. FEMA Region III unstructured modeling mesh, showing the overall modeling domain (left), and topographic detail within Region III (right).
- Period of record covered 1975 – 2009
- Cumulative Distribution Function defined using equivalent to Gumbel plotting position \( \frac{n}{N+1} \), where \( n \) is the rank and \( N \) is the total number of years included in the analysis.
Combined 100-year water levels are less than 3 m.
Combined 500-year water levels are less than 3.5 m.
The EST method also did not include epistemic or aleatory uncertainty.

- This will be included within the JPM analysis conducted for the PSEG Site.

Figure 2.22. 500-year return period scatter plot with error estimates at validation stations.
Modeling range depends on asymptotic surge response to parameters

**Functional dependence of the surge on forcing parameters as they become large-valued.**

\[ \zeta = \left( \frac{\rho_a}{\rho_w} \right) c_d V^2 \frac{L}{g} \int_0^1 h(x) \, dx \]

*Storm Intensity*

\[ \zeta = \chi_1 \Delta p \frac{L_s}{h_0 \phi_x} \psi_x \left( \frac{R}{L_s} \right) \]

*Storm Size*

\[ \psi_x \left( \frac{R}{L_s} \right) = \left( \frac{R}{L_s} \right) \text{ when } \left( \frac{R}{L_s} \right) \leq 1 \]

\[ \psi_x \left( \frac{R}{L_s} \right) = 1 \text{ when } \left( \frac{R}{L_s} \right) > 1 \]

\[ \zeta = \chi_1 \Delta p \frac{L_s}{h_0 \phi_x} \psi_x \left( \frac{R}{L_s} \right) \psi_x \left( \frac{t_s}{t_\infty} \right) \]

*Storm Forward Speed*

\[ \psi_x \left( \frac{t_s}{t_\infty} \right) = \left( \frac{t_s}{t_\infty} \right) \text{ when } \left( \frac{t_s}{t_\infty} \right) \leq 1 \]

\[ \psi_x \left( \frac{t_s}{t_\infty} \right) = 1 \text{ when } \left( \frac{t_s}{t_\infty} \right) > 1 \]

If we focus on the “tail” of the distribution, we see that some physical limits appear.
The epistemic uncertainty is added via:

\[ F_c(\eta) = \int \ldots \int p(x_1, \ldots, x_n, \varepsilon) H[\eta - \Lambda(x_1, \ldots, x_n) + \varepsilon] dx_1 \ldots dx_2 \]

\[ + \int \ldots \int p(z_1, \ldots, z_m) H[\eta - \Lambda(z_1, \ldots, z_n)] dz_1 \ldots dz_2 \]

where

\( \varepsilon \) is the random uncertainty term, assumed to follow a Normal distribution with a mean of zero and a standard deviation given by the sum of a number of error contributions

\[ \sigma^2_{total} = \sigma^2_{tide} + \sigma^2_{model} + \sigma^2_B + \sigma^2_{waves} + \sigma^2_{winds} + \sigma^2_{residual} + \sigma^2_{sampling} \]

Epistemic uncertainty

Aleatory uncertainty

Has a different form than epistemic
Aleatory uncertainty becomes very large at large return periods

Uncertainty in an estimate is very difficult to estimate without some assumptions regarding parent distributions and the “effective” number of samples (which depends on the autocorrelation attributes of the phenomenon). For extremes, the overall characteristics tend to vary as a function of the return period and the number of samples.

\[ S_x \sim \phi \left( \frac{T}{\sqrt{N}} \right), \text{ where } S_x \text{ is the rms of the Gaussian uncertainty band} \]

For a Gumbel Distribution, with a distributional rms of \( S \)

\[ S_x \sim S \sqrt{\frac{1.100 y^2 + 1.1396 y + 1}{N}}, \text{ for large } T \ y \approx \ln(T) - \frac{T}{2} \]

Unfortunately, this makes the estimation of very-low-probability events very uncertain. For hurricane surges the typical rms value of the uncertainty is in the 10% range for the 100-year return period (assuming a Gumbel Distribution).

For very low frequencies (very large \( T \)), the confidence limits become much larger than the predicted surge values.
Using standard form for CDF and return period, we can develop a continuous estimate for central pressures from Table 7 in the report.

\[ a) \quad F'(x) = \exp \left\{-\exp \left[-\left(\frac{x-a_0}{a_1}\right)\right]\right\} \quad x = 1013 - c_p, \]

where
\[ a_0 = 31.7 \] and \[ a_1 = 12.34 \]

\( F'(x) \) is the best fit to the data not adjusted to an annual basis

and the Poisson-Gumbel Distribution for return period is:

\[ b) \quad T_r = \frac{1}{\lambda [1 - F'(x)]} \]

where
\[ \lambda \] is the annual frequency (= 16/280)

[Note: 280 = 70 × 4 adjusts for size differential in sample] and;

\( T_r \) is the return period in years; which yields for the annualized CDF, \( F(\eta) \):

\[ c) \quad F(x) = 1 - \frac{1}{\lambda T_r}. \]
Inclusion of Aleatory risk can be accomplished by incorporating the effect of sampling uncertainty on the input parameters to the JPM.

Examples here are for central pressures.

\[
p(x) = \int_{0}^{\infty} \int_{-\infty}^{\infty} p[\hat{x}(T_r) + \varepsilon | \hat{x}] p(\hat{x}) p(\varepsilon) \delta(\hat{x} + \varepsilon - x) d\varepsilon d\hat{x}(T_r)
\]

where
\[
\hat{x}(T_r)
\]
denotes the deterministic estimate of \( x \) for a given return period and \( \varepsilon \) denotes the deviation from the the deterministic surge estimate.
Aleatory Impact on Encounter probabilities of central pressures

Estimated return periods with and without uncertainty:
Case 1&2: deterministic and delta function approximation
Case 3: estimated standard deviations divided by 2
Case 4: estimated standard deviations

Study Area

1
Estimated return periods with and without uncertainty:

Case 1&2: deterministic and delta function approximation
Case 3: estimated standard deviations divided by 2
Case 4: estimated standard deviations
Wind fields will be generated using models consistent with recent FEMA and USACE surge studies.

V&V will include comparisons of radial wind profiles, maximum winds, and wind angles within storms.

Extratropical storms will include storms which have transitioned from tropical origins to extratropical form.
Summary of JPM approach for PSEG Site

- JPM method used for tropical storms is equivalent to those used in previous USACE, FEMA, and NRC studies.
- Very-low probability surges from extratropical storms will likely be dominated by tropical systems that have transitioned to extratropical form and by well-defined storms of extratropical origin.
- Definition of combined tropical and extratropical surge probabilities is straightforward.
- Wind field methodologies are well-tested.
- Incorporation of uncertainty will be performed using previously tested and published methods.
Selection of Storm Surge Model
Storm Surge Model Selection

- JLD-ISG-12-06 describes ADCIRC as a current state of the art storm surge model.

- JLD-ISG-12-06 also describes SWAN (Simulating Waves Nearshore) as a capable model for analyzing wave conditions.

- FEMA Region III Storm Surge Study using ADCIRC w/SWAN
Overview of FEMA Region III Risk Assessment Analysis
**FEMA Study**

- Region III (includes Delaware Bay)
- Corps of Engineers were the technical lead
- Model system to assess storm surge risk
- Developed a high resolution ADCIRC mesh
- 10-, 50-, 100- and 500-yr flood levels
- Used the same ADCIRC+SWAN model system that is being applied to the ESP Flood Re-analysis

Source: U.S. Army Corps of Engineers, ERDC/CHL TR-13-XX, Submission No. 2
**Advanced Circulation, Two-Dimensional Depth-Integrated (ADCIRC-2DDI) model**

- Long-wave, coastal and ocean circulation model
- Finite element based
- Simulates astronomic tides and hurricane storm surge
- Can include wave influences through coupling with SWAN
- Both ADCIRC and SWAN are in the current ISG as recommended modeling tools for surge and waves
Study Region

Sources: ESRI, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors.
FEMA Region III ADCIRC Mesh

1,875,689 nodes
3,731,099 elements
FEMA Region III ADCIRC Mesh

Model Boundary

Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org and other contributors
ADCIRC Verification and Validation for the PSEG ESPA Flood Re-Analysis
Goal: To develop and document a state-of-the-art modeling tool that will support JPM-OS work now underway

Purpose A: Verify that the project computer platform produces the expected results

Purpose B: Verify that site specific modifications made to the storm surge model produce the expected results
ADCIRC V&V Steps

- Obtain ADCIRC mesh used in recent FEMA study for this region (Purpose A)
- Obtain input/output files from FEMA for a couple storm events to use for verification (Purpose A)
- Recreate FEMA results for the selected events using the project computer platform (Purpose A)
- Adjust ADCIRC mesh to incorporate PSEG site topography (Purpose B)
- Validate new PSEG ADCIRC mesh (Purpose B)
Stokes Advanced Research Computing Center at the University of Central Florida

- [http://webstokes.ist.ucf.edu/](http://webstokes.ist.ucf.edu/)
- ~16 trillion floating point operations per second
- 3100 total processing cores
- ~6 TB of RAM
- 144+ TB total storage
- RHEL 5.0-5.4 operating system (Linux environment)
Recreate FEMA Results Using the Project Computer Platform


**Simulation Process**

45-day Tidal Spinup

- Allows enough time for full tidal resonance to be achieved within the domain
- “Hotstart” file is created from this simulation to jump start the ensuing ADCIRC+SWAN simulation

Tides+Surge+Waves

- ADCIRC+SWAN code
- Event specific wind files used
Notes on Results

- Plots compare our results to the previous FEMA results to note any differences

- All results shown were produced using the ADCIRC+SWAN code
Validation Event

Hurricane Isabel

September 12, 2003 – September 20, 2003
# Hurricane Isabel Peak Water Level Comparison

<table>
<thead>
<tr>
<th>Location</th>
<th>NOAA Gage No.</th>
<th>Atkins Peak (ft)</th>
<th>FEMA Peak (ft)</th>
<th>Difference (%)</th>
<th>Difference (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship John Shoal</td>
<td>8537121</td>
<td>4.44</td>
<td>4.48</td>
<td>-0.89%</td>
<td>-0.48</td>
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<tr>
<td>Marcus Hook</td>
<td>8540433</td>
<td>5.65</td>
<td>5.69</td>
<td>-0.70%</td>
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<tr>
<td>Philadelphia</td>
<td>8545240</td>
<td>5.18</td>
<td>5.22</td>
<td>-0.77%</td>
<td>-0.48</td>
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<tr>
<td>Reedy Point</td>
<td>8551910</td>
<td>5.04</td>
<td>5.07</td>
<td>-0.59%</td>
<td>-0.36</td>
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<tr>
<td>Brandywine Shoal</td>
<td>8555889</td>
<td>4.05</td>
<td>4.01</td>
<td>0.99%</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Note: Peak water level elevations are referenced to the NAVD88 vertical datum.
Validation Event

Nor’easter Ida

November 10, 2009 – November 16, 2009
## Nor’easter Ida Peak Water Level Comparison

<table>
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</thead>
<tbody>
<tr>
<td>Ship John Shoal</td>
<td>8537121</td>
<td>5.35</td>
<td>5.34</td>
<td>0.19%</td>
<td>0.12</td>
</tr>
<tr>
<td>Marcus Hook</td>
<td>8540433</td>
<td>5.12</td>
<td>5.11</td>
<td>0.20%</td>
<td>0.12</td>
</tr>
<tr>
<td>Philadelphia</td>
<td>8545240</td>
<td>5.76</td>
<td>5.74</td>
<td>0.35%</td>
<td>0.24</td>
</tr>
<tr>
<td>Reedy Point</td>
<td>8551910</td>
<td>4.89</td>
<td>4.88</td>
<td>0.20%</td>
<td>0.12</td>
</tr>
<tr>
<td>Brandywine Shoal</td>
<td>8555889</td>
<td>5.50</td>
<td>5.49</td>
<td>0.18%</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Note: Peak water level elevations are referenced to the NAVD88 vertical datum.
Our modeling platform produces similar results to the FEMA modeling platform.

Slight differences exist due to differences in compilers, changes in the ADCIRC code (they used version 49.60 whereas we are using 50.84), etc.
Refine and Update FEMA ADCIRC Mesh with Site Specific PSEG Topography Data
Construction Drawings
- Sea wall crest elevations
- Salem water intake topo
Updated PSEG ADCIRC Mesh
Validate Updated ADCIRC mesh with PSEG
Site Specific Topography Included
Validation Event

Hurricane Isabel

September 12, 2003 – September 20, 2003
~1 mile north

~1 mile west

~1 mile south
## Hurricane Isabel Peak Water Level Comparison

<table>
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<tr>
<th>Location</th>
<th>Post-Grid Modification Peak (ft)</th>
<th>Pre-Grid Modification Peak (ft)</th>
<th>Difference (%)</th>
<th>Difference (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Mile West</td>
<td>4.95</td>
<td>4.98</td>
<td>-0.59%</td>
<td>-0.35</td>
</tr>
<tr>
<td>One Mile South</td>
<td>4.92</td>
<td>4.96</td>
<td>-0.79%</td>
<td>-0.47</td>
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<tr>
<td>One Mile North</td>
<td>4.97</td>
<td>4.99</td>
<td>-0.46%</td>
<td>-0.28</td>
</tr>
</tbody>
</table>

Note: Peak water level elevations are referenced to the NAVD88 vertical datum.
Nor’easter Ida

November 10, 2009 – November 16, 2009
~1 mile north
~1 mile west
~1 mile south
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<th>Difference (%)</th>
<th>Difference (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Mile West</td>
<td>5.18</td>
<td>5.25</td>
<td>-1.31%</td>
<td>-0.83</td>
</tr>
<tr>
<td>One Mile South</td>
<td>5.20</td>
<td>5.28</td>
<td>-1.49%</td>
<td>-0.95</td>
</tr>
<tr>
<td>One Mile North</td>
<td>5.15</td>
<td>5.20</td>
<td>-0.95%</td>
<td>-0.59</td>
</tr>
</tbody>
</table>

Note: Peak water level elevations are referenced to the NAVD88 vertical datum.
Purpose B Conclusions

- Refined PSEG ADCIRC mesh produces results that are similar to FEMA’s results in Delaware Bay

- Model is ready for the JPM process
  - Currently in progress
  - Preliminary simulations are underway
Summary of RAI 67 Response Approach

- Use of JPM Approach – presented today

- Develop ADCIRC w/SWAN model that captures the nuances of the bathymetry and topography – presented today

- Refine PMSS parameters and develop synthetic storm set to determine the PMSS water level - Future

- Calculate Wave Run-up for PSEG Site - Future
<table>
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<tr>
<th>Event</th>
<th>Date</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>NRC Public Meeting</td>
<td>7/1/2013</td>
<td>Today</td>
</tr>
<tr>
<td>NRC Public Meeting</td>
<td>9/24/2013</td>
<td>On Schedule</td>
</tr>
<tr>
<td>Submit Revised SSAR Subsection 2.4.5</td>
<td>10/31/2013</td>
<td>On Schedule</td>
</tr>
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</table>
Discussion and Questions

- Thank You

- Open for discussion and questions