Efficient Methods for Storm Surge Hazard/Risk Estimation

Don Resio, Senior Scientist, ERDC-CHL

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Two Major Types of Data Needs

**Forecasts:**

- **Go/No-Go Evacuation Decision**
  - long lead time (3-5 days)
  - must be conservative
  - uncertainty “factored in”

- **Storm-Approach Operations**
  - time-phased information
  - late evacuation routing
  - gate/spillway decisions
  - uncertainty quantified

- **Post-Storm Operations**
  - time-phased information
  - accurate damage assessment
  - accurate systems assessment
  - critical recovery decisions

**Planning/Risk Mitigation:**

- **Accurate Hazard Climatology**
  - consistent data set
  - long period of record
  - uncertainty quantified
  - climatic variability

- **Accurate Response Specification**
  - human response
  - system response

- **Quantified Risk/Alternatives**
  - time-phased options ****
  - climatic variability
  - uncertainty quantified
  - Objective “cost” estimates

**Net Change:** We need more accurate information and uncertainty estimates – Reliance on “Status quo” methods can create problems.
Hurricane Surge Forecast Uncertainty

• Dominated by meteorological uncertainty

• Track predictions are improving

• Intensity predictions are not improving much (lack of understanding of physics)

• Surge models can have relatively large random deviations but should not underpredict surges
Hazard/Risk involves exceedance of thresholds:
Hurricane Gustav 2008 ---- need much higher accuracy than forecasts!!

New Orleans - IHNC
Three Modules Utilized For Typical River Risk Estimates

• Flooding frequency estimation (hazard exposure from measurements)

• Inundation estimation

• Damage estimation
Hurricane Risk in Coastal Areas Adds Complexity Due to Modeling

- Long-term estimate/measurements of historical hurricane surges are questionable

- In surges flooding process is two dimensional rather than one dimensional

- Processes forcing surges are multi-dimensional
Non-stationarity in the historical record. Highest surge level (feet)

<table>
<thead>
<tr>
<th>Location</th>
<th>1800-1960</th>
<th>1960-2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biloxi</td>
<td>13</td>
<td>27</td>
</tr>
<tr>
<td>Bay St Louis</td>
<td>11.8</td>
<td>25</td>
</tr>
<tr>
<td>Shell Beach</td>
<td>11.2</td>
<td>18.2</td>
</tr>
</tbody>
</table>

Climate change?
Changes in the physical system?
Sampling variability?
Hurricane Surge Hazards: An Historical Perspective

• Design Storm Approach
  – Standard Project Hurricane
  – Probably Maximum Hurricane

• Statistical Approach Based only on Historical Storms
  – More computations than SPH/PMH
  – Typically about 20 storms (but only a few truly local)

• Joint Probability Method
  – Computationally cumbersome
  – Multivariate probabilities difficult to specify

• Joint Probability Method – Optimal Sampling
  – Attempts to retain the accuracy of the JPM with less storms simulated
Non-event asymptotic form will not contribute significantly to flooding at Katrina level.

Example of problem with approach based only on historical storms:

- Estimate based on Poisson frequency and CDF
- Addition of 1 storm creates a very large deviation in the 100-yr surge level. From over 1000 years to about 100 years and if we use less years in our record it could be the 65-year storm or less.

LOG Return Period Plot of ADCIRC Results

Lake Ponchartrain Point 1
Some Key Modeling Issues

• Forcing – How much fidelity do we have??
  – Winds + Waves or just Winds
  – River Discharge (recently added to modeling suite)
    – Barrier Erosion (needed but not well modeled)

• Boundary Conditions – Is our current method for coupling interior/exterior polder flooding adequate?

• Resolution – what scales must be resolved for processes and factors influencing response

• Coupling – Appears to be a critical efficiency issue
Some Key Statistical Issues

• Model results must be unbiased

• Need to understand the trade-off between improved modeling of a single storm and the information (dimensions) needed to model an entire storm population
  – Original JPM: constant intensity, size, speed, track
  – Revised JPM: variable intensity, size, Holland B constant speed and track

• Objective, non-storm-specific calibration methods are essential to quantification of inherent uncertainty

• All aspects of uncertainty need to be quantified and incorporated into hazard and risk levels
Winds are Primary Driver of Waves and Surge

- Best-estimate winds have far too many degrees of freedom to be effectively used in JPM
- Comparisons between blended best-estimates winds and the PBL-generated snapshots indicate that the PBL approach captures much of the storm structure (good for forecasting!!)
- Must allow storm variation during approach to land

Reconstructed Winds, 1200 UTC 29 Aug 2005

Comparison of “best” winds to PBL winds for Katrina
Along E-W radials  (OWI = blended “best” winds)

Comparison of “best” winds to PBL winds for Betsy
Along N-S radials  (best = blended “best” winds)
National Hurricane Center has now supplemented USACE-FEMA pre-landfall decay patterns with analysis of decay in 12-hour interval before landfall. 

Example of data showing the consistent decay of storm intensity during approach to coast. Old JPM underestimated offshore intensities due to this.
On steep slopes, waves become the dominant surge generator. This includes local scale near levees. Examples: reefed islands and many rocky coastlines. About 30% of total surge during Hurricane Opal in Panama City.

Upper and lower limits of typical wave model contributions to total surge – **not a universal constant** - cannot be simply “factored out.”

On very shallow slopes, wave setup is still important. Added about 2-4 feet of surge in Hurricane Katrina.
Schematic depiction of 5-parameter JPM probability space. The solid line on the graph to the right represents the resulting cumulative distribution function for a hypothetical site. The dashed line gives an example of a upper bound confidence limit for surges at this site.
In any dimension we have for the pdf the ability to map from an n-dimensional space into a 1-dimensional space via a Dirac delta-function $\delta$,

$$p(\eta) = \iiint p(x_1, x_2, ..., x_n) \delta[\Psi(x_1, x_2, ..., x_n) - \eta] dx_1 ... dx_n$$

$x_i$ is a parameter affecting hurricane surge levels

$p(.)$ is the pdf

$\eta$ is the surge level

$\Psi$ is an analytical operator (modeling system) that converts a specific set of values of $x_i$ to a surge

And the CDF which uses the Heaviside Function (an integral of the delta function)

$$F(\eta) = \int ... \int p(x_1, x_2, ..., x_n) H[\eta - \Psi(x_1, x_2, ..., x_n)] dx_1 dx_2 ... dx_n$$
Since we remain imperfect, we need to consider an error term also!!!!

\[ F(\eta) = \int \cdots \int p(x_1, x_2, \ldots, x_n, \varepsilon) H[\eta - \Psi(x_1, x_2, \ldots, x_n) + \varepsilon] dx_1 dx_2 \cdots dx_n d\varepsilon \]

\( \varepsilon \) is the uncertainty in the surge level from the modeling

This means that we can leave some degree of randomness in our solutions – as long as we can estimate the statistical characterization of this term – which also includes tides, wind field errors, errors in physics, other omissions, etc.

The expected return period can be estimated from the CDF via the assumption that the storm occurrence is governed by a stationary Poisson process, with an average frequency of occurrence of \( \lambda \).

\[ T(\eta) = \frac{1}{\lambda \left[1 - F(\eta)\right]} \]

Unfortunately, nature often deviates from this simplistic assumptions – with years containing many storms not following the same distribution as years with few storms
Schematic depiction of 5-parameter JPM probability space. The solid line on the graph to the right represents the resulting cumulative distribution function for a hypothetical site. The dashed line gives an example of a upper bound confidence limit for surges at this site. The horizontal line at the location of the red dot now indicates that now part of the probability in each of the small cubes is distributed into different surge bins.
Years with < 4 storms in Gulf of Mexico

Years with ≥ 4 storms in Gulf of Mexico

NOTE: Over a 30 mb difference at 100 year return period!
PBL based probability space:

\[
F(\eta) = \int \ldots \int p(c_p, R_p, v_f, \theta_t, x, B) p(\varepsilon) H[\eta - \Psi(x_1, x_2, \ldots, x_n) + \varepsilon] dx_1 dx_2 \ldots dx_n d \varepsilon
\]

After moving random B variations into “error” terms

\[
F(\eta) = \int \ldots \int p(c_p, R_p, v_f, \theta_t, x) p(\varepsilon | \eta) H[\eta - \Psi(x_1, x_2, \ldots, x_n) + \varepsilon] dx_1 dx_2 \ldots dx_n d \varepsilon
\]

Some terms inside of “error” term even without wave set-up contribution:

1) tides,
2) random variations in B,
3) track variations not captured in storm set,
4) model errors (including errors in bathymetry, errors in model physics, etc.), and
5) errors in wind fields due to neglect of variations not included in the PBL winds.
For the “primary” dimensions of intensity and radius to maximum wind

\[ \eta_{\text{max}}(x, y) = \phi_{k_{mn}}(\Delta p, R_p, x, y) \]

For alternative tracks/parameters

\[ \phi_{k_{mn}}(\Delta P, R_p, x, y) = \phi_{k_{0m0n}}(\Delta P, R_p, x, y) + \Psi_{k_{mn}} \]

where

The subscript "0" refers to the central speed and angle categories for a specific landfall location; and

\[ \Psi_{k_{mn}} = \frac{\partial \phi_{k_{mn}}(\Delta P, R_p, x, y)}{\partial v_f} \delta v_f + \frac{\partial \phi_{k_{mn}}(\Delta P, R_p, x, y)}{\partial \theta_i} \delta \theta_i \]

Important aspect is to cover the range of the parameters that affect the coast in a given area
Characteristic Form of Spatial Surge Response Functions (SRF)

Track A

\[ x' = \left( \frac{x - x_o}{R_p} \right) - \lambda - F(1 - R')H(1 - R') \]

\[ \zeta' = \frac{\gamma \zeta}{\Delta p} + m_x \Delta p \]

Track D
Effects of Variable River Discharges

- Variations in river discharge do not appear to affect the surge levels outside of the river much.
- Variations in river discharge affect the surge levels inside the river quite strongly.
- There is no single discharge that is the “right” discharge for a 100-year event.
- Similar to the situation for the multivariate probabilities of hurricane parameters, a particular surge in the river can be produced by a continuum of hurricanes and discharge values.
Impact at specific points along MS River

Table 3-1 Surge statistics based on original results with constant discharge and new method with variable discharge.

<table>
<thead>
<tr>
<th>Point ID</th>
<th>Location</th>
<th>Original approach with constant discharge</th>
<th>New results with effect of discharge variability included</th>
</tr>
</thead>
<tbody>
<tr>
<td>188</td>
<td>Bonnet Carry Spillway</td>
<td>13.5</td>
<td>17.1</td>
</tr>
<tr>
<td>186</td>
<td>New Orleans Int Airport</td>
<td>13.8</td>
<td>17.4</td>
</tr>
<tr>
<td>705</td>
<td>Carrollton Ave</td>
<td>14.0</td>
<td>16.6</td>
</tr>
<tr>
<td>183</td>
<td>Algiers Canal</td>
<td>14.2</td>
<td>16.1</td>
</tr>
<tr>
<td>182</td>
<td>Caernarvon Diversion</td>
<td>14.5</td>
<td>16.0</td>
</tr>
<tr>
<td>180</td>
<td>Hero Canal</td>
<td>15.9</td>
<td>15.9</td>
</tr>
</tbody>
</table>

Observed increase of 1.5 – 2.5 ft seems realistic based on stage-discharge relationships for New Orleans area.

Direction of River flow

Calibration of stage-discharge relationship
What about situations where we want to estimate a very extreme surge

• Some Examples
  – Nuclear power plants in coastal regions
  – Subway systems exposed to flooding
  – Areas which affect primary fresh water supplies

• How can we do this and include the effects of uncertainty
  – Modeling uncertainty
  – Statistical uncertainty
  – Climate uncertainty
Functional dependence of the surge on forcing parameters as they become large-valued.

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

**Storm Intensity**

\[ \zeta = \chi_1 \Delta p \frac{L_s}{h_s \phi_s} \psi_x \left( \frac{R}{L_s} \right) \quad \psi_x \left( \frac{R}{L_s} \right) = \left( \frac{R}{L_s} \right) \quad \text{when} \quad \left( \frac{R}{L_s} \right) \leq 1 \]

**Storm Size**

\[ \zeta = \chi_1 \Delta p \frac{L_s}{h_s \phi_s} \psi_x \left( \frac{R}{L_s} \right) \psi_t \left( \frac{t_s}{t_\infty} \right) \quad \psi_t \left( \frac{t_s}{t_\infty} \right) = \left( \frac{t_s}{t_\infty} \right) \quad \text{when} \quad \left( \frac{t_s}{t_\infty} \right) \leq 1 \]

**Storm Forward Speed**

If we focus on the “tail” of the distribution, we see that some physical limits appear.
So how large are the different contributions to the overall uncertainty?

\[ \text{PMSS} = \text{PMSS}_{\text{deterministic}} + \text{Uncertainty}_{\text{MPI+Models}} + \text{Uncertainty}_{\text{Climate}} + \text{Tidal Effects} \]

For our site (feet):

\[ 35.75 = 30.11 + 4.04 + 1.2 + 0.4 \]

+ Sea Level Rise (1 to ?? feet)

Main contributions were:

- Modeling random errors \( \text{rms} = 2.0 \text{ feet} \)
- Estimation of error in MPI \( \text{rms} = 0.5 \text{ feet} \)
- Climatic effects of storms \( \text{rms} = 0.5 \text{ feet} \)
- Sea level rise \( \text{rms} \) unknown?
Engineering Trade Off’s??

Decisions to have
- higher levees south of N.O.
- river flow channelized south of N.O.
- Navigation canal into the IHNC from east
- Blockage of flow into Lake Pontchartrain

Can make differences of 2-5 feet in local 100-year surge levels.
Conclusions:

Tools for hurricane surge hazard/risk (including uncertainty) are improving – still need work

Suppressing variation in factors that contribute to surge under-predicts hazard/risk

Anthropogenic factor have large impact on hazards/risks

“A model should be as simple as possible … but no simpler”

A. Einstein

Extreme events often transcend the empirical calibration basis of operational models = need the right physics!
The Future:

CLIMATE MODELS: GLOBAL & VERY LONG TERM

STORMS: DOWNSCALING RANGE OF SCALES

SURGE AND WAVE RESPONSE TO STORMS

IMPLICATIONS FOR DESIGN AND PLANNING DECISIONS

QUESTIONS???