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Moving Forward: Next Steps for Confronting Increased Flood Risks

Molly Mitchell
Virginia Institute of Marine Science
Moving Forward: Next Steps for Confronting Increased Flood Risks

Hampton Roads Sea Level Rise/Flooding Adaptation Forum

Oct 2, 2013
Norfolk, VA

Molly Mitchell
Multilayered Flood Protection & Flexible Adaptation

Layer 1 = Prevention

Layer 2 = Spatial Development

Layer 3 = Disaster Management

Adaptable because:
• Timing can be changed
• Can switch between options
• Structures designed to be upgraded
• Land planning includes potential future uses
• Considers new infrastructure planning

Monitor 10 indicators: MSL, peak surge tide level, conditions of flood defense structures, developed area, intertidal habitat, etc.
• **Assessment of vulnerability** to climate change
• Summary of considerations used to set priorities and select actions
  • Planning typically requires some narrowing of the scope to focus efforts on areas or resources that are most at risk, have the greatest chance of success
• Key considerations:
  • Timing of projected impacts (e.g., short-term, mid-term, long-term) relative to the timing of management decisions and actions.
  • Probability of occurrence of different impacts.
• Description of specific adaptation actions for implementation
• Plan for communicating with stakeholders and decision makers
• Plan for monitoring and evaluating results.


<table>
<thead>
<tr>
<th>Areal type</th>
<th>Frequency of flooding, years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1: Areas that tolerate frequent flooding: coastal parks, promenades</td>
<td>5-10</td>
</tr>
<tr>
<td>Type 2: Areas with limited damage: sports facilities, roads</td>
<td>20</td>
</tr>
<tr>
<td>Type 3: Areas that can tolerate some flooding: marinas, roads</td>
<td>50</td>
</tr>
<tr>
<td>Type 4: Houses</td>
<td>100</td>
</tr>
<tr>
<td>Type 5: Areas that do not tolerate flooding: Metro</td>
<td>10,000</td>
</tr>
</tbody>
</table>

1. Identify problem and objectives
2. Establish decision-making criteria, receptors, exposure units and risk assessment endpoints
3. Assess risk
   - Risk prioritisation
   - TIER 1: Risk screening
   - TIER 2: Generic quantitative risk assessment
   - TIER 3: Detailed quantitative risk assessment
4. Identify options
5. Appraise options
6. Make decision
7. Implement decision
8. Monitor
Creating the topographic surface

- LIDAR data was acquired from VGEN and individual localities
- Source data was processed into consistent datum's & units
- Data were projected into Virginia State Plane HARN with units of feet (for end users)
- MHW (from NOAA) was used as the shoreline boundary
- Land elevations were referenced to MHW using Vdatum
- “Filling” was used to remove isolated, land-locked low spots
Generating the flood levels

- Used the raster calculator tool to extract all raster cells below given elevation levels
- These raster cells are the different “lifetime” coverages
- A raster collection called a mosaic dataset was created for each timeframe

The web applications were developed in Microsoft Visual Studio 2010 Professional and Microsoft Expression Blend 4 and run in a Silverlight framework
The slider moves forward in time from 2012- 2112 in 10 year increments.
Press the solid arrow to see an animated time progression.
Areas inundated constantly or by daily tides

These are areas that (in the absence of protection) will be underwater.
Storm surge zone. Shows how many years until inundation.

These areas are vulnerable to storm surge. Adaptations for flooding should be considered. Areas that are more red, will shortly be inundated. Protection strategies or retreat actions should be considered.
These areas are currently safe (except from extreme storms); however, the green areas will shortly be in the storm surge zone. These areas should be considered for management and accommodation strategies.
Sea Level Rise - City of Virginia Beach

To zoom in, press and hold Shift key and click and drag left mouse key to define a zoom box.
To zoom out, press and hold the Ctrl and Shift keys and click and drag left mouse key to define a zoom box.
SLR Demonstration

Sea Level Rise - City of Virginia Beach

Historic
Low
High
Highest

To zoom in, press and hold Shift key and click and drag left mouse key to define a zoom box.
To zoom out, press and hold the Ctrl and Shift keys and click and drag left mouse key to define a zoom box.
SLR Demonstration

Sea Level Rise - City of Virginia Beach

Historic

Low

High

Highest

Click arrows for time change
2072

Lifetime Zones

Inundated

Zone 2 (0-7 ft)

0-10 years
10-20 years
20-30 years
30-40 years
40-50 years
50-60 years
60-70 years
70-80 years
80-90 years
90-100 years

Zone 3 (> 7 ft)

0-10 years
10-20 years
20-30 years
30-40 years
40-50 years
50-60 years
60-70 years
70-80 years
80-90 years
90-100 years

To zoom in, press and hold Shift key and click and drag left mouse key to define a zoom box.
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SLR Demonstration

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SLR Demonstration

Sea Level Rise - City of Virginia Beach

Historic

Low

High

Highest

Click arrows for time change

2112

Lifetime Zones

- Inundated
- Zone 2 (0-7 ft)
  - 0-10 years
  - 10-20 years
  - 20-30 years
  - 30-40 years
  - 40-50 years
  - 50-60 years
  - 60-70 years
  - 70-80 years
  - 80-90 years
  - 90-100 years
- Zone 3 (> 7 ft)
  - 0-10 years
  - 10-20 years
  - 20-30 years
  - 30-40 years
  - 40-50 years
  - 50-60 years
  - 60-70 years
  - 70-80 years
  - 80-90 years
  - 90-100 years

To zoom in, press and hold Shift key and click and drag left mouse key to define a zoom box.
To zoom out, press and hold the Ctrl and Shift keys and click and drag left mouse key to define a zoom box.
This begins to answer the question of probability of flooding...

Next step: HAZUS-type analysis of impacts from flooding at different time scales
The risk of damage depends on the assets in the areas affected by flooding and can be assessed on the basis of land use. To assess the risk in those areas that may be subject to flooding, a calculation has been made of vulnerability based on the costs associated with damage at high waters.

Hot spot analysis – time series

• Look for clusters of areas where there is a nexus between probability of flooding and cost (impacts)

Clusters help prioritize areas for action
Can be done separately for storm surge risk and SLR risk

• Consider options – maybe test out the impact of some structures?
Target appropriate measures

Consider measures at all levels of planning.
Build in redundancy where necessary
Coordinated across multiple scales

<table>
<thead>
<tr>
<th>MEASURES</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure Geography</td>
<td>Reduce probability</td>
<td>Reduce scale</td>
<td>Reduce vulnerability</td>
</tr>
<tr>
<td>Region</td>
<td>Establishment of dikes</td>
<td>Establishment of warning system for high waters</td>
<td>Protection of vulnerable infrastructure, metro, S-trains, tunnels</td>
</tr>
<tr>
<td>Municipality</td>
<td>Establishment of dikes</td>
<td>Planning, warning</td>
<td>Planning, preparedness</td>
</tr>
<tr>
<td>District</td>
<td>Raised building elevation, dikes</td>
<td>Preparedness, sandbags etc.</td>
<td>Moving of vulnerable functions and installations</td>
</tr>
<tr>
<td>Street</td>
<td>Raised building elevation, dikes</td>
<td>Preparedness, sandbags etc.</td>
<td>Moving of vulnerable functions and installations</td>
</tr>
<tr>
<td>Building</td>
<td>Raised building elevation</td>
<td>Backwater valves, sealed basements, preparedness, sandbags etc.</td>
<td>Moving of vulnerable functions and installations</td>
</tr>
</tbody>
</table>
“Large Scale Storm Tide and Super-High Resolution Local Inundation Modeling for Hurricane Sandy”

Harry V. Wang\textsuperscript{1}, Derek Loftis\textsuperscript{1}, David Forrest\textsuperscript{1}, Aron Roland\textsuperscript{2} 
Zhuo Liu\textsuperscript{1} and Joseph Zhang\textsuperscript{1}

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College of William and Mary 
Gloucester Point, VA 23062 
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\textsuperscript{2}Institute of Hydraulic and Water Resources Engineering, Technische Universität, Darmstadt, Germany
Outline

• Large scale Storm tide modeling using unstructured grid model SELFE

• Linked with wind wave model WWM II

• Super-high resolution, local inundation modeling using ‘sub-grid’ for directly coupling with LIDAR data
Time step: 6 minutes

The model is forced at its open boundary by 8 tidal constituents: M2, S2, N2, O1, K1, Q1, P1, and K2

Winds: NOAA NCEP NARR (24km) and NAM (5km) wind fields; both every 3 hour interval
I. Large-scale Storm Tide modeling

The model used is SELFE (Semi-implicit, Eulerian-Lagrangian, Finite Element) http://www.ccalmr.ogi.edu/CORIE/modeling/SELFE/)

Key Features:

• Unstructured triangular grid in the horizontal dimension & hybrid SZ coordinates in the vertical dimension.

• Semi-implicit finite-element Eulerian-Lagrangian algorithm to solve the Navier-Stokes equations not constrained by CFL stability -> numerical efficiency.

• It is naturally incorporate simulation of wetting-and-drying process.

• Several related codes constitute an interdisciplinary modeling system that is growing organically around SELFE.
Friction formulation using Manning coefficient

Manning $n = 0.025$ everywhere except

(1) New York Harbor $n=0.010$

(2) East and Harlem Rivers $n = 0.045$
The Battery, NY

Water Level in MSL (m)

Days since Oct. 27, 2012

NOAA Observation
Model Result

The Battery, NY

y = 0.9713x + 0.1507
R² = 0.93053

Tide only

y = 1.5629x - 0.0347
R² = 0.96522
New Haven, CT

\[ y = 0.8269x + 0.1886 \]

\[ R^2 = 0.92919 \]
Benchmark for large scale SELFE model:

1. There are 208,029 nodes and 392,062 elements in the large scale SELFE storm tide model. It covers the domain along the US East Coast from Florida to Maine.

2. The finest grid resolution is about 75 m Inside the New York Harbor and 10 km further offshore. Given the efficiency of semi-implicit, Eulerian-lagrangian scheme the time step used was 6 minute for this application.

3. For tidal simulation, SELFE finished 30 days runs within 6 hours using 64 processors in Linux cluster – It translates to about 120:1 real time: CPU hour ratio. For storm tide, when wind fields were internally interpolated every 3 hour, the real time: CPU hour is 62:1. It translates to 30 minutes for ~30 hour forecast

4. The overall relative mean error for the storm tide prediction is around 5% - 8%, if the quality of wind field is adequate.
II. SELFE link with wind wave model

- WWM fully coupled to SELFE
  Callable as a routine
  Use same grid – efficiency

- Radiation stress formulations
  Longuet-Higgins and Stewart (2D)
  Xia (2004), Mellor (2003, 2008), Arduhin (VF formulations, in progress)
  Wave boundary layer - enhanced bottom stress
  Grant and Madsen formulation (1979, 1999, 2004)

- Numerical methods for the sub-program
  - Geographical space
    - Galerkin schemes (non-monotone, conservative, implicit)
    - Residual distribution schemes (monotone, conservative, higher order, explicit/implicit – parallelization of implicit scheme underway)
  - Source term integration
    - Semi-implicit (WAM) or (SWAN)
    - Dynamical (WWIII)
    - Runge-Kutta
  - Spectral space
    - Ultimate Quickest (explicit, 3rd order in space and time)
    - Crank-Nicholson (implicit, 2nd order in space and time)
    - Runge-Kutta WENO (explicit, 5th order in space, 3rd order in time)
For the Chesapeake Bay work, refer to:

A fully coupled 3D wave-current interaction model on unstructured grids

Aron Roland, Yinglong J. Zhang, Harry V. Wang, Yanqiu Meng, Yi-Cheng Teng, Vladimir Maderich, Igor Brovchenko, Mathieu Dutour-Sikiric, and Ulrich Zanke

Received 31 January 2012; revised 13 August 2012; accepted 21 August 2012; published 29 September 2012.

[1] We present a new modeling system for wave-current interaction based on unstructured grids and thus suitable for very large-scale high-resolution multiscale studies. The coupling between the 3D current model (SELFE) and the 3rd generation spectral wave model (WWM-II) is done at the source code level and the two models share same sub-domains in the parallel MPI implementation in order to ensure parallel efficiency and avoid interpolation. We demonstrate the accuracy, efficiency, stability and robustness of the coupled SELFE-WWM-II model with a suite of progressively challenging benchmarks with analytical solution, laboratory data, and field data. The coupled model is shown to be able to capture important physics of the wave-current interaction under very different scales and environmental conditions with excellent convergence properties even in complicated test cases. The challenges in simulating the 3D wave-induced effects are highlighted as well, where more research is warranted.

Figure 31: Model forecast tracks for Sandy at 0000 UTC 23 October (a), 000 UTC 24 October (b), 000 UTC October 25 (c), and 000 UTC 26 October, (d).

The ECMWF is in coral, the GFS ensemble in yellow, the GFS in cyan, and the TVCA model consensus is in red.
Preliminary recommendation from WWM II

• Wind wave is quite sensitive to the quality and resolution of the wind fields

• Collaborating with Germany who have the access to European ECMWF

• The long-term goal is to fully coupled wave, current and atmosphere model as it is now being developed in Germany putting COSMO (LM Atmosphere) into SELFE-WWMII.
III. High-resolution, sub-grid dynamic modeling

Fundamental Idea of “Subgrid Modeling”

- The availability of super computing power, solid and stable semi-implicit methods, structured or flexible unstructured grids, are useful tools but, alone, are still insufficient to faithfully account for complex topographic features.

- The availability of detailed bathymetry data within a coarse grid model can and should be used to further improve a model accuracy

The Key elements for the sub-grid modeling *Casulli and Sterlling (2011) are:

- A differential form of conveyance formulation implemented on a sub-grid scheme
- Nonlinear semi-implicit solver for surface elevation

High resolution, local inundation dynamic model on sub-grid scale

Base-Grid Nodes: 9,946
Base-Grid Cells: 9,663
Sub-Grid Cells: 3,865,200
High-resolution, sub-grid setup for Hurricane Sandy

- Open Boundary Forcing from NOAA Stations
  - West Boundary: Bergen Point, NY  NOAA Station #8519483
  - East Boundary: Kings Point, NY  NOAA Station #8516945
  - South Boundary: near Sandy Hook, NJ  NOAA Station #8531680

- Flux Boundary Forcing from USGS Station
  - North Boundary: Hudson River near Wappinger Falls
    USGS Station #01372500

- Model Setup for 10 days from 00:00, 10/25/2012 to 00:00, 11/04/2012

- Atmospheric pressure and wind data retrieved from Bergen Point, NY, at NOAA Station #8519483

- Runtime: 68 minutes on Dell Precision T-3500 Workstation
  with Intel Xeon W3670; Windows 7 64-bit OS; 24 GB RAM
Manhatten
NOAA Observation

Model Result

\[
y = 0.8973x \
R^2 = 0.9816
\]
USGS Rapid Deployment Gauge Comparison

USGS Gowanus Canal, Brooklyn KIN-003WL

- **Water Level above MSL (m)**
- **Days since 10/25/2012**

**USGS Observation**

**Model Result**

*Storm Tide Sensor*

SSS-NY-KIN-003WL
Gowanus Canal at Gowanus at Brooklyn, NY

**Status: approved**
**Status update: 2/7/2013 7:00 PM**

Kings County
storm tide
latitude: 40.68
longitude: -73.99
Peak storm tide elevation of 11.08 ft above NAVD88, recorded on 10/30/2012 1:04:30 AM GMT

Link to full data record
(If site symbol is outlined, data is available)

Zoom to
Video time
## Measure of Uncertainty

### East River, NY

<table>
<thead>
<tr>
<th>Survey Region</th>
<th>East River NY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-Predict (%)</td>
<td>3,357,069</td>
</tr>
<tr>
<td></td>
<td>17.00</td>
</tr>
<tr>
<td>Match (%)</td>
<td>14,180,524</td>
</tr>
<tr>
<td></td>
<td>71.81</td>
</tr>
<tr>
<td>Under-Predict (%)</td>
<td>2,211,023</td>
</tr>
<tr>
<td></td>
<td>11.20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>19,748,616</td>
</tr>
</tbody>
</table>
### Measure of Uncertainty

**Hudson River, NY**

<table>
<thead>
<tr>
<th>Survey Region</th>
<th>Hudson River NY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Over-Predict (%)</strong></td>
<td>1,234,304, 7.44</td>
</tr>
<tr>
<td><strong>Match (%)</strong></td>
<td>13,076,031, 78.80</td>
</tr>
<tr>
<td><strong>Under-Predict (%)</strong></td>
<td>2,283,797, 13.76</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>16,594,132</td>
</tr>
</tbody>
</table>
## Measurement of uncertainty

Hudson River, NJ

<table>
<thead>
<tr>
<th>Survey Region</th>
<th>Hudson River NJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-Predict (%)</td>
<td>1,922,727</td>
</tr>
<tr>
<td></td>
<td>8.41</td>
</tr>
<tr>
<td>Match (%)</td>
<td>17,539,367</td>
</tr>
<tr>
<td></td>
<td>76.73</td>
</tr>
<tr>
<td>Under-Predict (%)</td>
<td>3,397,304</td>
</tr>
<tr>
<td></td>
<td>14.86</td>
</tr>
<tr>
<td>Total</td>
<td>22,859,398</td>
</tr>
</tbody>
</table>
## Measure of Uncertainty (all areas)

<table>
<thead>
<tr>
<th>Survey Region</th>
<th>Match</th>
<th>(%)</th>
<th>Under-Predict</th>
<th>(%)</th>
<th>Over-Predict</th>
<th>(%)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>New York</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East River NY</td>
<td>14,180,524</td>
<td>71.81</td>
<td>2,211,023</td>
<td>11.20</td>
<td>3,357,069</td>
<td>17.00</td>
<td>19,748,616</td>
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<tr>
<td>Harlem River NY</td>
<td>4,457,765</td>
<td>70.34</td>
<td>918,108</td>
<td>14.49</td>
<td>961,151</td>
<td>15.17</td>
<td>6,337,024</td>
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<tr>
<td>Hudson River NY</td>
<td>13,076,031</td>
<td>78.80</td>
<td>2,283,797</td>
<td>13.76</td>
<td>1,234,304</td>
<td>7.44</td>
<td>16,594,132</td>
</tr>
<tr>
<td><strong>All New York</strong></td>
<td>31,714,320</td>
<td>74.31</td>
<td>5,412,928</td>
<td>12.68</td>
<td>5,552,524</td>
<td>13.01</td>
<td>42,679,772</td>
</tr>
<tr>
<td><strong>New Jersey</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hudson River NJ</td>
<td>17,539,367</td>
<td>76.73</td>
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<td>14.86</td>
<td>1,922,727</td>
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<td>1,922,727</td>
<td>8.41</td>
<td>22,859,398</td>
</tr>
<tr>
<td><strong>All Hudson River</strong></td>
<td>30,615,398</td>
<td>77.60</td>
<td>5,681,101</td>
<td>14.40</td>
<td>3,157,031</td>
<td>8.00</td>
<td>39,453,530</td>
</tr>
<tr>
<td><strong>Total Across Domain</strong></td>
<td>49,253,687</td>
<td>75.15</td>
<td>8,810,232</td>
<td>13.44</td>
<td>7,475,251</td>
<td>11.41</td>
<td>65,539,170</td>
</tr>
</tbody>
</table>
Summary

1. The capabilities of a suite of a large scale storm tide, wind wave, and high resolution, sub-grid inundation models were presented.

2. The large-scale storm tide and wind wave model covering the entire US East Coast is feasible for use in forecasting mode with efficient solver and moderate computing resources.
3. The high resolution, sub-grid model can incorporate LIDAR data directly without interpolation and was demonstrated to generate very accurate inundation results on a street-level scale, as demonstrate by the Hurricane Sandy application. The model can run on high-end PC.