COASTAL AND INLAND FLOODING SIMULATION FOR RESILIENCE OF NEARSHORE INFRASTRUCTURE: HURRICANE GEORGES IN EASTERN PUERTO RICO

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Lessons Learned and Best Practices: Resilience of Coastal Infrastructure, March 8-9, 2017
Agenda

- Resilience of Coastal Infrastructure
- Area of Interest
- Hydrologic Model
- Storm Surge Model
- Coupling Technique
- Results
- Conclusion
- Acknowledgment
- Questions

Arecibo Bridge collapse after the pass of hurricane Georges (from: http://ecoexploratorio.org/amenazas-naturales/inundaciones/que-son-las-inundaciones/)
Resilience of Coastal Infrastructure and Ecosystems
The risk of flooding has increased in most coastal regions of the United States and its island territories since 1900, and that risk is projected to grow even more this century.

Coastal lifelines, such as water and energy infrastructure, and nationally important assets, such as ports, tourism, and fishing sites, are increasingly vulnerable to sea level rise, storm surge, erosion, flooding, and related hazards. Socioeconomic disparities create uneven vulnerabilities.

https://toolkit.climate.gov/topics/coastal-flood-risk
Resilience of Coastal Infrastructure and Ecosystems

- Climate change will result in further reduction or loss of the services that coastal ecosystems provide, including potentially irreversible impacts.

- The combination of inland flooding and storm surge can worsen inland impacts.

- Tropical Storm Dennis dropped a lot of rain in eastern North Carolina in 1999. Right after that, Hurricane Floyd hit the same area. Floyd’s storm surge together with already swollen rivers from Dennis led to epic (500-year) flooding in places like the Tar/Pamlico River basin.
Clatsop County, Oregon

- Flooding associated with Ecola Creek, coupled with high tides, locally induced surges and large waves
- The processes cause Ecola Creek to back up, which leads to flooding in low-lying areas adjacent to the town, including the sanitary facilities located within the flood plain
- Stores and business establishments, public buildings, and residential properties are flooded. Water and sanitary facilities are damaged, creating a health hazard.
Hurricane Georges over Puerto Rico

- Puerto Rico (PR) is located in a zone susceptible to hurricane impacts.
- Puerto Rico has many communities near river mouths along the coastline.
- Tropical islands are vulnerable to simultaneous effects of storm surge plus inland flooding.

- Hurricane Georges (1998) was the second stronger hurricane during the 1998 season
- Caused 602 deaths in Dominican Republic and Haiti
- Reached a Category 4 hurricane (Sustained winds of 155 mph)
Resilience of Coastal Infrastructure

- Landed in the southeast coast of Puerto Rico on Sept. 21, 1998
- Crossed the Island from East to West
- Caused severe damage to infrastructure and agriculture
- Severe damage to coastal properties and severe coastal erosion
- Georges produced a total damaged of nearly $2Billion.

Reflectivity over Puerto Rico during Hurricane Georges at September 22, 1998 from 00:01:43 to 3:03:26 GMT. (from National Center for Environmental Information, NOAA)
Area of Interest
The AOI is located within Fajardo and Ceiba, east coast of PR.

Consist of four watersheds.

The total area of AOI is 19.7 km$^2$ (4,866 acres).

59% classified as Pastures and Shrubs, 27% as Forests and Woods, and 11% as Urban Develop.

Maximum storm surge of 10 feet was recorded near Fajardo, PR.

Cumulative rainfall at the AOI was close to 10 inches.
Hydrologic Model
Hydrologic Model: GSSHA

- Gridded Surface Subsurface Hydrologic Analysis (GSSHA) from U.S. Army Corps of Engineer.
  - Physically based, distributed-parameter, structured grid, two-dimension hydrologic model.
  - Simulates the hydrologic response of a watershed subject to given hydro-meteorological inputs.
- The Green and Ampt model was selected for simulating infiltration.
- Hydrologic routing was performed using the diffusive wave formulation.
- Required data for a hydrologic model: DEM, stream channel cross-section, land use cover map, soil type map, radar precipitation data, and Manning’s roughness surface coefficient.
Hydrologic Model Data

- Digital Elevation Model (DEM): 3D representation of a terrain's surface created from terrain elevation data.
  - DEM used 10-m of resolution.
  - Needed to delineate the watershed of any river system.
- Stream Channel Cross Section: obtained from LIDAR data.
  - Vertical accuracy of 18.6 cm
  - Spatial resolution of 1.0-m
  - Needed to perform the hydraulic routing.

DEM graphical representation for the Fajardo and Ceiba, PR
Hydrologic Model Data (cont.)

- Land Use Cover Map: obtained from the UPR-RP and the PRPB.
  - Since it is dated 2006, it was corrected to represent conditions back in 1998 by using aerial photos.
  - Needed to assign the surface roughness coefficient for overland flow.
- Soil Type Map: obtained from the USDA-NRCS and dated on 2004.
  - Hydraulic conductivity, soil texture, wilting point and initial moisture
  - Needed for simulating the infiltration process.

Legend
- Basin Boundary
- Land Use Cover
  - Forest and Woods
  - Urban Developments
  - Wetlands
  - Pasture and Shrubs
  - Beach

Land use cover within the area of interest for the 2006 conditions. The watershed boundaries are shown with a black solid line.
Radar Precipitation Data: obtained from the WSR-88D radar located in Jayuya, PR.

- The reflectivity depends on the strength of the returned signal.
- This reflectivity was converted to rainfall intensity using the Rosenfeld Tropical Equation.
- Essential for two-dimensional hydrologic models, since it provides the precipitation as a function of time and space.

Manning’s Surface Roughness Coefficients

- For the floodplains values varied between 0.050 and 0.460.
- For the stream bed values vary between 0.040 and 0.045.
- Used to estimate overland and channel flow resistance.
Storm Surge Model
Storm Surge Model

- Mesh includes detailed representation of reefs, sand banks, mangrove forests, and benthic habitat classifications.
- ADCIRC+SWAN computed a maximum water surface elevation of more than 1.5-m over mean sea level.
- Storm Surge penetrated inland significantly at some locations such as Ceiba.

Coupling Technique
Simulation from the storm surge model were executed first.

The sites of maximum storm surge inland penetration were identified along the coastline.

A spatial mesh with a resolution of 30-meters was created covering each focus site.

The vertices of each cell were assigned with a time series of water elevations.

This simulates the dynamics of the storm surge in the hydrologic model.

Storm surge mesh within the AOI for the coupled model. Each point represents a vertex of the mesh, where the point contains the water surface elevation time series from the storm surge model.
Results: Demajagua River Watershed
Results
Demajagua River Watershed

For the Maximum Flood Depth:

- For the surface runoff flooding **without** storm surge penetration: 1.75-1.50 meters.
- For the surface runoff flooding plus storm surge **with** storm surge penetration: 2.50-2.25 meters.

Maximum flood depth for the different flooding scenario at the Demajagua River watershed. Surface runoff flooding scenario (Top). Surface runoff plus storm surge flooding scenario (Bottom).
Results: Demajagua River Watershed (cont.)

Flood depth animation at the Demajagua River watershed for the surface runoff plus storm surge flooding scenario starting September at 21:23:00 UTC until September 23 at 2:06:34 UTC
Results: Demajagua River Watershed (cont.)

Discharge hydrograph for both flooding scenario and at different locations for the Demajagua River watershed. A) At 0-meters from the stream outlet. B) At 50-meters from the stream outlet. C) At 100-meters from the stream outlet.
Results: Demajagua River Watershed (cont.)

Table 1: Total volume produced by the two flooding scenarios for Demajagua River Watershed at different locations

<table>
<thead>
<tr>
<th>Location</th>
<th>SR+SS (m³)</th>
<th>SR only (m³)</th>
<th>SS Contr. (m³)</th>
<th>% SS Contr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-meters</td>
<td>475,984</td>
<td>342,830</td>
<td>133,154</td>
<td>27.97%</td>
</tr>
<tr>
<td>50-meters</td>
<td>323,560</td>
<td>252,182</td>
<td>71,378</td>
<td>22.06%</td>
</tr>
<tr>
<td>100-meters</td>
<td>317,716</td>
<td>242,926</td>
<td>74,791</td>
<td>23.54%</td>
</tr>
</tbody>
</table>

SR= Surface Runoff  
SS= Storm Surge
Conclusion
Conclusion

- Combination of storm surge and inland flash floods could aggravate coastal flooding producing hazardous conditions.

- Present storm surge maps do not take inland flooding into consideration.

- The net effect of the storm surge flood depends on the watershed conditions, the spatial and temporal distribution of rainfall and the local conditions of the river morphology near the coastline.

- A more realistic scenario is obtained when the combined effects of coastal storm surge plus inland runoff are both accounted for in a dynamic simulation.
Acknowledgment
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Question?