Next-Generation Flood Warning: Rapid Prototype Development

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Current warning systems cannot always accurately predict the effects of storm surges. A prototype system combines more capable models to help organizations visualize these effects and plan a response.

On August 29, 2005, two words that identified the worst natural disaster in our nation's history became indelibly etched in the memories of US citizens—Hurricane Katrina. The costliest and one of the most deadly, hurricanes ever, resulted in unprecedented devastation, not because of the storm surge alone, but because the Mississippi River and Gulf Outlet Canal had swelled to more than the levees could withstand.

This disaster underlines an important area in forecast modeling: Although atmospheric forecasting models can now pinpoint the harbingers of major storms as well as their movement and intensity, our ability to predict and visualize flooding remains limited. This is especially true for areas affected by both storm surge and increased downriver flow from heavy rain in the watershed—a combination that can endanger lives, shut down businesses, and cripple infrastructure, such as utilities.

The metropolitan Washington, DC, area, situated in the upper tidal region of the Potomac River, has long endured the effects of the river's upstream discharge and the storm surge from the Chesapeake Bay. The area's last major storm, the relatively weak Category 2 Hurricane Isabel, passed 100 miles west of Washington, where it dumped several inches of rain in the Shenandoah and Potomac watersheds to provide the discharge effect. Further, the orientation of Isabel's wind produced a 9-foot storm surge that coursed up the Potomac River and through Old Town Alexandria and neighboring communities. The combined surge and discharge effects caused more than $10 million in damage to 2,200

Inside Track

- The newest hydrodynamic models can give a picture of expected flooding rather than just water height at the shoreline. Combining them with higher resolution atmospheric models might yield more accurate flood predictions.
- The atmospheric model provides an order of magnitude greater resolution, and the unstructured grid of the hydrodynamic model accounts for the complex geometry of the Chesapeake Bay and its tributaries.
- The prototype combines upstream Potomac River discharge from rain in the watershed with storm surge moving upriver from the Chesapeake Bay to provide a prediction more accurate than with surge effects alone.
- The visualization methods are an improvement over current text message products and assist emergency managers in preparing for expected effects on critical infrastructure and public services.

homes and more than 60 businesses.[1] Figure 1 gives only a flavor of the devastation from such flooding. The sidebar "Why the Chesapeake Bay?" explains some of the contributing topographical dynamics.

The ultimate goal is to develop warning systems that can predict and visualize the impact of such catastrophic flooding events and help minimize storm-related disruptions. Emergency managers rely on the US National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) to predict the height and timing of storm surges from hurricanes and major storms. NWS forecasters currently apply a general hydrodynamic model to coastal waters and estuaries to estimate the water's likely height at the shoreline. Emergency managers then use this information to estimate what areas will flood, usually on the basis of past events.

This approach works fairly well for many areas, but there is room for improvement. The newest hydrodynamic models, for example, can project land inundation—what happens when the water actually flows over surrounding land. Consequently, these models can give a picture of expected flooding rather than just water height at the shoreline. A system that combines these capabilities with higher resolution atmospheric models might be able to predict flooding more accurately and assist federal, regional, and local agencies in better response planning.

To explore this possibility, in fall 2005, Mitretek Systems, the Virginia Institute of Marine Science, and NWS Forecast Offices in Wakefield and Sterling, Va., agreed to collaborate in achieving four objectives:

- Develop a prototype system that integrates high-resolution storm-surge and atmospheric wind models.
- Evaluate the prototype's ability to predict land inundation from storms in the Washington, DC, and the tidal Potomac River areas.
- Provide prediction results to emergency managers using emerging visualization technologies and show the value of improved methods.
- Document what it would take to make the prototype operational at NWS.

The result of this initial collaboration is a prototype system that can predict inundation and depict it using cutting-edge visualization techniques. We are presenting this system to emergency managers and other planners with the aim of evaluating and determining the effort needed to make it operational at NWS.

The power of two

The prototype system exploits the interrelationship of two models. One is an atmospheric model—a wind-field model—for the mid-Atlantic region, including the Chesapeake Bay and its tributaries. The output for that model serves as input to a hydrodynamic model of the Chesapeake Bay and the tidal Potomac River that includes land inundation.

Figure 1. Flooding in Old Town Alexandria on September 19, 2003. (Photo by Mark Young)

Wind-field model

The Chesapeake Bay's topography greatly influences many weather situations over the mid-Atlantic region. The finest resolution model now in use at the NOAA National Centers for Environmental Prediction (NCEP) for North America has a horizontal resolution of 12 km—not adequate to account for weather events that result from the localized effects of air, land, and water interaction induced by complex topography. To improve the forecasts of such events, NCEP needed a higher resolution model. One such model, officially released in May 2006, is the North American Mesoscale Weather Research and Forecasting (WRF) model. With some tailoring, this

Why the Chesapeake Bay?

It might seem unexpected to select the Potomac River to evaluate our prototype flood warning system, but hurricanes and northeasters have been impacting the area for generations. Metropolitan Washington, DC, is situated along the Potomac River, and the driving influence for flooding is the Chesapeake Bay—again seemingly innocuous with a tidal cycle averaging only 1 to 3 feet.[1] Indeed, storm effects are inconsequential for most of the year, but the potential energy in 18 trillion gallons of water in the nearly 200-mile-long Chesapeake Bay is poised to deliver unfathomable devastation along the bay's nearly 5,000 miles of coastline.[2] Hurricane Isabel, a relatively mild Category 2 hurricane when it made landfall on the North Carolina coast and weakened further as it moved through southern Virginia, produced an 8-foot storm surge in the Chesapeake Bay and Potomac River and destroyed more than 4,000 homes. A future stronger hurricane could magnify those totals to unprecedented levels.

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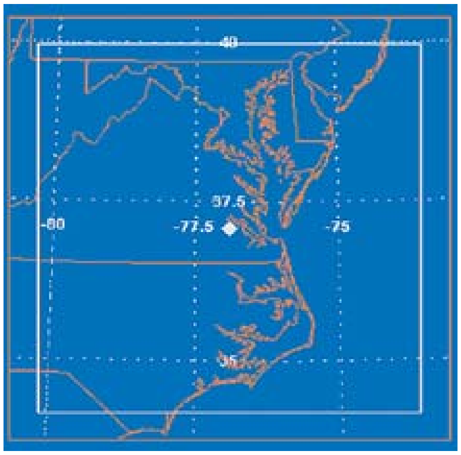

Figure 2. Model domain to account for geographic variability of the Chesapeake Bay and its tributaries. Without a sufficiently high resolution model, it is impossible to account for the localized effects of weather events.

system can run for any local area on a forecast office workstation.

As part of our collaborative project, the NWS Wakefield Office runs this model at approximately 4 km horizontal resolution—sufficient to provide details of the bay's influences on the weather. Figure 2 shows the domain for this local area. The initial fields come from a Local Area Prediction System (LAPS) analysis that incorporates all relevant observational data in Wakefield's Advanced Weather Interactive and Processing System. This data includes output from observational networks such as the Physical Oceanographic Real-Time System, road and weather information from the Virginia Department of Transportation, and numerous other local and regional mesonet data sets. With this broad spectrum of data, LAPS produces an improved detailed analysis for the region, which in turn helps the wind-field model improve its local forecast.

We are using the new wind-field model capability to provide more detail about tropical systems (such as hurricanes) and northeasters, which will improve the ability to detect local wind-field effects in tributaries and coastal regions.

High-resolution storm-surge model

How a storm surge impacts coastal regions depends on many factors, including the intensity of forcing (how forcefully the wind pushes the water), the storm's path, characteristics of the water body's floor (bathymetry), and the water body's shape and size. Because storm surge simulation frequently relies on numerical techniques,[2] an accurate simulation of coastal surge and inundation requires an adequate grid shape and high enough resolution to numerically identify and depict intertidal zones and their properties.

Meeting this requirement for the Chesapeake Bay is not trivial. Because the waterways comprise many tributaries and coastal basins, an accurate representation requires a grid resolution of about 50 to 100 meters and mixed triangular and quadrilateral cells to cover the bay's irregular shorelines and intertidal zones. The total number of cells in an unstructured grid for the Chesapeake Bay ended up at about 420,000, with 120,000 covering the water body, and another 300,000 covering the intertidal zone. Simulating a storm surge in such a large model domain while maintaining an extremely high grid resolution poses a daunting computing challenge. Figure 3 shows the complexity for just a section of Wash-

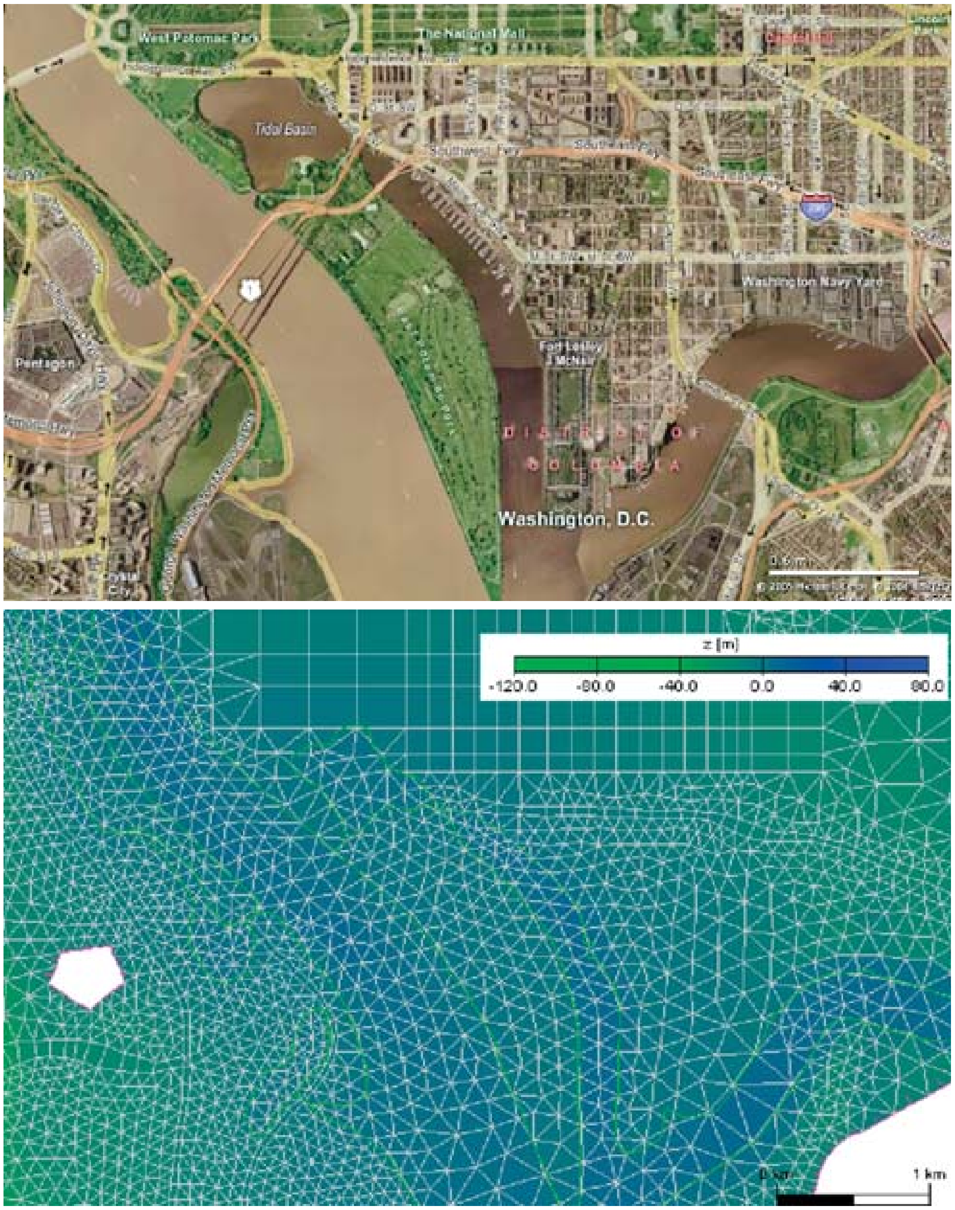

Figure 3. Geographic representation with required resolution for a grid to represent storm surge in Washington, DC. The grid for the entire shoreline and intertidal zone is about 420,000 cells. This grid alone has approximately 30,000 cells. For current methods, it is a considerable computing challenge to model a grid this large with enough time steps to depict the flooding event.

ington, DC—one of many areas the grid must cover.

To address this problem, we turned to the Eulerian Lagrangian Circulation model[3,4]—a finite volume/finite difference model that the Virginia Institute of Marine Science had successfully used to simulate storm tide in the Chesapeake Bay during Hurricane Isabel in 2003—and extended it up the Potomac River.[5,6] The model uses an orthogonal, unstructured grid with mixed triangular and quadrilateral grid cells. Such a grid conforms to the complex geometry and shipping channel naturally without additional coordinate transformation. The grid size is adjustable to be finer where it needs to be and coarser where it does not. The model calculates flooding and receding robustly in the intertidal zone through a semi-implicit, finite-difference scheme to update the momentum equation. Finally, because of the way the model calculates convective terms, it can use a three-minute time step for the storm tide simulation in the Chesapeake Bay, even with a local grid resolution as low as 30 meters. The savings in computing time is a hundredfold, relative to what is possible with traditional numerical methods.

Figure 4 shows forecast and observed water-level heights at various stations throughout the Chesapeake Bay. Overall, the verification is extremely good. The model results in Figure 5 provide a similar depiction for a sensor in the upper tidal Potomac River, but they do not show the same degree of correlation of the observations with the hydrodynamic model's storm surge prediction. There has been considerable interest in determining if including the outflow from the upper Potomac River would improve verification. The results in Figure 5 imply that it would.

Adding observation data

A forecasting model from an integrated coastal-observation and flood-warning system requires readily available observational data from atmospheric and water sensors. In our work, we surveyed the observation sensors available through the Chesapeake Bay Observing System (CBOS; http://www.cbos.org), which is part of the Mid-Atlantic Coastal Ocean Observing Regional Association within the Integrated Ocean Observing System (IOOS). We then began an analysis of the observation data pattern

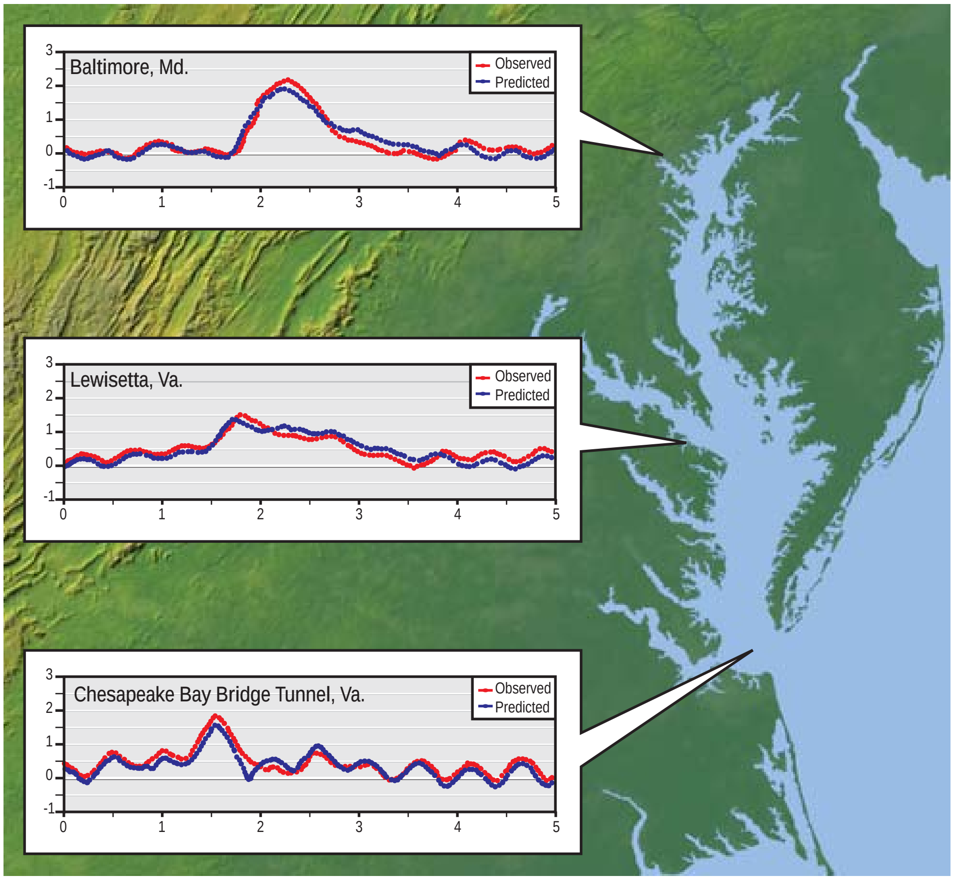

Figure 4. Sample results from a simulation of Hurricane Isabel's impact on the Chesapeake Bay area in 2003 using the Eulerian Lagrangian Circulation model. Model results agree well with observations in the open Chesapeake Bay. Red lines indicate the observed water level from installed gauges; blue lines denote predictions. All graphs are elevation in meters (y axis) and number of days (x axis).

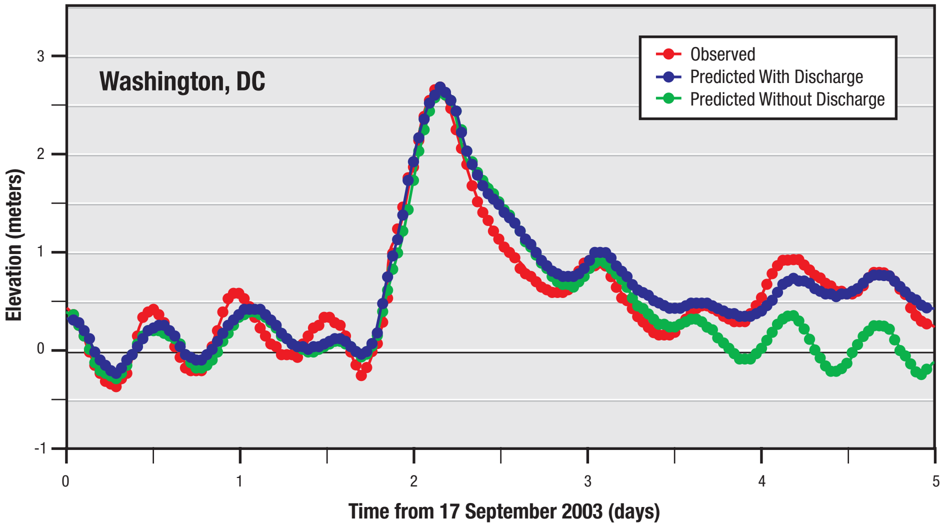

Figure 5. Correlation results of the model in Figure 4 with and without river discharge. The model with just the storm surge (green line) does not correlate well with observations in the upper Potomac River (red line). Including the river discharge with the storm surge (blue line), however, significantly improves agreement. The model run with river discharge includes the increased river flow from on-land rainfall that drains into the upriver tributaries and typically arrives in Washington, DC, a day or more after the original storm's passage.

to identify any observational gaps and to determine if the current observational network required updates. Finally, we developed initial recommendations for the next steps to implement an observation network that can support an operational forecasting model.

Our search for observational sensors began with a review of Web sites for federal and state agencies, universities, and other organizations. Although there was some overlap, no single location collected all the required information. In addition, the team looked for "ghost" sensors—sites in which sensors collect data, but the data is not shared beyond the original user. To evaluate gaps in the sensor data, we worked with the modelers to determine what inputs were needed, the accuracy and precision of these inputs, the timeliness of the data, and the locations from which data would be most important. We then evaluated available inputs, identified gaps, and pursued options to improve the current observation situation. From the collaboration of the US Geological Survey (USGS), CBOS, and Mitretek, for example, came the installation of a new sensor midway up the Potomac River, near the US Highway 301 Bridge. The new sensor provides an observation location essentially halfway between the sensors in Lewisetta, Va. (near the mouth of the river), and the upriver sensors in the Washington, DC, and Alexandria, Va., areas. Most important, it is an alternative for the sensor in Colonial Beach, Va., which Hurricane Isabel destroyed.

The final objective is to identify how the observational network must change to support an operational forecasting model. This involves conducting a systems-engineering analysis that will look at both the location of sensors within the network and the current communication systems, survivability, and power systems. There is a need, for example, to install and sponsor additional sensors in CBOS to provide a more comprehensive observation network within the Potomac River.

Visualization strategies

Communicating flood predictions to emergency managers and planners and to the public before and during a storm event is a critical part of any forecasting system. The NWS currently uses text methods to provide the forecast of water height expected at the shoreline. We believe that visualization methods will provide more useful output. NOAA recently conducted a survey of user needs and reported four major findings,[7] two of which became guiding principles for our project. One is that users of these analyses and forecasts need inundation information and historical maps in displays and outputs that are as user friendly as possible without compromising the data. The other is that users need community-level risk and vulnerability information for emergency planning, coastal management, and land-use planning.

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Use what's there

One of our strategies in deriving suitable visualization methods is to look at public service functions that already use geographic information systems (GIS) tools in their operations, such as police, fire and rescue departments, and emergency dispatchers. Integrating the results of our prototype forecasting system with current visualization methods allows emergency managers to evaluate forecast effects on critical infrastructure with enough lead time to prepare for the storm event or to plan restoration and recovery efforts.

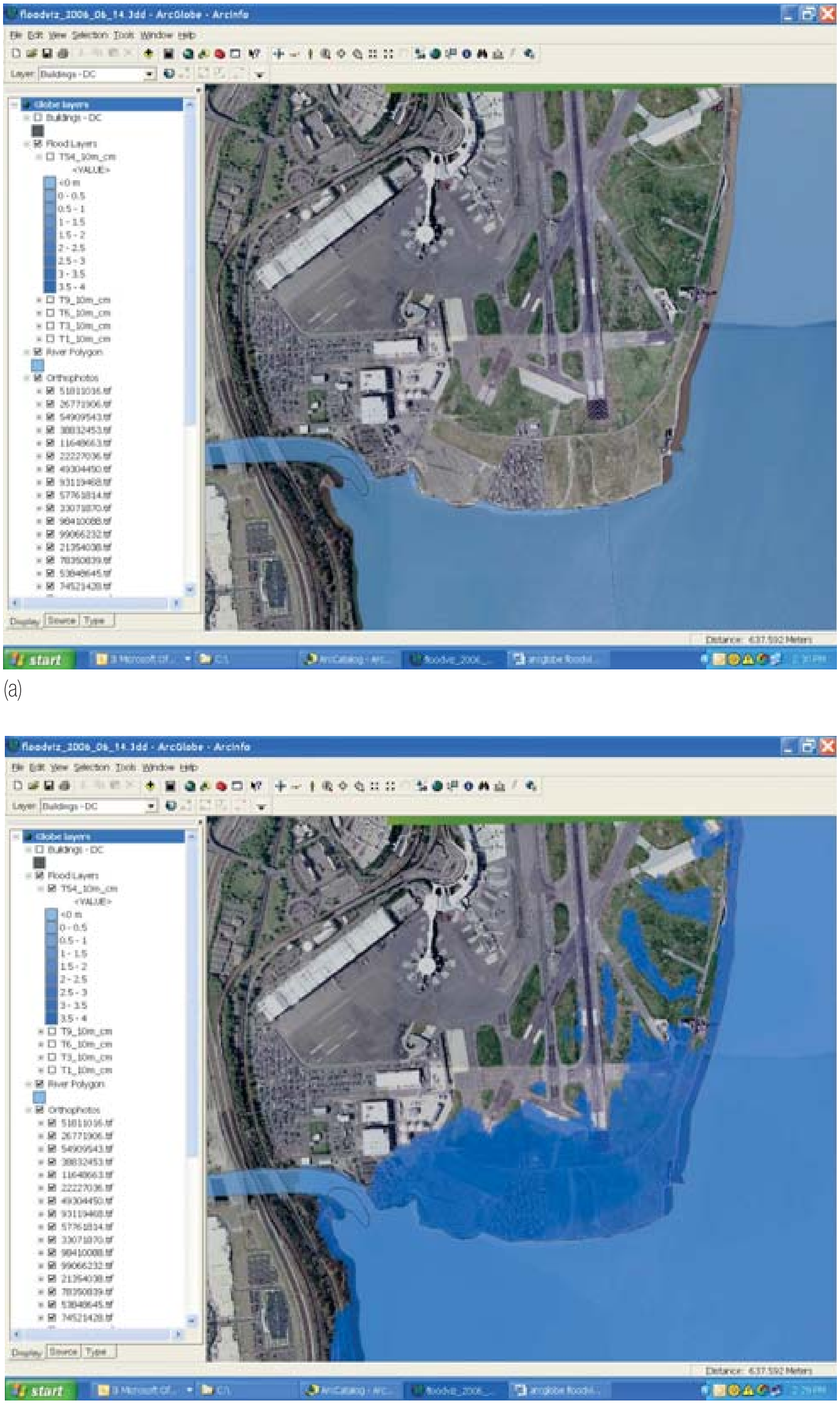
Visualization is also important to the general public and first responders in smaller communities that might not have public service GIS tools. To address these needs—and reach the broadest cross-section of users—our strategy is to make graphical inundation analyses and forecasts accessible through a Web browser. The proliferation of mapping and display tools, such as Google Earth, is making it easier to deliver products to the public rapidly and interactively. The prototype system will similarly convert inundation model output data into geographically referenced overlays or images and integrate them into Internet display tools so that emergency planners and other interested parties can determine which products will best meet their requirements.

Leverage existing standards

Providing products that are either end-state or suitable as input to a GIS could significantly enhance currently offered services. The amount and diversity of geospatial data pose a formidable challenge in meeting our visualization goal. Digital elevation models and light detection and ranging (Lidar) tiles must have sufficient accuracy and resolution in describing the area of interest. A gradual ground elevation slope means that small errors in land elevation have the same impact as errors in water-level analyses and forecasts. The result could be large errors in the visualized inundation. There is also a need to understand water flow and frictional components that can be assessed as water flows over different terrain, such as grass, open soil, concrete, or asphalt, or as it flows between buildings and other structures. Orthometric height (height above mean sea level) and water-level data must comply with recognized standards, and data transformations will be required to compare geospatial data from diverse sources. Mapping and display techniques must account for limitations in the geospatial data's resolution and accuracy so that display products do not convey a false picture.

One solution to managing geospatial data is to leverage existing standards, such as the North American Vertical Datum of 1988 and the National Tidal Datum Epoch of 1983–2001. We are using both these datum standards where practical, as well as using NOAA's VDatum tool, which lets users interactively transform elevation data from one vertical datum into another to combine or compare data.

As the sample output in Figure 6 shows,



(a)

(b)

Figure 6. Screen capture of inundation prototype output. In the vicinity of Washington Reagan National Airport before the storm surge (a) and during maximum flooding (b) from Hurricane Isabel. In (b), the blue shading over the airport's southern tip, depicts submerged portions and is keyed to a depth scale to the left of the image. Emergency managers can select which orthophoto layers to display: roads, buildings, or other services.

the GIS work in this project used Environmental Systems Research Institute's ArcGlobe, which has a look and feel similar to Google Earth. In this system, images and features (points, lines, and polygons) are draped over a base elevation dataset. The user can use either the global elevation dataset or add his own. To obtain the output in Figure 6, we initially used the USGS National Elevation Dataset with 30-meter resolution for the upper Potomac area and USGS 0.3-meter resolution orthophotos for viewing when zooming on the areas of interest. Using orthophotos is much easier than trying to re-create the landscape with point, line, and polygon features, and it provides a more realistic depiction. ArcGlobe uses the water elevation value for each grid cell center point from the main dataset and then runs it though a spline interpolation to generate a raster image of the data with the water elevation as the z-value. Using the Lidar data, it then clips the flooding overlays to show only the raster cells that have a higher elevation than the land surface.

The result is a much finer visualization of the flood boundary than using the model grid outputs alone. Animating the time step layers provides important insight about changing water depths (variations of blue shading in the prototype). By combining these layers with water velocity vectors, emergency managers will have both an illustrative and quantitative forecast product to assist planning and operations.

Future visualization efforts could include the integration of 3D depictions and animations of inundation conditions. These visualizations will provide users with additional insight into the impact of flooding on localized infrastructure. A prerequisite for these higher resolution products is a set of highly accurate digital elevation models that include the vertical dimensions of structural dimensions as well as land elevation data. Inundation analyses and forecasts must also be validated and have comparable vertical accuracy for these products to have credible value.

Emergency management and planning

During storms, emergency managers and responders need timely and accurate predictions of flooded areas and depths to

- determine which areas to evacuate and when to issue evacuation notices;
- identify the threat to vulnerable facilities, such as hospitals, nursing homes, public utilities, and critical infrastructure; and
- adjust response actions to the flooding as it occurs, such as routing emergency vehicles to avoid flooded roads and areas.

At present, NWS provides local emergency managers and planners with the predicted storm surge height. Planners use this information to identify areas that flood under various conditions, develop land use plans and regulations that are based on the predicted flooding potential, and prepare emergency plans for dealing with flooding events. A NOAA survey[7] of emergency and other planners and responders involved with storm surge flooding has identified shortcomings in the current prediction capability and with the products available to emergency professionals and the public. Using this NOAA survey as a starting point, we have begun working with regional emergency managers to confirm that their needs are generally reflected in the survey and identify needs specific to the Washington, DC, metropolitan area and the tidal Potomac region. We are reviewing support issues with individual jurisdiction emergency managers and planners, and through the Metropolitan Washington Council of Governments and other regional agencies, so that the direction of future work on this prototype system can meet their needs for the planning, response, and effective communication of predicted storm flooding.

Together with emergency managers and planners and regional agencies, we are analyzing the results of initial inundation modeling and possible output types using visualization techniques. In addition to this prototype, we have developed a Web portal that consolidates all current observation and modeling information for the Chesapeake Bay and the Potomac River to assist NWS forecasters and others in the mid-Atlantic IOOS community. Developing the concept of operations, systems architecture, engineering plans, and program management plans will move the project from identifying sensor needs to assimilating improved modeling and support functions into operational agencies, local governments, and industry, and it will provide the basis for academic partners in this project to research ways to realize the full value of this capability.

This interaction will continue to promote an understanding about the value of this collaboration within the Chesapeake Bay region to rapidly develop prototype capabilities and to evaluate this approach with other IOOS regional associations throughout the US, with Southeastern University Research Association, and with other developing projects, such as NOAA's Gulf of Mexico Storm Surge Partnership. With this far-reaching collaboration, we hope to better understand and predict coastal flooding events, thereby significantly enhancing the quality of life for coastal residents.❖

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