USING INTEGRATED MULTIHAZARD NUMERICAL MODELS IN COASTAL STORM HAZARD PLANNING

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Abstract: Storm damage in the coastal zone results from the forces of wind, waves, and rising water. Rising water, in turn, is a combination of storm surge, tides, and rainfall. These forces and their secondary effects interact in complex non-linear ways that must be analyzed and presented to groups ranging from engineers and disaster planners to the general public. Due to the infrequent nature of extreme events at any given point, simulation techniques are normally required to anticipate storm hazards. This increases the complexity of both the analysis and presentation of the results. This paper describes an integrated approach to analysis of hazards from coastal storms, focusing on tropical cyclone hazards. Simulation techniques are discussed, ranging from operational (real time) hazard assessment through long-term planning and design involving return periods. The incorporation of uncertainty is discussed, as are techniques for the presentation of hazard study outputs. Examples are noted from the Caribbean Disaster Mitigation Project, the Florida Local Mitigation Strategy Mapping Project, and commercial applications. Distribution of hazard data, including the use of interactive web based systems, is discussed.

INTRODUCTION

Severe storm events such as tropical cyclones are too infrequent to rely on history as the only guide to storm impacts. In addition, storm impacts are highly dependent on the precise characteristics of the driving event, as well as being sensitive to both natural and anthropogenic alterations in the environment. These factors make numerical simulation an essential element of coastal hazard studies. This paper describes some of the techniques used by the author in various projects for the Organization of American States, the State of Florida, and various commercial projects such as for The Weather Channel. The success of these projects combines three key technologies:

1) Use of a modular, integrated approach to hazard modeling;
2) Use of appropriate statistical techniques to capture the uncertainty of both the simulation process and input data; and,
3) Use of electronic data distribution, including interactive web sites and compact disks.

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MODULAR, INTEGRATED STORM HAZARD MODELING

Historically modeling of coastal hazards has been approached in a piecemeal fashion. In the US, for example, coastal wave studies, storm surge, and riverine flooding studies are conducted by different agencies using different approaches and standards (Watson, 1995). This makes integration and comparison of these hazards difficult. Take, for example, the case of the interaction between riverine flooding and storm surge. Even within a single study, feedback and interaction mechanisms such as that of tides and storm surge are treated simplistically. Studies are also often approached using arbitrary "basins" due to limitations in the modeling process (Jelesniaski et al, 1992). This results in discontinuities. There may be differences in resolution or even different versions of the models applied to adjacent areas. The TAOS storm hazard modeling platform was developed in order to address some of these difficulties (Watson, 1995, Watson and Johnson, 1999). The TAOS platform is designed to allow the simultaneous simulation of many different aspects of coastal and inland storms including interactions. Each of these sections has one or more user selectable modules. The aspects simulated through the use of modules are:

• Wind	SLOSH, Cardone/COE PBL model, MM5, NCEP, and others, including gradient winds, boundary layer models, and trajectory-based models of the effects of topography and land cover
• Waves	Parametric, WISWAVE, WaveWatch, WAM, and others
• Rainfall	NCEP, MM5, Sinclair, others
• Storm surge	Harris, 3/5 layer in-house, POM, couple to MOM
• Hydrology	has several sub sections, including astronomical tides, infiltration and runoff, surface flow, subsurface flow, and wind stress
• Coastal erosion	Delft, in-house
• Damage	Australian, Friedman, Clemson/Sill, Clemson/Sparks, Utex, and others
• Debris generation	Two different in-house developed modules

For tropical cyclones, TAOS currently has a dozen different internal wind models which the user can select from, in addition to the ability to ingest external wind or general circulation model inputs such as from NOAA and UKMET global weather models such as the Aviation model, ETA, Nested Grid, etc. When combined with the options for other modules, the user can create over a thousand different storm "models" by combining different wind, wave, hydrology, and rainfall runoff modules.

There are numerous advantages to a modular approach. First, modules appropriate to the problem at hand can be selected. In real time modeling, for instance, high resolution and multi-layer hydrology is normally not required since the uncertainty in the forecast track and intensity would overwhelm any additional accuracy in the modeling itself. A modular approach avoids commitment to any single approach or combination of approaches. Given the complexity of storm hazard modeling, it is unlikely that any single combination of wind, wave, or storm surge methods would be "best" in all situations. By using a number of different approaches and combining the results intelligently, this trap is avoided. Recognizing that no single model is perfect, having the ability to run multiple models in a common context allows the use of statistical methods to assess, and in some cases reduce, the uncertainty involved in the storm hazard modeling process. From a scientific standpoint, the ability to understand the interactions between different aspects of the storm hazard phenomena can lead to improved models. Finally, the use of modules avoids the temptation to "over tune" a particular combination of models. For example, if a given combination of wind and wave model produces results that are consistently low, the temptation is to simply multiply the wind value by an arbitrary amount to bring things in line. In a platform where numerous wind and wave models are available, it can be quickly established if the fault lies with the wind or wave model, and efforts made to determine the physical cause of the inaccuracy. This approach obviates spurious "calibration."

Simultaneous simulation of all storm hazards in a single model run has benefits beyond interaction. Up until now, it has been tempting to focus on one hazard at the expense of others due to the unique features of specific storm events. For example, after Hurricanes Mitch and Floyd, inland flooding was in the spotlight. Hurricane Hugo led to an emphasis on inland winds, while Hurricane Opal highlighted the danger of high coastal waves. Presenting all of these hazards in a single coherent fashion helps to prevent this kind of focusing on the problems presented by last year's storm.

THE ROLE OF STATISTICS

Statistical analysis is a vital component of coastal hazard assessment. Engineers designing a structure are concerned with the parameters related to the interaction of the use of the structure, the design lifetime, and cost. This is often expressed in terms of the return period for a given hazard. Emergency managers are concerned with the impact of specific events. Both engineers and emergency managers should be concerned with the accuracy of any predictions resulting from numerical modeling (Vermeiren and Watson, 1994). This uncertainty is an ever-present specter haunting both the modeler and user of simulation results. There are many sources of uncertainty, such as:

- Errors in the input data, such as positions and intensity of storm events
- Errors in observations used to validate a model
- Numerical errors (rounding, noise from numerical methods, etc.)
- Errors in model physics
- Short record of observations when assessing return periods
- Changes, both natural and manmade, in the environment.

Incorporating this uncertainty must be part of the hazard modeling process. One method that we have used successfully in projects ranging from the Florida Local Mitigation Strategy project to assessments of risk for commercial projects is the use of prediction limits. By fitting the results of simulations of historical storms to statistical distributions such the two parameter Weibull distribution, estimates of uncertainty in the form of prediction limits can be made (Johnson, 1997). The basic output of a study is the Maximum Likelihood Estimate (MLE). This is our "best guess" at the truth, based on maximizing the goodness of fit by the algorithm that computes the two parameters of the Weibull distribution. This allows us to compute other estimates with varying degrees of security built in. For example, we would expect the 50-year MLE estimate of wind to be high in about half of a large number of 50-year periods, and low in about half of 50-year periods. Suppose, for example, that we wish to make sure that our 50-year estimate is not exceeded in more than 10% of a large number of 50-year periods. This can be computed as the 90% prediction limit – it will be high 90% of the time, but only exceeded 10% of the time. Similar techniques can be used for event specific outputs such as Maximum Envelope Of Water (MEOW) maps or overall maxima (Maximum Of Maxima, or MOM) maps. For example, a MLE MEOW of storm surge from a 90-knot storm can be generated, or a 90% prediction limit MEOW for the same event could be calculated. Areas where the two diverge significantly should be examined more closely to determine if the cause of the divergence is the complexity of the terrain, input data limitations, model physics limitations, etc.

The TAOS platform was designed with the ability to call a variety of statistical modules at run time, in a manner similar to the model physics modules. This tight integration of the statistical methodologies with the numerical models is essential for computational efficiency. A typical analysis requires hundreds of storm hazard runs, with statistical analysis being conducted at literally millions or billions of data points. Manual post-processing with a stand-alone desktop package would be impossible in that environment.

PRESENTATION OF STUDY RESULTS

Distribution of the results of a hazard study can be an overwhelming task. The format usable for engineering studies may not be suitable for planners or the general public (Vermerien et al, 1994). In addition, amount of raw data output by a comprehensive storm hazard simulation can be staggering. For example, a single high-resolution (30-meter grid) storm model run for the State of Florida Local Mitigation Strategy studies generated 6,787,468,800 bytes (approximately 6.8 gigabytes) of data for each output variable. Thus, a single storm run creating data layers for peak wind speed and direction, peak wave height, direction, and period, and water height produced approximately 40 gigabytes of data. A storm hazard study for an area the size of the state of Florida requires thousands of simulations of storms of various directions and intensities, thus generating several hundred terabytes of raw outputs. Even after discarding all the results except local maxima and processing into MEOW's, MOM's, and Return Period data bases, the data provided to the end user can be overwhelming, due to derived variables such as quantity of debris and damage for various types of structures.

In the case of Florida studies, the raw raster data was first aggregated in to MEOWS and MOMS, then converted to vector geographic data sets in a common commercial digital format. Wind contours were created at 5 mph intervals, storm surge at 1 foot intervals, damage at 5 percent intervals. Each of these vector data sets was subset at the county level for distribution on several CD-ROMs per county. While this method did provide the data to one set of end users (the county governments), further distribution to non-governmental end users has been limited due to the difficulty in mass reproduction.

INTERACTIVE WEB-BASED DISTRIBUTION OF HAZARD DATA

The Internet has created outstanding opportunities for the distribution of coastal hazard data. As part of the Post Georges Disaster Mitigation Project, the Organization of American States has sponsored the creation of an interactive web-based coastal hazard web site. The Hurricane Hazard Information for Coastal Construction system was designed to provide storm hazard data useful for practicing engineers, architects, and planners in the Caribbean. Hazards reported are wind, wave, and storm surge, for 10-, 25-, 50-, and 100-year return periods. Return period data is characterized at maximum likelihood (MLE), 75%, 90%, and 95% projection limits. Two web sites are to be established. The primary is to be located at the University of the West Indies in Trinidad, while a backup server is to be established at Old Dominion University in Norfolk, Virginia. The developmental server is available at http://weather.methaz.com/cdcm/ until the permanent servers are up and running, hopefully in late 2001. In addition to the data sets themselves, the web sites have documentation on using the data, as well as on the modeling and statistical techniques used in the hazard studies.

All of the software used in the Caribbean hazard data web site is open source, running on Linux based computers. The two key packages are the Apache web server, which is packaged with most Linux distributions, and Mapserver, a GIS/Mapping package developed by the University of Minnesota under the sponsorship of Minnesota DNR and NASA (Mapserver can be found at http://mapserver.gis.umn.edu). The data sets can be queried by either a point and click interface, or by the direct entry of latitude and longitude coordinates. The point and click interface allows the user to pan and zoom around the region, clicking any point to generate a report. Likewise, entering a latitude and longitude point will generate a report. The report contains maps of the area surrounding the point of interest as well as the values for wind speed, wave height, and storm surge height.

Two data sets are initially installed on the servers. The first data set covers the Eastern Caribbean Leeward Islands from Puerto Rico through Trinidad and Tobago. This data set was derived from the Caribbean Disaster Mitigation Project (CDMP), a 5 year program of hazard mapping studies sponsored by the US Agency for International Development (Vermeiren, 2000). The return period calculations were based on an analysis of hurricanes from 1886 to 1998, with storm hazard model runs conducted using a regional 30 arcsecond (nominal 926 meter, loosely referred to as 1 km) grid. This is comparable in resolution to the SLOSH outputs used for evacuation planning in the United States. The second data set was developed for the Post Georges Disaster Mitigation Project, also sponsored by USAID. It covers the islands of St. Kitts, Nevis, Barbuda, and Antigua. The return period analysis was based on data from 1851 through 1999. The storm hazard model runs were made at a resolution of 6 arcseconds (182 meter grid). Each data set includes wind, wave, and storm surge hazards. The high resolution data includes a "best estimate", or MLE, hazard data at the 10-, 25-, 50-, and 100-year return periods. The regional 1km data sets also includes 75, 90, and 95% projection limits for these variables. As additional high-resolution studies are created they can be easily added to the on-line data sets.

These techniques can also be used for real time hazard monitoring and data display. A Mapserver based application similar to the Caribbean hazard data system has been developed, and is on-line at http://weather.methaz.com/wxdata/tcindex.html. This experimental system allows the user to display real time observations and forecasts for tropical cyclones anywhere in the world.

CONCLUSIONS

Coastal storm hazards are the result of a complex interplay of wind, water, and local features. Our best tools for assessing these hazards are numerical models combined with statistical analysis. By using these tools, along with appropriate presentation techniques, these hazards can be understood and accounted for in the planning process.

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