

THE ARBITER OF STORMS: A HIGH RESOLUTION, GIS BASED SYSTEM FOR INTEGRATED STORM HAZARD MODELING

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Abstract

Traditional approaches to modeling the effects of storm systems have relied on custom data bases and computer code. In addition, the effects of wind, waves, and storm surge are rarely modeled simultaneously using the same data structures or algorithms. For the coastal engineering and emergency planning community, this results in having to use different and complex sources of information. In addition, output products are often in formats difficult to use with planning support systems such as Geographic Information Systems (GIS) and Computer Aided Drafting. This paper describes a method of modeling the effects of large scale storm systems using an approach based on GIS technology, called 'TAOS'. A generic data base structure was developed, using available 'off the shelf' data sources such as satellite imagery and public domain data where possible. Surface characteristics are determined from the results of satellite imagery. Meteorological input parameters may be in three modes: from historical storms, from hypothetical storms, or directly from the National Weather Service's (NWS) National Meteorological Center and National Hurricane Center model outputs for forecasting. The TAOS storm model relies on solving flow equations for air and water via coupled finite difference solutions. The code is heavily optimized to run on either Intel 486, Pentium, or SPARC based computers, with the option to parallel up to three machines. Model runs result in output data bases in GIS format for the parameters of interest, such as maximum wind at surface, maximum still water height, maximum wave height, etc. As the outputs are in a standard GIS format, non-technical users may quickly access model output products. The results of TAOS are compared with existing storm models. Results of the TAOS runs on historical storm systems generally equal or outperform existing modeling techniques. Finally, the application of the TAOS system in the Caribbean Disaster Mitigation Project for a regional storm hazard assessment is outlined.

1. Introduction

Numerical simulation of storm systems is an essential component of coastal zone management. SLOSH (Sea, Lake, Overland Surges from Hurricanes), the model used by the National Oceanic and Atmospheric Administration (NOAA) to predict storm surge and create evacuation zones, and WHAFIS (Wave Height Analysis for Flood Insurance Studies), the program used by the Federal Emergency Management Agency (FEMA) to create flood insurance zones, are two of the most notable examples. Unfortunately for the users of these models, they require custom data bases and long development times. For example, the recent creation of a SLOSH model basin for the northern Bahamas (New Providence and Eluthera) took over a year (personal communication with Arthur Rolle, Bahamas Weather Service). Although SLOSH shows considerable skill in forecasting storm surges, the end products can be rather difficult to use by plan-

ners. The FEMA WHAFIS program, which calculates wave damage zones, requires storm surge data from external sources, manual compilation of topological and land cover data along single transects, manual compilation of the results, and extrapolation to nearby areas (FEMA 1989). Finally, modeling of wind effects are presently not considered by any widely available model, even though wind damage is arguably one of the most significant hazards associated with storms. These facts, along with the author's previous experience with coastal zone management at the Town of Hilton Head Island, South Carolina (Watson 1992c), led to the development of a new storm hazard model. Building on the legacy of SLOSH for storm surge modeling, and by adding wind damage estimates and explicit wave effects, The Arbiter Of Storms (TAOS) system was born. The numerical techniques for solving the complex equations of fluid flow came from the astrophysics community, who often have difficult factors to consider when modeling fluid flow in stars and gas clouds, such as electromagnetic and relativistic effects. In addition, by paralleling two microcomputers and a Sun workstation, large basins at higher resolution may be modeled. By using the latest techniques of computer-based mapping and remote sensing, basin development times are vastly reduced. For example, runs for the Bahamas area (including the SLOSH model basin mentioned above) were completed in 3 working days.

This paper describes some of the technical aspects of the TAOS system, concentrating on storm surge modeling. An overview of the components of the system and the importance of Geographic Information System technology are given first, followed by a description of the physics of the model, and implementation and coding issues. Then the results of comparisons between TAOS and post storm measurements, and with other models in use, are presented. The final section outlines the use of TAOS in the Caribbean Disaster Mitigation Project.

2. System Overview

Most numerical models have specialized data input needs. Rather than design a custom data base management system for TAOS, it was decided to take advantage of recent advances in computer based mapping. In the last decade, Geographic Information System (GIS) and remote sensing have revolutionized the mapping sciences (URISA 1992). GIS evolved from Computer Aided Design (CAD) software as a way to process spatial data. Essentially, a GIS combines the graphics capability of CAD with a data base management system, and adds map processing abilities such as the ability to create digital terrain models from a set of contours. Computer models which take advantage of this technology can greatly reduce data base development times. For example, there are many existing digital data bases, such as the U.S. Department of Defense, Defense Mapping Agency (DMA) Digital Chart of the World and the

many U.S. Geological Survey (USGS) digital products. Models which use GIS data bases can readily access this large library of data. GIS software allows the easy update of data bases. This is especially important in developing areas, and is critical in coastal zones due to the changing nature of the near-shore environment. For example, storms can create or remove dunes, sand bars migrate, etc. In addition, most GIS software packages can import and export a wide variety of CAD data. This allows one to rapidly model the impact of proposed developments by importing the actual engineering plans. Remote Sensing, especially by low-earth orbiting satellites such as LANDSAT and SPOT, allows the modeler to create data bases over large areas in great detail with current information. Images from these satellites can be used to create up-to-date bathymetric data bases, as one example (Watson 1992a). Readers interested in learning more about GIS and Remote Sensing of land cover may wish to review two books from the American Society for Photogrammetry and Remote Sensing: *Geographic Information Systems: Principles and Applications*, and *Introduction to Remote Sensing* (ASPRS, P.O. Box 1504, Cranberry Township, Pennsylvania, 16066-0504).

Figure 1 is a block diagram of the TAOS system. It is quickly apparent that GIS technology and remote sensing are critical aspects of the overall TAOS system. Data management on both the input and output sides of the model are handled entirely by GIS. Creation of the data base for any physical modeling process often requires data in different formats. For TAOS, sources of data include satellite images, paper maps, and existing digital data bases. Satellite images from low-earth observation satellites such as LANDSAT and SPOT are an excellent

source of information. Through image processing, land cover may be determined, and water depths in the near-shore area may be calculated by using the amount of light reflected from the bottom. TAOS can directly use data bases created by three of the more popular GIS packages. Idrisi, from Clark University, is the most widely used and one of the most inexpensive GIS packages available (GIS World January 1994). Idrisi is the GIS package of choice by many in the research community, and is the standard package for the Caribbean Disaster Mitigation Project. GRASS, a public domain effort of the U.S. Army Corps of Engineers (USACOE), is also widely used. The UNIX source code for GRASS is freely available, making it an attractive option for the computer modeler. The UNIX version of TAOS uses GRASS as its data base manager. Arc/Info, a commercial GIS package from Environmental Systems Research Institute, Inc., is widely used by U.S. Federal, State, and local governments. TAOS also supports several Arc/Info binary formats. As indicated in Fig. 1, the GIS processes the raw data in to three of the four input parameters: topography, land cover (for damage estimation purposes), and friction layer (to determine water and wind flows). The fourth data set, the meteorological parameters, comes from the NWS National Hurricane Center reports and data bases.

Once a data base of the physical environment can be accessed, the actual numerical modeling can begin. Sections 3 and 4 describe the physics of the model and the implementation, respectively. A storm hazard model generates huge amounts of output data, and the management of this data can be as much of a problem as creating the input data bases. In order to be of general use, it is important for model outputs to be in a

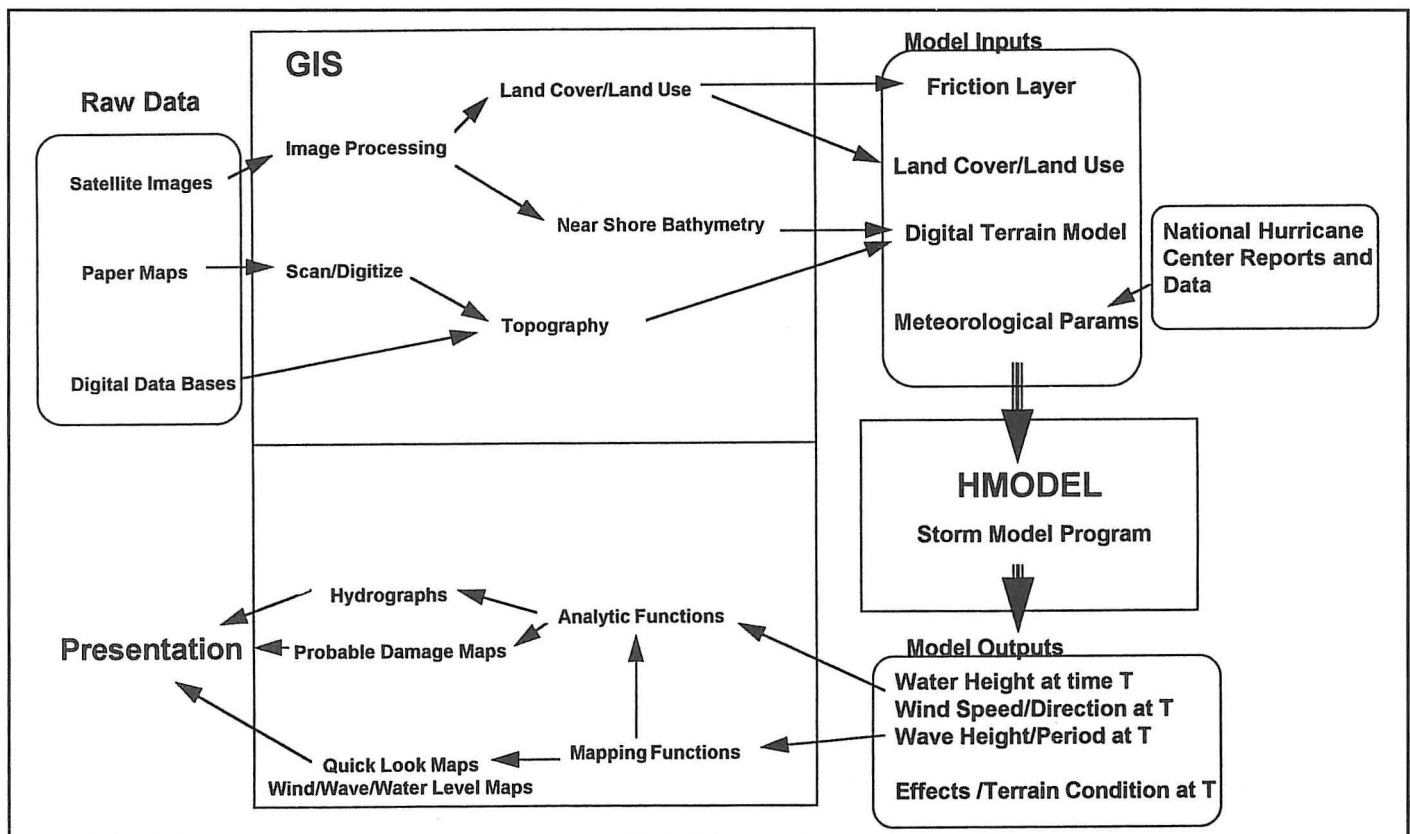


Fig. 1. TAOS storm modeling process.

format easily accessible by a variety of users. Again, GIS provides a convenient mechanism. Again referring to Fig. 1, the TAOS storm model (HMODEL) outputs storm variables in the same format as the input data bases. This allows the GIS package to access model outputs, and all of the GIS map production and spatial data management options are available. For example, the entire Caribbean basin may be modeled using a single coordinate system. The maps for individual countries can then be readily created using the projection functions inherent in GIS, using the established coordinate system for each island. The mapping system used by the end user becomes unimportant. Figure 2 is a sample map, produced for the Caribbean Disaster Mitigation Project storm hazard assessment of St. Lucia. This map was generated by using TAOS with Idrisi, and Microsoft Powerpoint.

3. Physical Principles

The basic physics of modeling storm surge are by now well established. The equations of motion for water flow which are used in TAOS are the vertically integrated forms by Harris, as noted in the USACOE Shore Protection Manual (USACOE 1973-92). Advection of momentum is not currently modeled,

and tide terms are calculated separately. The basic partial differential equations are given below:

$$\begin{aligned}\frac{\partial U}{\partial t} &= fV - gD \frac{\partial S}{\partial x} + \frac{\tau_{sx}}{\rho} - \frac{\tau_{bx}}{\rho} + gD \frac{\partial \xi}{\partial x} \\ \frac{\partial V}{\partial t} &= -fU - gD \frac{\partial S}{\partial y} + \frac{\tau_{sy}}{\rho} - \frac{\tau_{by}}{\rho} + gD \frac{\partial \xi}{\partial y} \\ \frac{\partial S}{\partial t} &= P - \frac{\partial U}{\partial x} - \frac{\partial V}{\partial y}\end{aligned}$$

where:

V	Volume transport in x direction
U	Volume transport in y direction
τ_s	Surface Stress
τ_b	Bottom Stress
D	Total Depth (nominal depth + S)
g	gravitational acceleration
S	Surge Depth
f	Coriolis parameter
P	Precipitation rate
ξ	Pressure deficit

Source: USACOE (1973, pg 3-94)

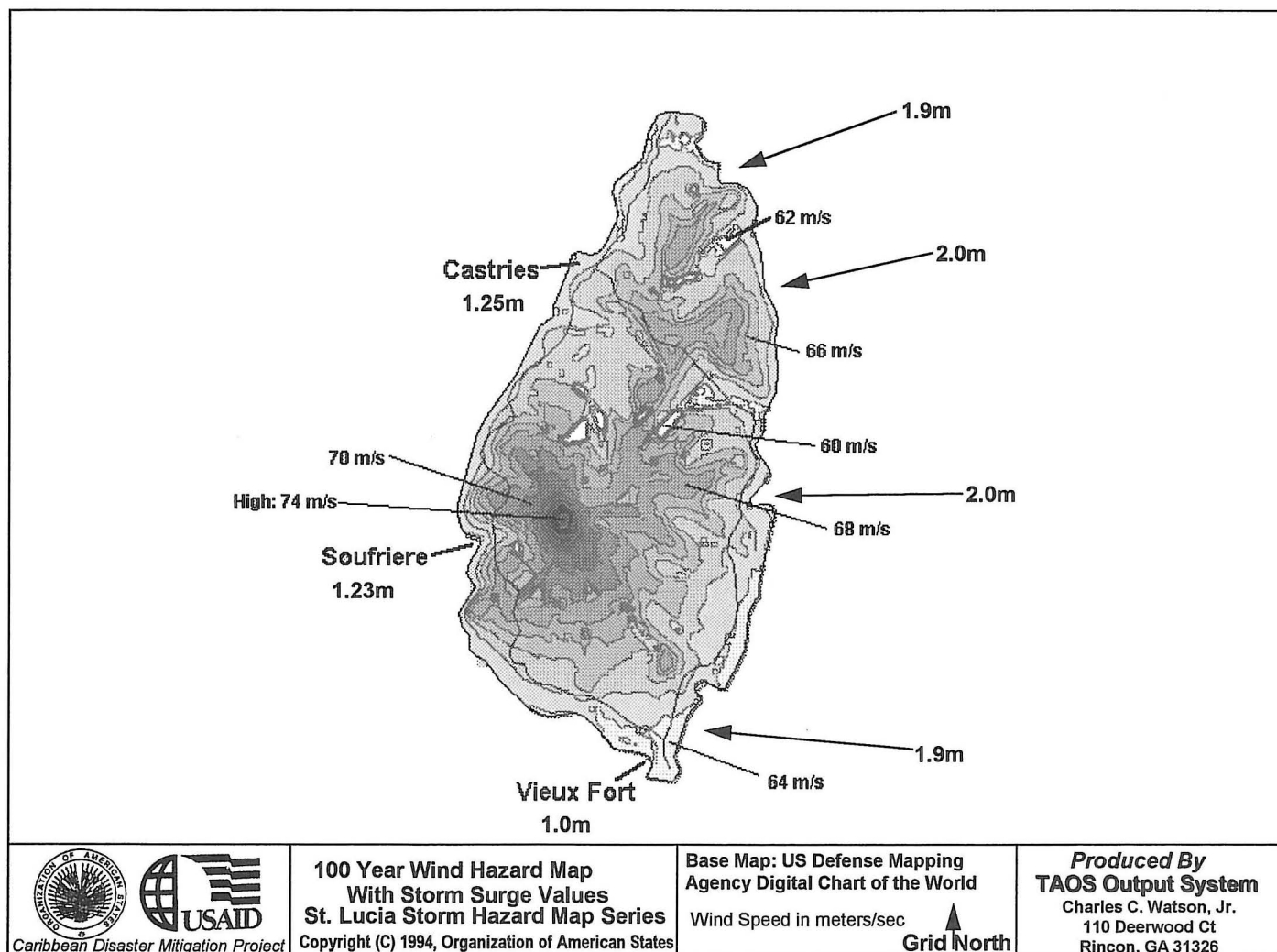


Fig. 2. Map created for St. Lucia Electric Company.

Table 1. Terrain types used in the TAOS model.

Sandy	
Short Grass (Height <0.5 meter)	} To be combined in a single category with sub-code for version 3.0
Tall Grass (Height >0.5 meter)	
Coral Reef	
Rocky 1 (small rocks)	} To be combined with subcodes
Rocky 2 (boulders)	
Scrub	} These three categories are sub-coded with species and density information such as height, thickness, etc.
Forest w/ understory	
Forest w/out understory	
Urbanized	} Coded with density and construction information.

Each of these terms must of course be defined and calculated. The wind stress coefficient is based on one from Van Dorn discussed in USACOE (1973). The wind field generated by the model is discussed below. Bottom stress is calculated from equations in USACOE (1973), sec 3.865, and are of the Chezy-Manning type. A uniform bottom stress coefficient K of $2.5e^{-3}$ is used for all areas with undisturbed water depths greater than 20 meters. Where bottom types are known or can be determined from satellite images, and over land inundated during the course of modeling, K is modified according to bottom/terrain type. Since all TAOS runs are made in a single 'basin', using standard terrain types, it is not necessary (or desirable) to calibrate the model in each area of interest. The bottom and terrain types being used in TAOS are summarized in Table 1. Sea bottom and terrain types are independent of the current water level of the cell. For example, a beach can be 'sandy' as well as an off-shore area. It should be noted that surface friction can be a dynamic term. Storms can modify terrain extensively. For example, high winds remove leaves from trees, decreasing their frictional effectiveness, and dunes are damaged or removed entirely. The current TAOS model incorporates dune removal and some vegetation changes. As more data and research become available, the terrain modification module can be updated accordingly.

Determination of the driving meteorological forces is of vital importance. Three methods are used in TAOS. First, a simple wind field model using equations modified from Harris, incorporating the storm motion correction term from Jelesnianski, as given in the USACOE Shore Protection Manual (USACOE 1973-92). This method is very similar to that used in SLOSH. The second method uses the simple model, modified with data contained in the NWS National Hurricane Center (NHC) Marine Advisories. These advisories contain the radius to various wind speeds, which can be used to control the shape of the wind field. The final method is to use pressure fields and other variables generated by the various NWS National Meteorological Center computer models such as the Nested Grid Model (NGM). This method is used for larger storm systems such as Nor'easters. Winds output by the NGM are modified according to the surface characteristics as determined from satellite images to obtain the winds at the 10 meter and 5 meter levels using a boundary layer model. Although the NGM outputs winds at the surface, the TAOS model has higher resolution terrain and surface characteristics. The higher level of detail is of importance in estimating wind forces on individual structures and small areas such as neighborhoods. This is especially important in the Caribbean, as mountainous areas can have highly variable winds as the wind accelerates over hill

crests (Davenport et al. 1985). Damage is estimated for each terrain type based on the total stress on the cell from wind and waves.

4. Implementation Principles

TAOS is primarily implemented in FORTRAN 77 and C. File access is compartmentalized to increase portability. The code has been compiled on both Intel and Sun SPARC architecture running MSDOS, Windows NT, and SunOS, using Watcom F77/32 and Borland C++ compilers on the Intel 486 and Pentium machines, and the GNU f2c/gcc compilers on the Sun workstation. TAOS solves the equations of motion using finite difference solutions (forward differences) on a variable size, traveling grid. For a discussion of the mathematical techniques and stability, see Bowers and Wilson (1991), chapters 1, 2 and 5. The nominal cell size for the regional model is 1 km per cell. The model can be run at resolutions of up to that of the satellite data, as fine as 10 meters per cell. High resolution runs are of particular importance when attempting to calculate wave damage zones. Bottom features which can effect wave refraction and breaking are well resolved in the 30 meter and smaller grids (Watson 1992a). Run times are reduced by using a variable adaptive step size. In the central core of a storm, flow rates force fairly small step sizes. By using small step sizes only where flow rates are high, and larger sizes in regions where flow rates are small, the overall number of computations is reduced. The regional TAOS model uses a storm centered computational grid. This means that driving forces and some other variables need not be recomputed unless the storm parameters or the underlying terrain change. In addition, the size of the computational grid can be varied as the storm varies in size. This also allows for regional models to be run with relative ease. For example, the 4 km/cell verification run outlined in section 6 using Hurricane Hugo was run on a grid of 1308 by 808 cells, covering the entire Caribbean, Gulf of Mexico, and Eastern U.S. Figure 3 shows the basin, track of Hugo, and storm surge results from this run. The storm-centered sub-grid varied from 100 by 100 to 150 by 150 cells, a manageable size for run times in the 2 to 3 hour range on a single microcomputer. There are numerous operational and computational advantages to using a storm centered grid as opposed to the traditional basin oriented approach to surge modeling. Boundary conditions are much simpler. Storms rarely confine themselves to a single basin. This requires runs with multiple basins using traditional methods, especially given the current uncertainty in the forecasting of storm positions in the 24 to 72 hour range. A storm run for a typical NHC Marine Advisory takes 8 to 15 minutes on a 60 MHz Pentium based computer.

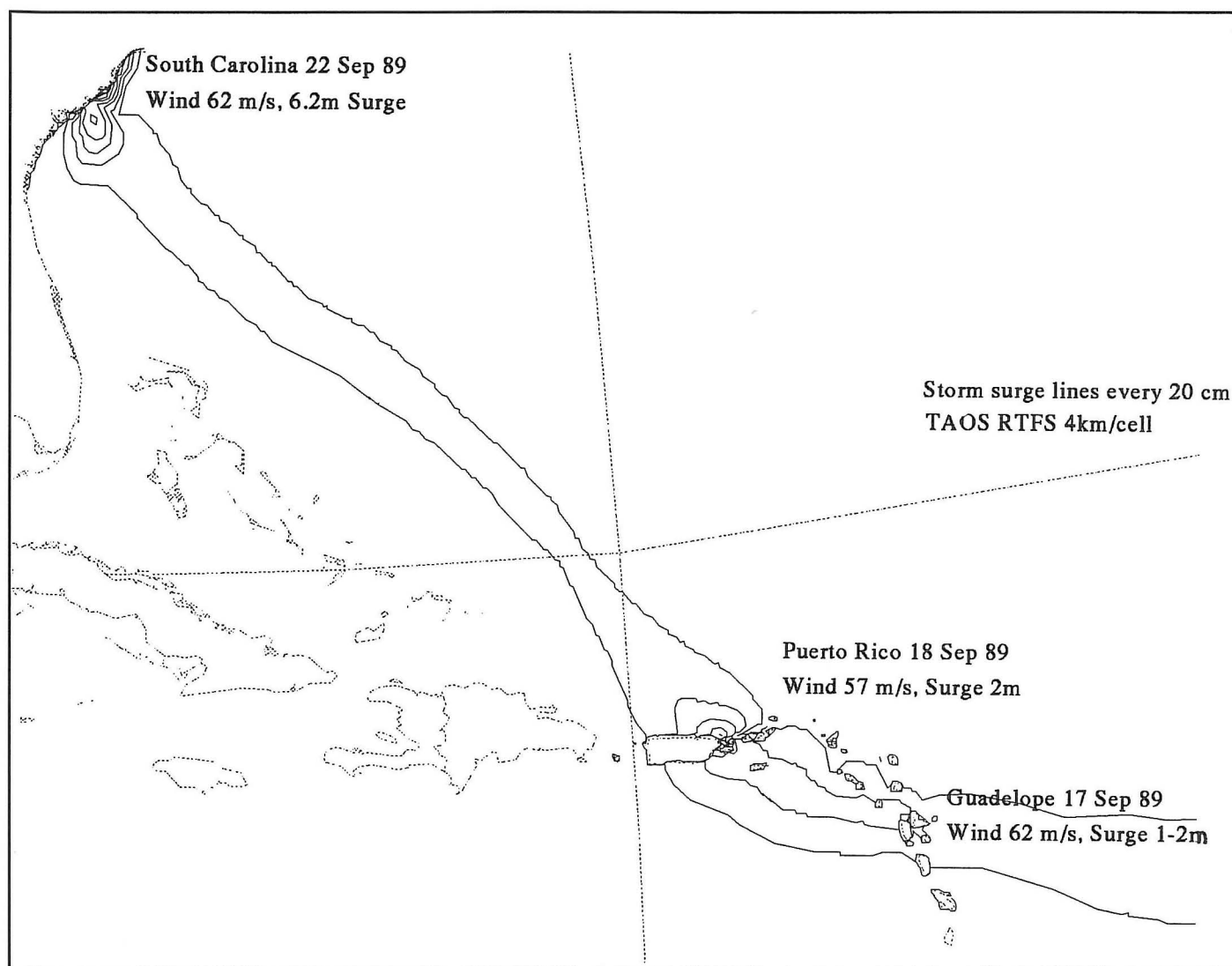


Fig. 3. Hurricane Hugo (1989) track and storm surge results from TAOS 4 km/cell run.

The modular nature of TAOS also lends itself well to distributed processing. A version of TAOS has been created which can parallel three computers communicating using thin wire ethernet, as shown in Fig. 4. This parallel processing can result in impressive performance improvements. The Hurricane Hugo run took 2.45 hours on a single Pentium/60 based machine. The same run on the parallel system took only 24 minutes. Interprocess communications was achieved by BSD sockets under Microsoft Windows 32bit API (Winsock/32) on the Intel machines. SunOS, being a UNIX derivative, has TCP/IP and BSD Sockets built into the operating system.

5. Verification and Comparisons with Existing Models

The ultimate test of any computer model is how well it compares with the real world. Also of interest is how well it performs when compared to existing techniques. A TAOS run was made for Hurricane Hugo, 1989, along its entire track using a 4 km per cell grid. Storm track and intensity data were from the National Hurricane Center. Deep water depths were

obtained using the USGS ETOPO5 data base, while topographic and other data was derived from the DMA Digital Chart of the World. Near shore depths were extracted from nautical charts, satellite images, and the ETOPO5 data. Inland friction data was obtained by using recent NOAA Satellite AVHRR data. Table 2 indicates the results for this run, and for two other tide gauge readings for runs of hurricanes Allen and David using the same data base. Also noted in the table are the results of two other models. The SLOSH runs are from data provided by Dr. Mercado of the University of Puerto Rico, while the Meteo-France model (based on the Australian BMRC model of Hubbert) data comes from an unpublished paper by Daniel (Personal communication with CMI, 1994)

As shown in Table 2, TAOS performs well, especially where the more accurate tide gauge readings are available. TAOS also produces good results with regard to the time history of the surge as recorded by tide gauges. Table 3 and the accompanying graph (Fig. 5) show a comparison of the hourly time history of the storm surge as recorded at Charleston, South Carolina, and the results of the regional Hurricane Hugo run. Also noted are the results of a second run using a 1 km per cell data base.

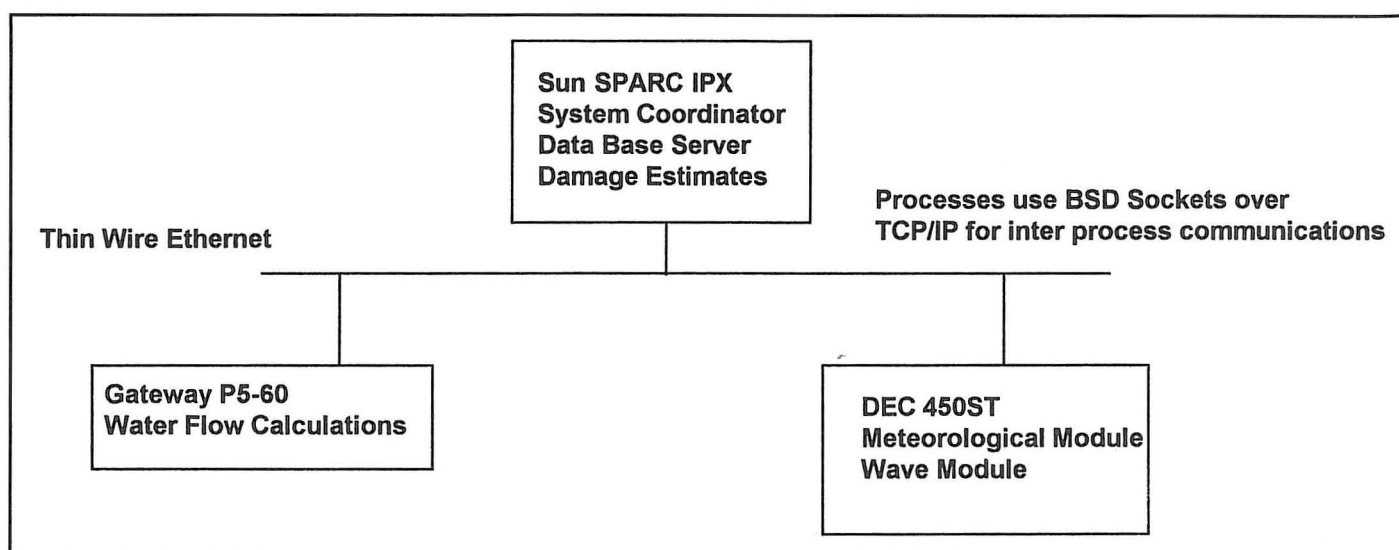


Fig. 4. Parallel processing system.

Additional verification runs have been made using storms crossing the Lake Pontchartrain, Louisiana, Charlotte Harbor, and Galveston Bay SLOSH basins which were documented in NOAA Technical Report NWS 48 (Jelesnianski et al. 1992). Using a 1 km regional (Gulf of Mexico, Atlantic from 5 N to 35 N, West of 50 W) model and post-storm tracks, the errors in surge height using tide gauge readings for the storms modeled thus far have been under 15%, with the average being 5%. The locations of the peak surges appeared to be within one cell (1000 meters) of the estimated location of peak surge based on post storm reports.

As noted in Jelesnianski, et al. (1992), peak surge readings are difficult to obtain, as they rarely occur near gauges, and when they do, they often destroy the instrument before the peak is recorded. In addition, the path and intensity of historical storms, particularly those before the advent of satellites and coastal radars, are rarely known with any true accuracy. This makes model verification problematic for single basins, as at best one or two well observed severe storms may have occurred. In many locations, no severe storms have occurred in the last 30 years. A key advantage of TAOS is the fact that the entire Atlantic hurricane region is modeled as a whole. This increases the level of confidence that the model is functioning properly,

as storms and basins are not calibrated separately. A single model run may cross a rocky Caribbean Island with no continental shelf, the mangroves of south Florida, and end on the Gulf shores of Texas. In addition, regional effects, such as the elevated water levels in the Gulf of Mexico created by Hurricane Carla in 1961, and the effects of the surrounding weather systems on the surge and wave fields can be modeled.

6. Applications in the Caribbean Disaster Mitigation Project

TAOS was selected by the Organization of American States, Department of Regional Development and the Environment (OAS/DRDE), as the storm model to create hazard maps for the Caribbean Disaster Mitigation Project (CDMP). CDMP is a joint effort of OAS and the U.S. Agency for International Development. TAOS was selected primarily because development of individual basins was not required, and that data bases could be quickly updated to reflect the rapid coastal development in many areas of the Caribbean. Figure 2, noted earlier, is an example of a National level product developed for the St. Lucia Electric Company and other interested parties. Although originally designed to create hazard maps, many users have expressed an interest in using the model for real-time storm hazard prediction. To this end, a Real Time Forecast System (RTFS) has been developed which automatically ingests National Hurricane Center reports and generates surge forecasts every 6 hours using the 4 km per cell grid. This system is undergoing evaluation during the 1995 hurricane season at the Caribbean Meteorological Institute in Barbados. On a stand alone Pentium/60, model runs based on the marine forecast can be made in under 20 minutes. A version of TAOS is under development which will incorporate forecast track uncertainty to dynamically generate and run multiple tracks to create a 'maximum envelope' prediction. This should aid emergency planners in the task of providing evacuation guidance.

Table 2. Comparisons of peak surge results in the Caribbean (in meters).

Storm	Location	Observed	TAOS	Other Models
Hugo	Pointe a Pitre	1.5 OB	1.51	1.48 (MF)
Hugo	La Puntilla	1.1 TG	1.20	0.82 (SLOSH)
Hugo	Lugillo	1.3 OB	1.50	1.2 (SLOSH)
Hugo	Los Machos	2.0 OB	2.00	1.9 (SLOSH)
Allen	Le Robert	0.6 TG	0.60	0.53 (MF)
David	Pointe Foullele	0.4 TG	0.40	0.25 (MF)

The Table 2 values are in meters, including tides. TAOS runs were using the uncalibrated RTFS, 4 km DB, with satellite data used for frictional values. OB = Observed (estimated from high water marks), TG = tidal gauge readings, and are in bold type. MF = The Meteorological model for Guadeloupe and Martinique, SLOSH = NOAA SLOSH model results from the Univ. of PR (From Mercado)

7. Summary

By incorporating GIS and remote sensing technology, computer-based storm hazard models can be developed which can

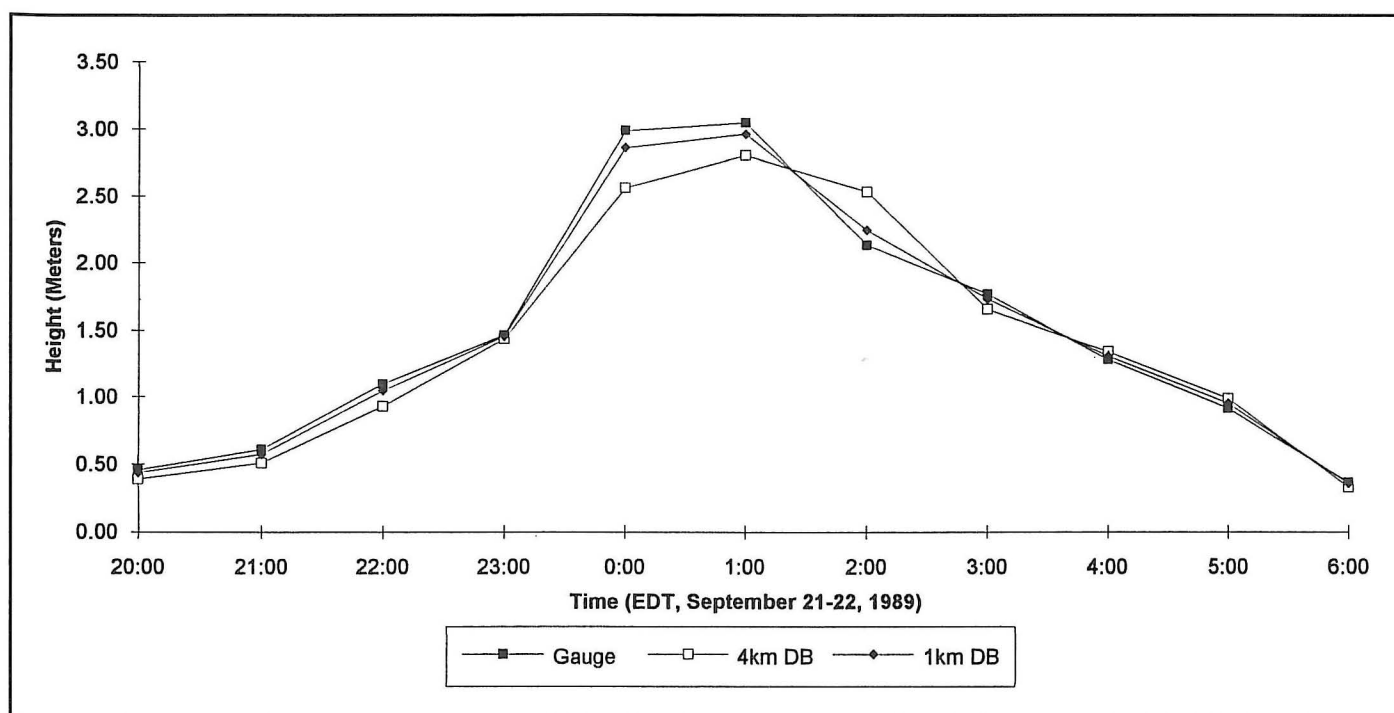


Fig. 5. Comparison of model output data with hourly tide gauge readings for Charleston, South Carolina for Hurricane Hugo (1989). (Data from Table 3.)

be rapidly updated for different locations, and to accommodate changes to areas previously modeled. Hypothetical runs can be easily made to estimate the impact of proposed developments in coastal areas. Using state-of-the-art computing technology, including microcomputer networks, allows paralleling several machines in order to increase the resolution of the models while keeping run times reasonable. Higher resolution data bases appear to result in more accurate results, especially when computed time histories are compared with tide gauge readings. Rather than calibrating separate basins, the effects of individual terrain types are determined, and incorporated in to a regional model. TAOS has been tested with a variety of storms and locations, and generates results for storm surges generally within 15% of measurements using a 4 km/cell data base, and within 10% using a 1 km/grid cell data base.

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Table 3. Detailed comparison of hourly tide gauge readings with TAOS model output data for Charleston, South Carolina, during Hurricane Hugo, 21–22 September 1989. Heights are in meters.

Time	Gauge	4 km DB	Diff (m)	% Diff	1 km DB	Diff (m)	% Diff
20:00	0.46	0.39	0.07	15%	0.44	0.02	5%
21:00	0.61	0.51	0.1	16%	0.57	0.04	6%
22:00	1.1	0.93	0.17	15%	1.05	0.05	5%
23:00	1.46	1.44	0.03	2%	1.45	0.01	1%
0:00	2.99	2.56	0.43	14%	2.86	0.13	4%
1:00	3.05	2.8	0.25	8%	2.96	0.08	3%
2:00	2.13	2.53	-0.4	-19%	2.25	-0.11	-5%
3:00	1.77	1.65	0.11	6%	1.73	0.04	2%
4:00	1.28	1.34	-0.06	-5%	1.31	-0.03	-2%
5:00	0.91	0.99	-0.07	-8%	0.95	-0.04	-4%
6:00	0.37	0.33	0.04	10%	0.36	0.01	2%

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