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ABSTRACT

In this study, the MTEVA (Developed as part of CMS #2009-010) has been advanced to apply storm surge and evacuation models to the greater Jacksonville area of Northeast Florida. Heuristic and time dynamic algorithms have been enhanced to work with the significantly larger network. Like the existing MTEVA, users are presented with graphical user interfaces to a modeling system which couples a storm surge and inundation model with congestion models for emergency situations. However, in the enhanced MTEVA, these interfaces are built with standards-compliant web services and hosted using a THREDDS Data Server (TDS). The Northeast Florida domain is developed using high resolution State of Florida LiDar data and the transportation network is based on the Northeast Florida Regionally Planning Model (NERPM).



EXECUTIVE SUMMARY

A top priority for emergency managers before, during, and after an emergency situation is to provide safe and efficient transportation routes. In many southeastern states along the Gulf and Atlantic coasts, this priority is complicated by the inherent combination of multimodal transport methods and choke points created by water barriers and the bridges and tunnels built to surmount them. Furthermore, in many of these areas, extreme tropical events can render ports (high waves), bridges (extreme winds) or roads (flooding) unusable, completely reconfiguring the transportation network. Combining these infrastructure issues with the unpredictability of human behavior leads to significant challenges in the study of multimodal congestion mitigation in coastal communities during extreme events, a form of non-recurrent congestion of importance to both native residents and coastal tourists alike.

To deal with these challenges, several research groups within the academic community began tackling the problem as part of a previously funded CMS project. In one group, coastal scientists are developing advanced atmospheric and estuary models to simulate the natural environment during a storm. In another group, traffic engineers and optimization experts are developing congestion mitigation models to plan the most efficient transportation routes. It was the goal of this study to continue the collaboration between these groups to enhance the publically available Multimodal Transportation Educational Virtual Appliance (MTEVA), a prototype virtual environment for interdisciplinary research and education. Currently, in this virtual environment storm surge and evacuation models are coupled and presented through an interactive demonstration for a hypothetical domain subject to hypothetical tropical storms. This demonstration is being used to educate future generations of scientists and engineers as well as provide outreach to the general public. This collaborative research environment facilitates interdisciplinary scientific discovery among these groups through model integration.

In this study, the MTEVA has been advanced to apply the storm surge and evacuation models to a real physical system of critical importance to the State of Florida (FL), the greater greater Jacksonville area of Northeast (NE) FL. Expansion of the MTEVA from a relatively simple hypothetical domain, to this significantly more complicated region represents a unique challenge to both the simulation of storm surge and inundation and the optimization of the transportation network, which are both orders of magnitude larger in size. As part of this effort, surge, inundation and transportation infrastructure risk maps will be developed for the region based on historical climatological data under present data conditions as well as under future conditions expected under global climate change. Like the existing MTEVA, users are presented with graphical user interfaces to a modeling system which couples a storm surge and inundation model with congestion models for emergency situations. However, in the enhanced MTEVA, these interfaces are built with standards-compliant web services and hosted using a THREDDS Data Server (TDS). The NE FL domain is developed using high resolution LiDAR data and transportation network is based on the Northeast Florida Regionally Planning Model (NERPM). The MTEVA itself has been upgraded such that it can be booted directly off a USB device maximizing applicability in nearly any computing environment. Finally, several educational and outreach initiatives have been conducted in the region.



1. BACKGROUND

Hurricanes, earthquakes, industrial accidents, nuclear accidents, terrorist attacks and other such emergency situations pose a great danger to the lives of the populace. Efficient evacuation during these situations is one way to increase safety and avoid escalation of damages. The penalties incurred when Hurricane Katrina caught the nation off guard were severe. It is estimated that Hurricane Katrina displaced more than 1.5 million people and caused economic damages of \$40-120 billion (DesRoches 2006). Such disasters are well documented, allowing better preparation for future extreme events. Over the past decade, evacuation problems have been given a heightened attention and there are numerous studies available in the literature on evacuation strategies (Wolshon et al. 2005; Gwynne et al. 1999; Kuligowski and Peacock 2005; Santos and Aguirre 2004; Bryan 2000; Radwan et al. 2005).

Models currently available in the literature are usually customized for the evacuation of specific geographic regions. These models have their relative advantages and disadvantages, but are customized to their specific needs. It is rather tedious to generate a unified model that can be used in all situations. Inclusion of several features impacts the complexity of the model and hence the computational speed. On the other hand, simplifying a model compromises the precision of the model. Modeling without the consideration of these features cannot be immediately implemented. Some features are considered by most of the models and are applicable in a general evacuation setting.

A comprehensive survey was carried out to identify and evaluate the existing techniques available in literature (Arulselvan et al. 2008). Recognizing a reasonable level of insufficiencies in multimodal transportation, alternate evacuation routes in case of accidents and congestion, and heuristic exploration of difficult optimization problems, this survey helped explain the deficiencies in current techniques and also identified the key features that significantly affect evacuation efficiency.

As part of a prior CMS initiative, Dr. Pardalos (Co-PI) addressed some of these features in evacuation modeling. In the previously mentioned survey, models were classified as analytical or simulation-based and the pros and cons of individual techniques were discussed. The simulation-based models are often employed in reality due to their practical benefits and their flexibility to adapt to dynamic factors (Wolshon et al. 2005). The optimization models have the benefit of being accurate but fail to compete with simulation-based models when applied in real time due to their computational complexity in large instances. There is a recent trend of hybrid models mixing analytical and simulation techniques, exploiting their relative advantages, to be reasonably accurate and precise. Based on this form of organization, Dr. Pardalos has developed a branch-and-price enabled integer programming formulation with a parallel computing capability which was then experimentally verified through simulations.



While a variety of evacuation and coastal/atmospheric computational models exist, several challenges arise when it is desired to couple the behavior of these models. Our efforts address information technology challenges that arise in this context with a unique approach using virtualization technologies. The goal is thus to provide consistent, self-contained execution environments packaged in software “appliances”, which facilitate the coupling of models.

Different models, in particular across disciplinary boundaries, are generally developed by different researchers, from different science domains, and programmed using different languages and software packages, so the option of developing coupled models from scratch or integrating at the source code level is often not available due to the associated high software development costs. Instead, our approach facilitates the coupling of models by presenting virtual environments where unmodified model binary programs can be composed. These environments build on modern virtualization technologies that are increasingly available and adopted in systems ranging from desktops to servers to large data centers, with freely available and commercial products from VMware (Player/Server), Citrix (Xen), Microsoft (Hyper-V), among others.

PIs Davis, Sheng and Figueiredo have ongoing collaborative efforts that leverage such virtualization technologies to create self-contained modeling virtual appliances for both education and research uses (Wolinsky et al 2006). These build upon the Grid Appliance system, which has been customized for educational and research goals in the context of coastal and estuarine sciences in the CI-TEAM and SCOOP projects (see <http://cseva.coastal.ufl.edu> and respective links for more details about these projects).



2. RESEARCH APPROACH

Leveraging the PIs experience developing educational virtual appliances for the study of storm surge and inundation, an appliance focusing on multimodal transportation is developed and deployed. This appliance is based on an enhanced version of the NSF CI-TEAM and SCOOP educational virtual appliances (<http://cseva.coastal.ufl.edu>) previously developed. The MTEVA leveraged a prior CMS study (Multimodal Solutions for Large Scale Evacuations: 2008-005) to couple advanced congestion models for multimodal evacuation models with a robust storm surge and inundation model.

Virtual appliances use virtual machines to encapsulate all necessary operating system, models, numerical libraries, GUIs, pre-/post-processing and advanced cyberinfrastructure (CI) tools. These machines then automatically securely access a world-wide “Grid” (aka “Cloud”) computing network to provide substantial computational resources for use in the interactive multimodal evacuation scenarios. To interface with the coupled modeling system, an interactive geo-referenced GUI is deployed based on the SCOOP appliance OpenLayers interface. This GUI allows users to select from different domains, storm characteristics, numbers of cars, analytic techniques for computation of the most efficient routes, etc.

Once simulation parameters are selected, a simulation is performed. First, the atmospheric and storm surge models simulate the wind and flooding potential. Next, the transportation network is reconfigured dynamically to account for high waves (closed ports), high winds (closed bridges) or flooding (closed roads). Finally, the most efficient routes are determined and displayed in the OpenLayers interface. After deployment of the coupled system, education content was prototyped to target specific examples. The long term impact of the proposed research is that the study of non-recurrent congestion during extreme coastal storms is better understood. In addition, a tool (the MTEVA) is developed and made available which can be used to facilitate interdisciplinary collaboration and to educate and deliver content for other multimodal solutions to congestion mitigation or transportation engineering in general.

From an analytical perspective of the transportation model, the branch-and-price integer programming formulation developed by the Dr. Pardalos is used to establish optimal routes of evacuation within the appliance. An initial optimal solution is established by the optimization model that incorporates multimodal transportation in its routes. The model later receives its input from the CH3D-SSMS storm surge and inundation model that provides the input to the model in terms of the failed links and nodes in the network (closed bridges and closed ports). The new set of optimal routes for this reconfigured network is then determined without solving the optimization model from scratch. Heuristic and exact strategies are developed to determine the alternate routes of evacuation. The heuristic explorations are based on re-calculating the shortest paths between pairs of origin and destination with link failures.



This solution procedure does not involve the entire optimization model for the new network but rather, uses heuristic algorithms to recalculate only those paths that have failed links and nodes and hence, provides a computationally effective strategy. The results from the heuristic are compared with the solution of the optimization model solved for the reconfigured network. Then, an empirical guarantee to the approximation of the solution is provided and theoretical guarantees to the solutions are provided. Exact techniques to establish these alternate routes without solving the optimization model entirely are developed using a mathematical formulation. The computation performance of these methods is then be compared and presented.

In the first stage of MTEVA development, with the assistance of Dr. Figueiredo's ACIS Laboratory, a baseline grid appliance is configured and deployed and project partners trained in its use and operation. In the second stage, the interfaces necessary to couple the storm surge and evacuation models are developed. In addition, the hypothetical study domains are constructed and a prototype of the input graphical user interface (GUI) is designed using model interchange formats. In the third stage the models are coupled and an output GUI was developed using OpenLayers. Finally, in the fourth stage, the models and GUIs are transferred to the grid appliance and educational content is developed. An example of a similar educational virtual appliance GUI is shown below.

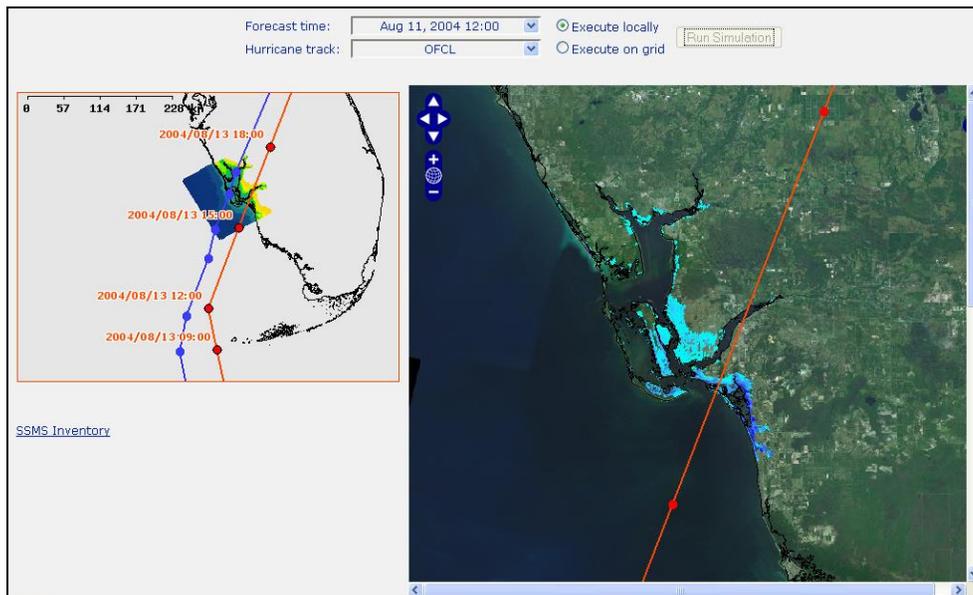


Figure 1 One of the web interfaces used in the SCOOP educational virtual appliance. This interface is used to demonstrate the “forecasting” of inundation during the passage of Hurricane Charley (2004) using different wind fields.



OVERVIEW OF A GRID APPLIANCE

A Grid Appliance (GA) is a self-configuring Virtual Machine (VM) that is used to create and deploy ad-hoc pools of computational resources (Wolinsky et al. 2006). A main motivation of the GA is to provide users who are not experts in information technology and cyber-infrastructure with a plug-and-play computational appliance that makes it possible for end-users themselves to deploy a computational appliance tailored to their own domain of interest. It accomplishes this by combining three key technologies: virtualization of machines and networks, zero-configuration based on peer-to-peer techniques, and job schedulers.

A VM can be thought of as providing a software instance of a physical resource. A VM runs within a Virtual Machine Monitor (VMM) (also called a hypervisor) which either runs within a host computer operating system (e.g. VMware Player) or directly on the “bare-metal” of a physical resource (e.g. VMware ESX). Although multiple VMs can be running simultaneously on a resource, VM’s are completely isolated from other running applications, thus providing numerous security, development, and software bundling benefits. Within a GA’s VM are all of the necessary operating system, modeling/visualization tools, self-configuration scripts, and cyberinfrastructure middleware for job scheduling and management, to provide the user with a complete end-to-end application.

The GA runs the Debian-based Ubuntu GNU/Linux operating system and includes a lightweight window manager (IceWM) for the X Window System. This interface is accessed through a console connection from the host running the VM (Figure 2-upper left). However, other mechanisms are available to access the appliance including SSH/SCP/SFTP for terminal connections and Samba for file sharing. Additionally, as was used in prior coastal and estuarine science applications, a web server (e.g., the Apache HTTP Server) can be installed to provide web-based access either through the console or through the host computer. Web-based Graphical User Interfaces (GUIs) can then be built to provide very rich and interactive user environments (Figure 2-upper right and lower left/right).

Appliances can run applications locally within the appliance itself or connect to other resources within either a local area network (LAN) or a wide area network (WAN). To date, a majority of appliance applications have focused on executing high-throughput, long-running jobs; however, appliances have also proven successful in performing real-time, forecasting simulations (Davis et al. 2010b). Appliances connect to other resources and form pools using a self-configuring peer-to-peer (P2P) virtual network using private IP addresses called IPOP (Ganguly et al. 2006). Upon starting an appliance, it is automatically connected to a pool of resources and is capable of submitting and executing jobs using a “Grid” scheduler (e.g. Condor, Globus GRAM, PBS, etc.).

Currently, a public infrastructure for bootstrapping such pools is running on PlanetLab (<http://www.planet-lab.org>); deployments on private resource pools are also supported. For example, pools are currently in place for researchers working on a U. S. National Oceanographic and Atmospheric Administration (NOAA) Integrated Ocean Observing System (IOOS) funded surge and inundation Testbed (<http://ioos.coastal.ufl.edu>) as well as for the Southeastern



Universities Research Association's (SURA's) Coastal Ocean Observing and Prediction Program (SCOOP) (<http://scoop.sura.org>). The GA approach is fully compatible with cloud-provided "Infrastructure-as-a-Service" (IaaS) resources (e.g. Amazon EC2) as well as national cyber-infrastructures for research and education such as the Science Clouds (<http://www.scienceclouds.org>) and the NSF FutureGrid (<http://www.futuregrid.org>). This compatibility is an advantage of virtual appliance packaging and the use of virtual networks, that is, a user can run an appliance on local resources, on cloud-provided resources, or both. Amazon EC2 provides an infrastructure where to run appliances, what the Grid Appliance provides in this context is an environment that is tailored to the science community, in particular educators.

To build an "educational" virtual appliance (EVA) like the MTEVA discussed herein, additional domain specific technologies are added to the base distribution of the GA. These technologies can include numerical models (executable or source), statistical analysis packages, data processing scripts, etc. which are then paired with educational lesson plans. This approach allows educators to develop educational content which can be delivered in a very low-level, hands-on environment. However, additional visualization tools can also be incorporated to facilitate the development of high-level, GUI-driven applications which may be more appropriate for some classes of students. The appliance is then used to educate scientists, engineers and students on three key aspects of such environments: application development and deployment on science gateways (for model developers); user, resource and application management (for CI technical personnel); and simulation-based experimentation on science gateways (for end users in research and education). Further details on prior coastal and estuarine science applications of the GA can be found in Davis et al. (2010a, 2010c).

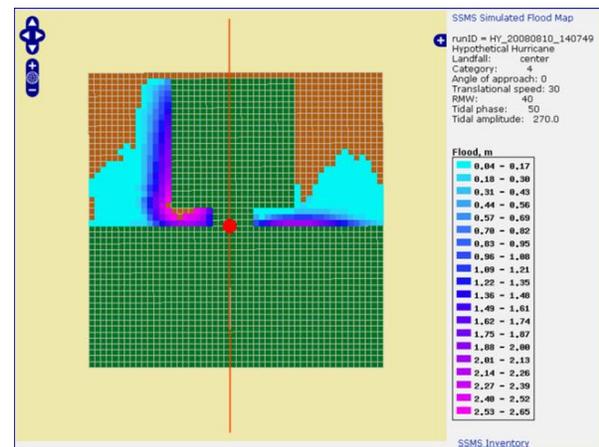
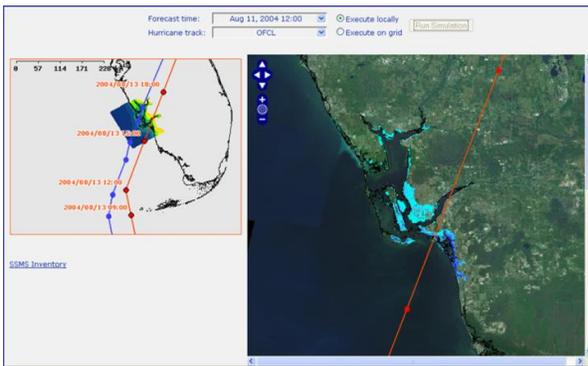
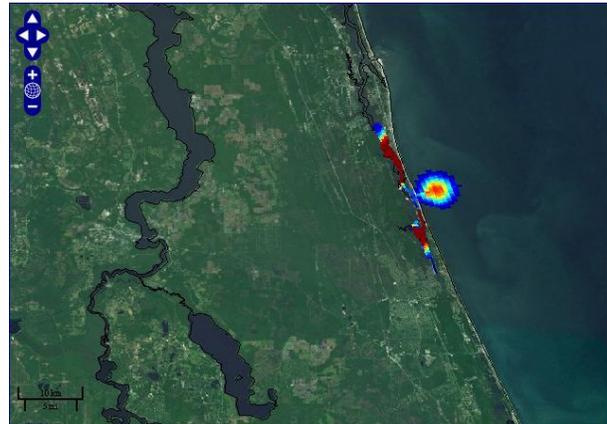
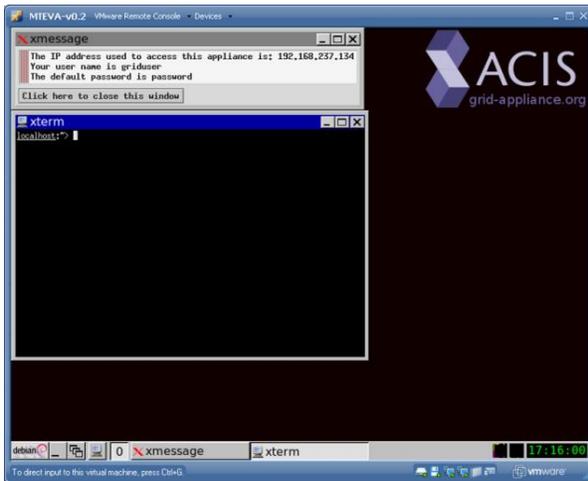


Figure 2 The basic Grid Appliance interface is provided through a simple X-Windows interface (upper left). Prior applications of the Grid Appliance for study of coastal and estuarine science include: a study of a tracer release in the Guana-Tolomato-Matanzas National Estuarine Research Reserve in Northeastern Florida; Charlotte Harbor, Florida’s response to Hurricane Charley (2004); and the response of a hypothetical domain to a variety of hypothetical storms.

A “LIVE” DVD/USB APPLIANCE

The original version of the Grid Appliance (GA) used as the foundation of the MTEVA uses two levels of virtualization. Machine hardware is virtualized through packaging of the GA within a virtual machine, and networking is virtualized through the use of the IP-over-P2P (IPOP) peer-to-peer (P2P) virtual network. Hardware virtualization is convenient in that all of the elements of a complex application (drivers, libraries, etc.) can be packaged together; however, a virtual machine monitor (VMM) is required to be pre-installed before the appliance can be started. As such, there can be instances when the user does not want or need full machine virtualization, for example, the user cannot install a VMM such as VMware Player or VirtualBox, or is solely interested in network virtualization. To overcome this, a new version of the GA is available for users through a Linux/Ubuntu repository which can be installed directly onto an existing machine. While the later version of the GA is more suited toward advanced users familiar with



running Linux desktops, the original VM-based GA can be still be tricky to install for inexperienced computer users. To meet the needs of inexperienced users or just those who would not try the technology if it took more than a couple minutes to install, a “Live” version of the GA has been developed. This version is much easier to use as it does not require any mutable (read/write) secondary (hard drive) storage (i.e. no software is installed on the user’s computer) as the GA is bootable directly off immutable (read-only) secondary storage (e.g., a DVD-R or USB flash drive) (see figure below).

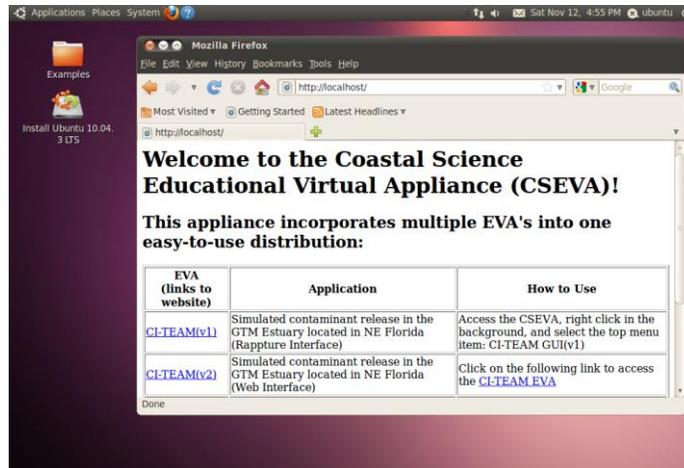


Figure 3 A screenshot of the Grid Appliance as it appears when running as a Live DVD/USB appliance.

The Live Grid Appliance was built using the following steps (adapted from <https://help.ubuntu.com/community/LiveCDCustomization>): An Linux/Ubuntu ISO (*.iso) which contains a Live version of the operating system is obtained and the file system extracted and uncompressed. Then, through the use of a chroot’ed environment, software is installed (including the GA software packages and CSEVA applications). The edited file system is then packed back together, compressed, and put back into an ISO. The ISO enables the image to be run from a VMM or it can be written to removable media and then used to boot a computer directly. Finally, documentation on this bootable appliance was added on the MTEVA website. A summary of the primary differences between the three versions of the GA is shown below.

Table 1 Overview of the different types of installation techniques of a GA.

Implementation Technique	Virtual Machine (VM)	Local Install	Live DVD / USB
Installation level of difficulty	Medium	High	Low
GA software (ipop, Condor, etc.)	Included in the VM	Installed on local secondary storage	Included on the DVD / USB
Application software (e.g. the CSEVA applications)	Included in the VM	Installed on local secondary storage	Included on the DVD / USB
Additional software installed on local secondary storage	Virtual machine monitor (e.g. VMware Player)	None	None
Requirements for networking	None	None	DHCP server on the local network
X11 Windows Manager	IceWM	None	Metacity
Automatic login username	“griduser”	None	“ubuntu”
GA connectivity indicator	Xmessage window	None	None
Distribution size	Medium	Low	High
Persistence of changes to the application or stored results	Yes	Yes	No
Data export level of difficulty	Medium (ssh/samba)	Low	High (ssh,USB)



MODELING COUPLING

The core of the MTEVA is a coupled storm surge and transportation network modeling system. This system, the optimization engine, and all of the associated pre- and post-processing utilities are then packaged into the MTEVA. The main driver of the coupled modeling system is the storm surge model. As this model is simulating the storm surge and inundation response of a storm, it periodically (e.g. once every 15 min) outputs the current pattern of storm surge and inundation as well as the state (all roads passable, certain roads flooded, etc.) of the transportation network. The transportation network optimization model then reads in the state of the network along with a set of capacities, demands etc. and determines the optimal traffic flow. Further details on each of the individual components of this system follow below.

STORM SURGE AND INUNDATION MODEL

The simulation of storm surge and inundation is performed using the CH3D-SSMS (<http://ch3d-ssms.coastal.ufl.edu>) modeling system (e.g. Sheng et al. 2010). The modeling system includes a high resolution coastal surge model CH3D which is coupled to a coastal wave model SWAN and large scale surge and wave models. Currently, CH3D and SWAN can receive open boundary conditions from a number of large scale surge models (ADCIRC, UnCH3D, etc.) and wave models (e.g., WaveWatch-III and SWAN, etc.). Finally, a hypothetical analytic storm (Holland 1980) model is also incorporated into the system which, due to high winds and the inverse barometric effect, is the forcing mechanisms which leads to flooding of various parts of the domain.

CH3D-SSMS is validated using many recent Atlantic Basin hurricanes (e.g. Sheng et al. 2010) and is used to produce a FIRM (Flood Insurance Rate Map) for Pinellas County, FL. CH3D-SSMS was also used to produce surge atlas which was compared with the SLOSH (the model used by the National Hurricane Center) surge atlas. Since 2004, CH3D-SSMS has been advanced to provide real-time forecast of hurricane wind, storm surge, wave, and coastal inundation for various parts of FL and Gulf coasts during hurricane seasons (Sheng et al. 2006; Sheng et al. 2010; Davis et al. 2010b).

The foundation of CH3D-SSMS is the CH3D (Curvilinear-grid Hydrodynamics in 3D) model developed by Sheng (1997, 1990). CH3D has been extensively applied to and validated with data from various coastal, estuarine, and lake waters throughout the U. S. For example, CH3D is the cornerstone of the Chesapeake Bay Model used by the U. S. Environmental Protection Agency and surrounding states to manage water quality and resources. For simulation of storm surge and coastal inundation, CH3D has been enhanced to include flooding-and-drying, current-wave interaction (current-wave bottom boundary layer, wave-breaking induced radiation stress, and wave drag), variable bottom roughness which depends on the variable land use types, and the ability to accept various realistic or analytic wind fields.



NETWORK OPTIMIZATION ALGORITHMS

Scenario Based Instantaneous Evacuation Planning (1st Generation Model)

A model to simulate the instantaneous evacuation planning given a specific scenario is developed in which both a transportation network and demands from all existing nodes are defined. This model minimizes the costs incurred by reversing arcs to evacuate people from all nodes if/when necessary. The solution will show which arcs have to be reversed and how many people should be evacuated through all the arcs. The formulation is shown as follows,

$$\begin{aligned}
 \text{Min} \quad & \sum_{(i,j) \in A} c_{ij} \beta_{ij} \\
 \text{s.t.} \quad & \sum_{j \in A_i^+} f_{ij} - \sum_{j \in A_i^-} f_{ji} \geq d_i, & \forall i \in N \\
 & 0 \leq f_{ij} + u_{ij} \beta_{ij} \leq u_{ij}, & \forall (i,j) \in A \\
 & -u_{ij} \leq f_{ij} \leq u_{ij}, & \forall (i,j) \in A \\
 & \beta_{ij} \in \{0,1\} & \forall (i,j) \in A
 \end{aligned}$$

where c_{ij} is the cost of reversing arc (i,j) , d_i is the demand of node i , and u_{ij} is the capacity of arc (i,j) . This is a mixed integer linear program, which includes both binary variables, β_{ij} 's, and continuous variables, f_{ij} 's, which are the flows of the arcs.

$$\beta_{ij} = \begin{cases} 1, & \text{Arc } (i,j) \text{ is reversed;} \\ 0, & \text{o/w.} \end{cases}$$

This problem is an NP-hard problem (a variant of the knapsack problem); however, it only has $|A|$ integer variables and can be easily solved using integer programming software.

Enhanced Instantaneous Evacuation Planning (Enhanced 1st Generation Model)

The original evacuation model did not include costs associated with travel on any of the arcs. As a result, “cycles” could form in which evacuees would repeat the same closed pathway over and over, an unrealistic result. To alleviate this issue and to make a more robust model, each arc was assigned a travel cost and then the optimization function was modified to minimize this value. The formulation of this new model can be written as:

$$\begin{aligned}
 \text{Minimize:} \quad & \sum_{(i,j) \in A} c_{ij} \beta_{ij} + \sum_{(i,j) \in A} h_{ij} |f_{ij}| \\
 \text{Subject to:} \quad & \sum_{j \in A_i^+} f_{ij} - \sum_{j \in A_i^-} f_{ji} \geq d_i, & \forall i \in N, \\
 & 0 \leq f_{ij} + u_{ij} \beta_{ij} \leq u_{ij}, & \forall (i,j) \in A, \\
 & -u_{ij} \leq f_{ij} \leq u_{ij}, & \forall (i,j) \in A, \\
 & \beta_{ij} \in \{0,1\}, & \forall (i,j) \in A,
 \end{aligned}$$



where N is the set of all nodes, A is the set of all arcs, f_{ij} is the flow through arc (i, j) , c_{ij} is the cost of reversing arc (i, j) , d_i is the demand of node i , u_{ij} is the capacity of arc (i, j) , h_{ij} is the travel cost of arc (i, j) , and the binary variable β_{ij} , is defined as

$$\beta_{ij} = \begin{cases} 1, & \text{if arc } (i, j) \text{ is reversed;} \\ 0, & \text{otherwise.} \end{cases}$$

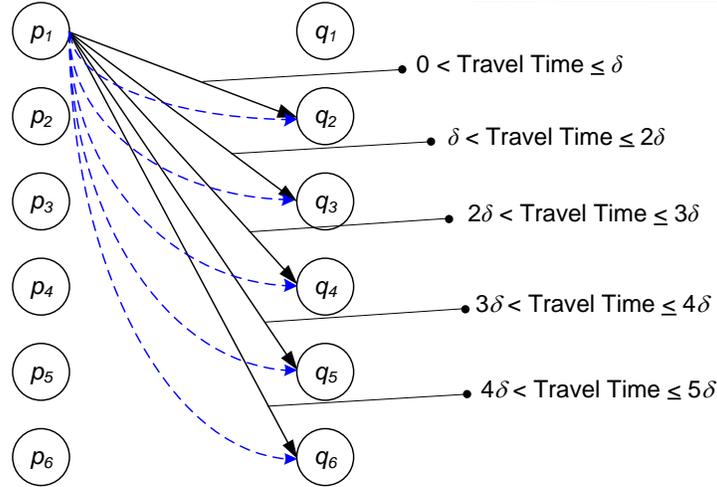
This new model was tested and incorporated into the MTEVA.

Dynamic Traffic Assignment Model for Evacuation Scheduling (2nd Generation Model)

Compared to the instantaneous model, a more comprehensive and realistic model should include the temporal information of all these arc reversals and flows. To be able to do this, a time expanded network model would be more appropriate, where all the arcs are given another index, time point.

When the temporal indices are added to all variables, it also greatly increases the computational costs, because it not only increases the number of integer variables to $O\left(|A| \times \frac{T(T-1)}{2}\right)$, but also introduces more constraints, such as travel time upper bound and lower bound constraints, first in first out constraints, unique realization constraints and so on. The next step builds a more realistic and comprehensive evacuation scheduling model on a time expanded network, which will help determine when to reverse an arc and what amount of people should be sent at a specific time point before a node is potentially destroyed by wind or water. Because of computational intensity of this model, developed a new decomposition algorithm has been developed to solve it both effectively and efficiently.

In the time expanded network, copies of each node are made first by adding time stamp to define the time expanded nodes. And then the time expanded nodes are connected to form time expanded arc, each of which has a tail node with smaller time stamp and head node with a bigger time stamp. The following is an example of a time expanded arc.



In the above graph, the binary variable $z_{p_t, q_{t+\tau}}$ is used to denote whether time expanded arc $(p_t, q_{t+\tau})$ is realized, because in reality there is only one unique travel time for anybody. The constraints are

$$\sum_{\tau \in \Delta_{p,q}} z_{p_t, q_{t+\tau}} = 1,$$

$$y_{p_t, q_{t+\tau}} \leq M_{p,q} z_{p_t, q_{t+\tau}}$$

where $y_{p_t, q_{t+\tau}}$ denotes the flow on the time expanded arc. In order to determine the travel time of an arc, the following constraint is included,

$$\sum_{\tau \in (\Delta_{p,q} \setminus \delta)} (\tau - \delta) z_{p_t, q_{t+\tau}} \leq \phi_{p,q}(x_{p,q}(t)) \leq \sum_{\tau \in (\Delta_{p,q})} \tau z_{p_t, q_{t+\tau}}, \quad \forall (p,q) \in A, t \in T$$

where $x_{p,q}(t)$ is the number of vehicles on arc (p,q) at time t .

In order to model arc reversal another variable $\beta_{p,q}^t$ is introduced to denote if the arc (p,q) is reversed at time t and use $z'_{p_{t+\tau}, q_t}$ to denote the realization of the reversal arcs,

$$\sum_{\tau \in \Delta} z_{p_t, q_{t+\tau}} \leq \beta_{p,q}^t$$

$$\sum_{\tau \in \Delta} z'_{p_{t+\tau}, q_t} \leq (1 - \beta_{p,q}^t)$$

However, the following tighter formulation can be used without using $\beta_{p,q}^t$

$$\sum_{\tau \in \Delta} z_{p_t, q_{t+\tau}} + \sum_{\tau \in \Delta} z'_{p_{t+\tau}, q_t} \leq 1, \quad \forall (p,q) \in A, t \in T$$



If an node (p) is not valid (destroyed by hurricane at time t), then

- 1) Arrival at the node must occur earlier than t

$$\begin{aligned} z_{q_{t-\eta}, p_t} &= 0, & \forall q, \eta, \tau \geq t \\ z'_{p_t, q_{t-\eta}} &= 0, & \forall q, \eta, \tau \geq t \end{aligned}$$

- 2) The node must be left by t

$$\begin{aligned} z_{p_t, q_{t+\eta}} &= 0, & \forall q, \eta, \tau \geq t \\ z'_{q_{t+\eta}, p_t} &= 0, & \forall q, \eta, \tau \geq t \end{aligned}$$

Actually this means that all these arcs can be dropped in the time expanded network. Upon the above definitions and formulations, the DTA-Evacuation model can be formulated as follows,

$$\text{Min} \quad \sum_{(p,q) \in A} \sum_{t \in T} \sum_{\tau \in \Delta} \tau (f_{p_t, q_{t+\tau}} + f'_{p_t, q_{t+\tau}})$$

s.t. Flow balance constraints,

Travel time constraints,

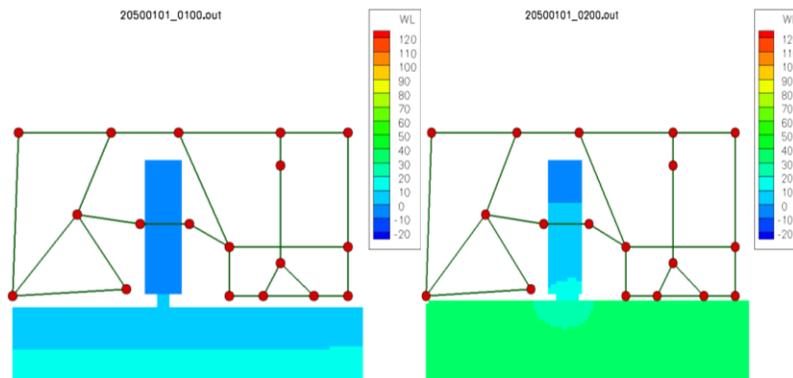
$$\sum_{\tau \in \Delta} z_{p_t, q_{t+\tau}} + \sum_{\tau \in \Delta} z'_{p_t, q_{t+\tau}} \leq 1, \forall (p, q), t$$

$$z_{p_t, q_{t+\tau}} + \sum_{\eta \in \Delta} z'_{p_{t+\zeta}, q_{t+\eta}} \leq 1, \forall \delta \leq \zeta \leq \tau - \delta$$

$$z, z' \in \{0,1\}^N$$

The following is a demonstrative example of the DTA-evacuation model to show its efficacy,

- 1) The following graphs show the water level Water level of +1 and +3 hour (planning horizon 1-2).





Heuristic Approach to Solution

In order for scalability to be ensured, a heuristic approach is designed and implemented. It was also tested in a series of large-scale randomly generated instances to validate it.

First, it is a known issue that in a real-life evacuation scheme, the original exact methodology proposed is highly inefficient and computationally expensive. It becomes imperative then to adopt a heuristic approach. When dealing with heuristic methods, the tradeoff between computational cost and solution quality must be analyzed.

In general, the algorithm for a dynamic traffic assignment/evacuation planning system is:

1. Read the node/arc status and the demands
2. Solve the network flow problem at each iteration
3. Update the demands
4. If there are still vehicles using the network, proceed to 1. Otherwise, terminate.

Clearly there are a couple of issues with the approach:

- How can the exact position of a vehicle be known after it has left a node?
- How can it be ensured that a vehicle is not routed towards an arc that has been destroyed?

The above questions, among others, have made the testing process of the algorithm a necessity. An Augmented Lagrange approach is being implemented to solve the issues encountered in a large-scale, dynamic framework. Preliminary results are presented below.

Table 2 Efficiency estimates of the Augmented Lagrange approach

Network Size (nodes)	Average Optimality Gap (%)	Maximum Optimality Gap (%)	Average Time Decrease (%)	Maximum Time Decrease (%)
16	0.21	1.05	90	91.5
100	0.26	0.98	94	95
1000	0.33	1.05	95	97
Overall	0.3	1.7	92	97

In the future, sparsity factors will be investigated along with the application of the algorithmic framework of Lagrange Duality in a real-life large-scale evacuation management suite.



ENHANCEMENT OF THE TIME STATIC NETWORK ASSIGNMENT MODELS

The original MTEVA uses a single static model that is solved periodically based on whether or not nodes/links are accessible:

$$\begin{aligned}
 \text{[I]} \quad & \min \sum_{(i,j) \in A} c_{ij} \beta_{ij} + \sum_{(i,j) \in A} h_{ij} (x_{ij}^+ - x_{ij}^-) \\
 & \text{s. t.} \quad \sum_{j \in A_i^+} f_{ij} - \sum_{j \in A_i^-} f_{ji} = d_i, \quad \forall i \in N \\
 & \quad \quad 0 \leq f_{ij} + u_{ji} \beta_{ji} \leq u_{ij}, \quad \forall (i,j) \in A \\
 & \quad \quad -u_{ij} \leq f_{ij} \leq u_{ij}, \quad \forall (i,j) \in A \\
 & \quad \quad x_{ij}^- \geq -f_{ij}, \quad \forall (i,j) \in A \\
 & \quad \quad x_{ij}^+ \geq f_{ij}, \quad \forall (i,j) \in A \\
 & \quad \quad \beta_{ij} \in \{0,1\}, \quad x_{ij}^+ \geq 0, \quad x_{ij}^- \geq 0, \quad \forall (i,j) \in A
 \end{aligned}$$

where

Notation	Description
N	The set of nodes in the network
A	The set of links (e.g. roads) in the network
d_i	The demand at each node
c_{ij}	The cost/time to reverse link $(i,j) \in A$
h_{ij}	The cost/time to traverse link $(i,j) \in A$
u_{ij}	The capacity of link $(i,j) \in A$
f_{ij}	Flow variable on link $(i,j) \in A$
β_{ij}	Binary variable which indicates if link $(i,j) \in A$ is reversed.

In this model, the total cost/time incurred is minimized subject to a series of constraints satisfying the transportation demand (the number of people/cars/etc. desiring to move from one node to a safety node, e.g. evacuating from their beach front houses to inland shelters), flow balance (the actual number moving), link capacities and the dummy variables involved. Unfortunately, this model is not tight since there are a number of redundant constraints that can be formulated better. As such, a new model is implemented:

$$\begin{aligned}
 \text{[II]} \quad & \min \sum_{(i,j) \in A} c_{ij} \beta_{ij} + \sum_{(i,j) \in A} h_{ij} f_{ij} \\
 & \text{s. t.} \quad \sum_{j \in A_i^+} f_{ij} - \sum_{j \in A_i^-} f_{ji} = d_i, \quad \forall i \in N \\
 & \quad \quad f_{ij} \leq u_{ij} + u_{ji} \beta_{ji}, \quad \forall (i,j) \in A \\
 & \quad \quad \beta_{ij} \in \{0,1\}, \quad f_{ij} \geq 0, \quad \forall (i,j) \in A
 \end{aligned}$$

In the new model, the objective function again minimizes the total costs incurred by using or reversing the links in the network. The first set of constraints ensures the flow preservation in each and every one of the nodes, while the second set controls the capacity of each link after



taking into consideration the fact that the links can be reversed. The new model is more computationally efficient and it is the one currently used as the “Time Static Deterministic Algorithm” found on the MTEVA.

Additionally, a new model is now implemented which solves the network assignment as a maximization problem. Whereas the previous model required that the demand be satisfied (in the minimum amount of time), the new model maximizes the flow (some demand may be unmet) given a specific time constraint. This is a more realistic representation of the original problem as demand may exceed network capacity (“gridlock”). This model efficiently solves the network assignment problem and only has to be updated when a link or node becomes unusable (e.g. a flooded road):

$$\begin{aligned}
 \text{[III]} \quad & \max \quad \sum_{i \in N/S} \sum_{j \in S} f_{ij} \\
 & \text{s. t.} \quad \sum_{j \in A_i^+} f_{ij} - \sum_{j \in A_i^-} f_{ji} \leq d_i, \quad \forall i \in N/S \\
 & \quad \quad \quad f_{ij} = 0, \quad \forall i \in S \\
 & \quad \quad \quad f_{ij} \leq u_{ij} + u_{ji} \beta_{ji}, \quad \forall (i, j) \in A \\
 & \quad \quad \quad \beta_{ij} \in \{0, 1\}, \quad f_{ij} \geq 0, \quad \forall (i, j) \in A
 \end{aligned}$$

where S is the set of all “safe” destination nodes, N/S is the set of all the nodes excluding S. Thus, combining S and N/S yields N, the set of all nodes in the graph.

QUASI-DYNAMIC ALGORITHM

It is clear that the time static models are useful only in theory, because we essentially assume that all roads are used instantaneously. That is, all vehicles have to leave at the same time, using the arcs of the network simultaneously. As a result, the capacity constraints enforced will make the problem infeasible and unrealistic. However, these models are easy to verify and can provide useful insight into the types of algorithms that can be applied. Unfortunately, they hold no practical use in real-life network assignment (e.g. evacuation management) problems. Hence, it is important from both the educational and the practitioner point of view to design and implement the so-called “time dynamic” models. In a dynamic approach, roads are allocated to vehicles at different times, an approach that makes the problem more realistic, but also much more complicated.

In order to solve this inconsistency of the static version, a quasi-dynamic algorithm is used in the MTEVA. Rather than solving for all flows simultaneously, the solution is iterated based on the flow and demand at a previous time:

Algorithm: Iterative algorithm to solve the maximization problem

```

while  $\sum_{i \in N/S} d_i > 0$  do
  Solve maximization problem [III]
  Update  $d_i, \forall i \in N$ 
end while

```



DEVELOPMENT OF THE TIME DYNAMIC NETWORK ASSIGNMENT MODELS

In this first dynamic model, the time it takes for all demand from the endangered areas to the safe areas is minimized:

$$\begin{aligned}
 \text{[IV]} \quad & \min \sum_{t \in T} \sum_{(i,j) \in A} c_{ij} \beta_{ij}^t + \sum_{t \in T} \sum_{(i,j) \in A} h_{ij}^t f_{ij}^t \\
 & \text{s. t.} \quad \sum_{t \in T} \sum_{j \in A_i^+} f_{ij}^t - \sum_{t \in T} \sum_{j \in A_i^-} f_{ji}^t = d_i, \quad \forall i \in N \\
 & \quad \quad \quad f_{ij}^t \leq u_{ij} + u_{ji} \beta_{ji}^t, \quad \forall (i,j) \in A, \quad \forall t \in T \\
 & \quad \quad \quad \beta_{ij}^t \in (0,1), \quad f_{ij}^t \geq 0, \quad \forall (i,j) \in A, \quad \forall t \in T
 \end{aligned}$$

Clearly the formulation presented in [IV] is more realistic; however, it is a more complex mixed integer problem. As the problem scales in size, the optimization techniques to solve this problem become less and less efficient. In the second model, the inflow to the safety zones is maximized during a given time horizon. This inflow is also the number of vehicles that eventually reach a safe location before the end of the evacuation phase:

$$\begin{aligned}
 \text{[V]} \quad & \max \sum_{t \in T} \sum_{i \in N/S} \sum_{j \in S} f_{ij}^t \\
 & \text{s. t.} \quad \sum_{t \in T} \sum_{j \in A_i^+} f_{ij}^t - \sum_{t \in T} \sum_{j \in A_i^-} f_{ji}^t \leq d_i, \quad \forall i \in N/S \\
 & \quad \quad \quad f_{ij}^t = 0, \quad \forall i \in S, \quad \forall t \in T \\
 & \quad \quad \quad f_{ij}^t \leq u_{ij} + u_{ji} \beta_{ji}^t, \quad \forall (i,j) \in A, \quad \forall t \in T \\
 & \quad \quad \quad \beta_{ij}^t \in (0,1), \quad f_{ij}^t \geq 0, \quad \forall (i,j) \in A, \quad \forall t \in T
 \end{aligned}$$

As with the previous model, it is a more complex optimization problem to tackle than the time static counterpart.

Overall, the MTEVA aims to simulate the time varying storm surge and inundation response of a region while at the same time solving the network assignment optimization problem. Hence, the optimization problem is solved at periodic intervals (e.g. every 30 min) to keep track of both demand, that has been met up to that point, as well as the state of the network. The new solution procedure now combines both the minimization and maximization problems in order to tackle this dynamically updated network. The MTEVA tries to satisfy as much demand as possible within a fixed time period, even if all demand cannot be satisfied.

OPTIMIZATION TECHNIQUES

We are currently researching a second heuristic method, one employing neural networks. It has already proved to be exceedingly fast, while the quality of solution remains high, in the first experiment results obtained. The heuristic method is coded in C++, as are all the other methods



already written, and employs the open-source solver GLPSOL. The algorithmic design of the heuristic is presented in Figure 1.

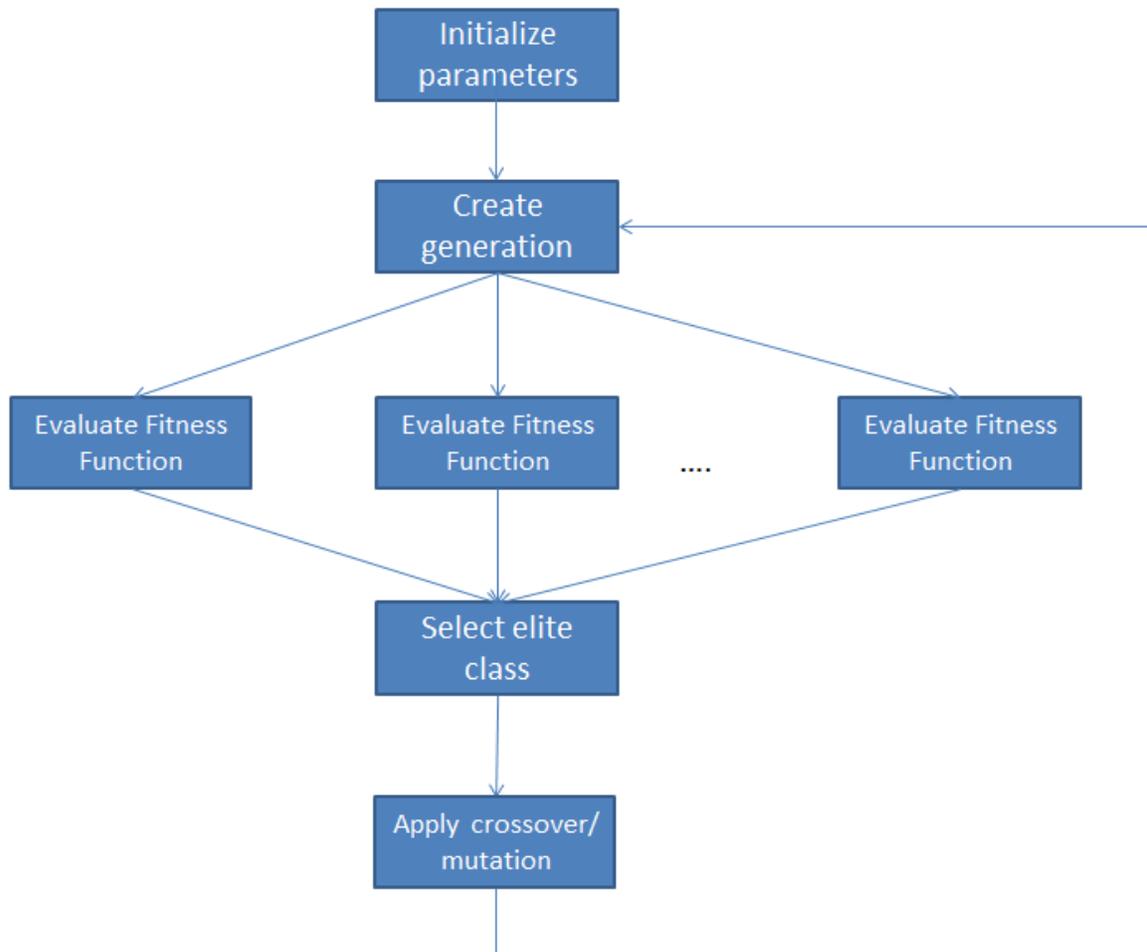


Figure 4 Neural network optimization for solving large scale evacuation problems with contraflow.

ALGORITHM IMPLEMENTATION

As with the original MTEVA, the public domain optimization software GLPK (GNU Linear Programming Kit) (<http://www.gnu.org/software/glpk>) is being used to implement the algorithms.

SURGE-TRANSPORTATION COUPLING

The evacuation planning and storm surge modeling system are coupled through the exchange of node-arc information between the two models. Initially, the storm surge model is provided with locations of the nodes and arcs. As a storm approaches and makes landfall, the storm surge model checks to see if the arcs become impassable (e.g. due to flooding or excessive wind speed on a bridge) and if so, the storm surge model informs the evacuation model and the evacuation plan is updated.



During a simulation, potential nodes fall into several possible categories: 1) The node is connected to one or more other nodes via an arc; 2) The node is isolated and no longer has any connections (e.g. due to a flooded road), but may reconnect in the future; or 3) The node has been destroyed and will never again be connected to any other nodes. Nodes are considered destroyed if flooding exceeds some critical value, H_{Ncr} .

Each arc within the network is defined as either a “road” or a “bridge”. A road is considered indestructible, while a bridge is not. Roads are assumed at some height, R_A , above (or below) the surrounding topography and become unusable if, during the course of a simulation, the water level at any location on the road exceeds some critical value, H_{Acr} , above the road. If, at any point of time later, the water level retreats – the road becomes usable again. Each bridge has its own elevation relative to the simulation vertical datum (e.g. NAVD88), B_A . If, during the course of a simulation, the water reaches the bridge, it’s then considered “destroyed” and permanently unusable. Additionally, regardless of water level, bridges are also assumed to be impassable during periods of high wind when the wind speed exceeds some critical value, W_{Acr} . Finally, for simplicity, optimization costs for the current application were set to constant values, each value of c_{ij} was set 1 and each value of h_{ij} was set to 0.1.

OVERVIEW OF THE NETWORK OPTIMIZATION INPUT AND OUTPUT FILES

During operation of the coupled modeling system, multiple input and output files are used (see Appendix). To support larger domains and better handle the new time dynamic algorithms, several enhancements have been made to the file specifications defined with the original MTEVA:

- Output files of CH3D model are provided in NetCDF format. NetCDF files are significantly more compact compared to the shapefiles that were used in the past and can be directly displayed by a variety of available NetCDF viewers
- Output files of the transportation model are still ASCII files, but the structure of the file is more compact, in addition a single output file now contains all time steps of the model. Model output, however, is now converted to a more portable KML file that can be readily accessed by many different viewers including Google Earth and integrated into Google Maps as well as the OpenLayers that is used for visualization within the appliance.

DESIGN OF THE MTEVA

Starting from the original MTEVA distribution, several new network algorithms have been added and the visualization interface has been updated. The list of available algorithms now consists of the following: Time Static Deterministic that aims at minimizing the time of evacuation, Time Static Deterministic that aims at maximizing the number of people evacuated, Time Dynamic Deterministic that aims at minimizing the time needed to evacuate everyone, Time Dynamic Deterministic that aims at maximizing the number of people to be evacuated (this can be used if the previous solution is infeasible) and Time Dynamic Heuristic that provides an alternative (non-exact) solution in a fraction of the time required for the deterministic algorithm.



3. FINDINGS AND APPLICATIONS

DEVELOPMENT OF THE NORTHEAST FLORIDA SCENARIO

In the new scenario, storm surge and inundation in the Northeast Florida region is simulated using a high resolution (100 m) CH3D-SSMS model for Northeast Florida (255x1201 cells). The domain extends from the Florida/Georgia border to West Palm Beach, Florida and extends ~40 km offshore. This model is then coupled with the same transportation network assignment models used in the theoretical domain using a simple idealized transportation network as inputs. Several scenarios describe a hypothetical storm, similar in size to Hurricane Katrina, making landfall on the east coast of Florida in presence of sea level rise (SLR) amount of which can vary depending on different estimates. Inputs to the scenario are provided through a simple GUI (Figure 5) which allows for variation of network assignment algorithm, amount of SLR, SLR algorithm, etc. The SLR values chosen are 100 year projections derived from a continuation of the approximate local linear trend (+21 cm) (the average of the nearby Mayport and Fernandina tide stations is +2.2 mm/yr) (NOAA Tides and Currents 2011), an estimate based on IPCC (Intergovernmental Panel on Climate Change) mid-range scenario A1B (+50 cm) (Meehl et al. 2007), and those of Vermeer and Rahmstorf (2009) (+ 150 cm). Two algorithms for determining the effect of SLR on storm surge and inundation are included. The first, referred to as the “ad-hoc” algorithm, simply adds the SLR onto the final simulated water level. The second, referred to as the “integrated” algorithm, add the SLR onto the water level boundary and initial conditions used in the model such that the model simulates the end effect of the SLR provides a much more realistic estimate of flooding due to SLR as it takes into consideration of the hydrodynamics. The atmospheric storm wind and pressure gradient forcing is supplied by an analytic wind model (Holland 1980) which uses a hypothetical Katrina-like storm (similar size and intensity) track that makes landfall in the region. Currently, the transportation network is a simple synthetic design. Incorporating a real network for the region is part of an ongoing effort. After a simulation is finished, simulated storm surge and inundation are plotted in an output GUI (Figure 6) which allows map navigation along with the ability to toggle display layers (surge and inundation, transportation network, background layers, etc.)



Network Optimization Algorithm:

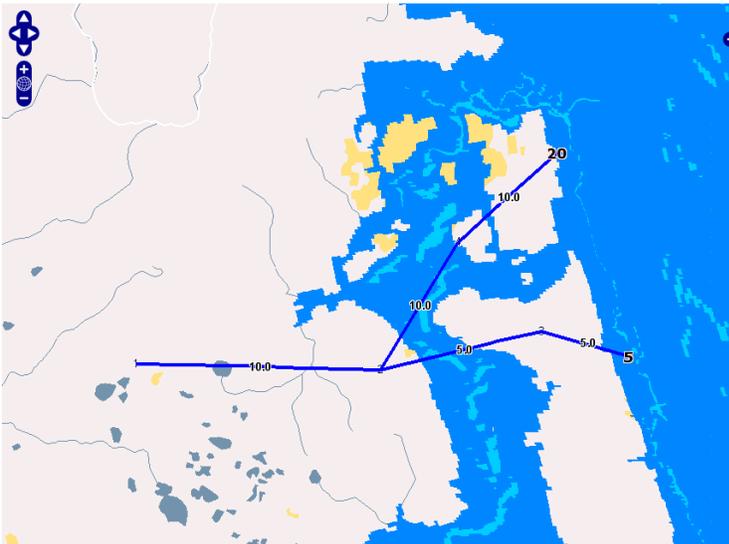
Sea Level Rise Scenario:

Sea Level Rise Algorithm:

Computational Resource:

[Simulation Inventory](#)

Figure 5 The input GUI for the northeast Florida scenario.



Base Layer:

Transportation Network:

Time:

Storm Surge and Inundation:

Optimized Traffic Solution:

[Simulations inventory](#) [MTEVA GUI](#)

Water level (cm)

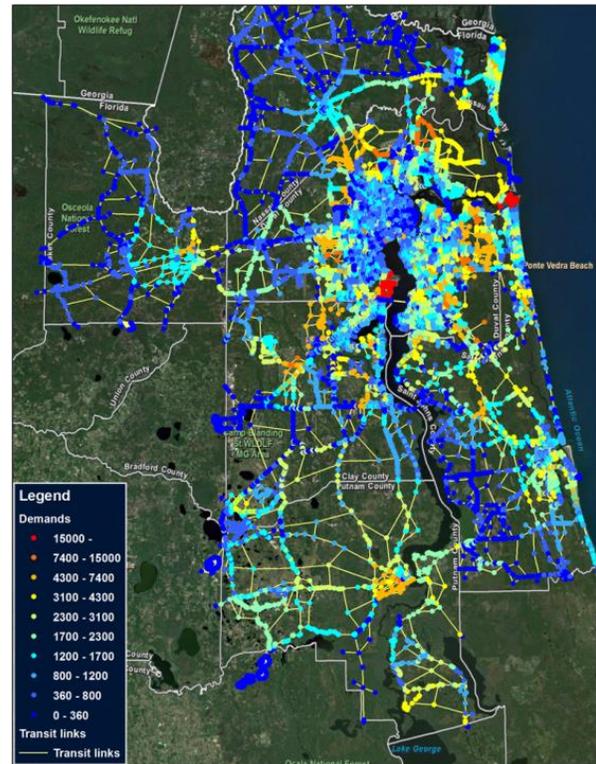
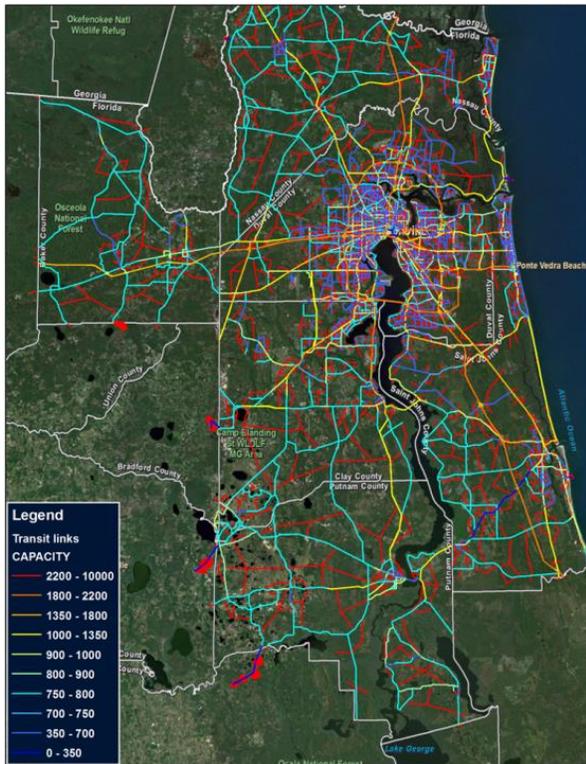
< -20 cm
-10 cm
-0 cm
10 cm
20 cm
30 cm
40 cm
50 cm
60 cm
70 cm
80 cm
90 cm
100 cm
110 cm
120 cm
120+ cm

Figure 6 A snapshot of simulated inundation and transportation network assignment of a Hurricane Katrina-sized storm making landfall in vicinity of the Lower St. Johns River (Northeast Florida).



Northeast (Florida) Regional Planning Model (NERPM) 4.1

The Northeast Florida Regionally Planning Model (NERPM) is a transportation network model currently used by the State of Florida to perform evacuation planning simulations. This model was developed for the Cube modeling system developed by Citilabs. Based on presentations made by Abishek Komma (a former student of CMS Partner Dr. Siva currently employed by Citilabs) and working with Md Shahid Mamun (a student of another CMS Partner, Dr. Yin), we extracted the networking information out of NERPM v.4.1 for use in our evacuation model. In particular, the locations of capacities and demands of the system as shown in the following figures:





JACKSONVILLE TRANSPORTATION NETWORK

Transportation network is based on the newest NERPM4 (NorthEast Regional Planning Model version 4, created for Northeast Florida) – “2005 base” scenario. The network includes 28,585 nodes and 57,814 links. Demands at the nodes are obtained by combining different types of demands (various types of cars, public transportation, etc.) data from the NERPM4 as the current network optimization model does not differentiate between different transportation modes..

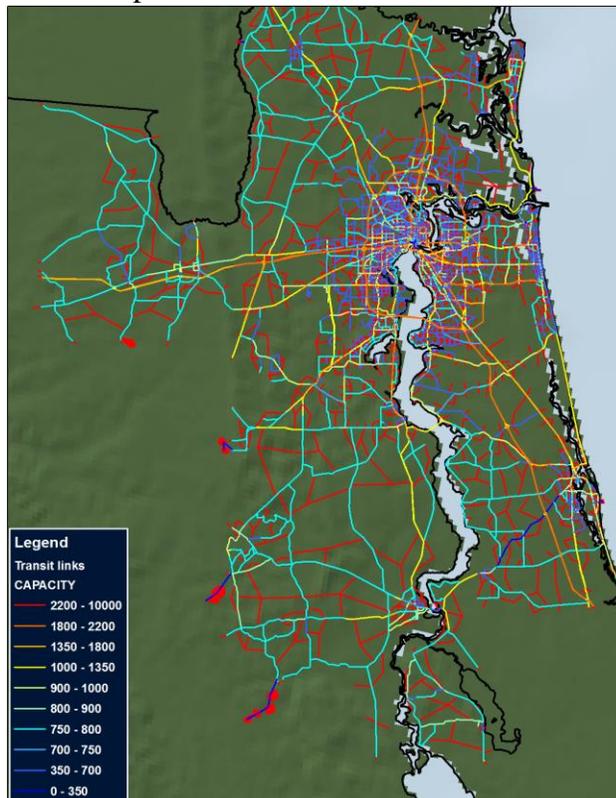


Figure 7 NERPM4 transit links loaded with road capacities

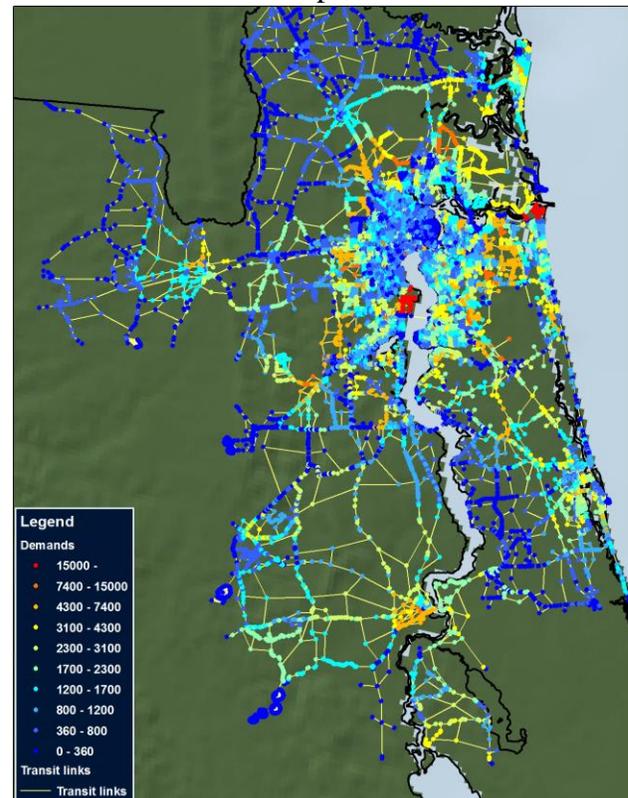


Figure 8 NERPM4 transit links and transportation model nodes, loaded with transit demands

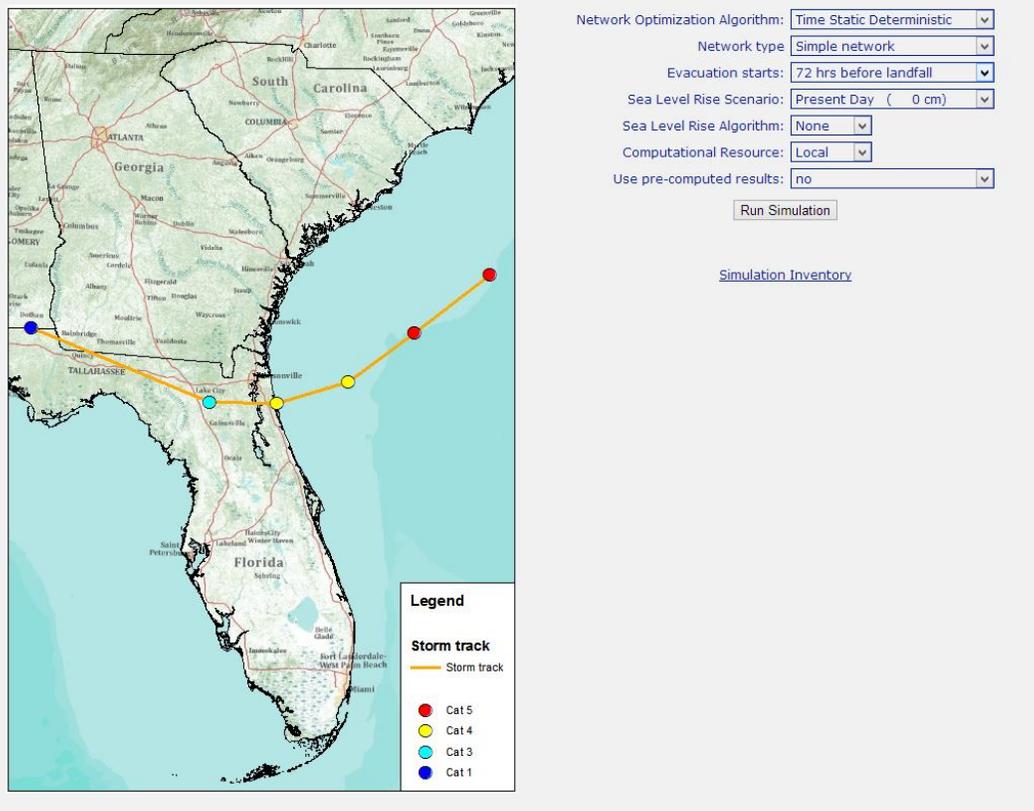
UPDATED WEB-BASED GRAPHIC USER INTERFACE (GUI)

The initial GUI has been expanded (Figure 9) to accommodate more algorithms, an option was added that allows to select between simple and NERPM4 network and another option allows to start evacuation at different time periods relative to the storm landfall and to use pre-computed results. Due to the NERPM4 network being rather large, the simulation of storm surge and transportation can take significant time (up to a few days) depending on the options selected – some pre-computed results are available. An option allows to use pre-computed data for the storm surge mode / or both surge and transport models. All the post-processing still occurs, but instead of actually running models MTEVA substitutes model output files with the pre-computed ones. This allows a user to quickly go to the output without waiting for all the models to finish computations.



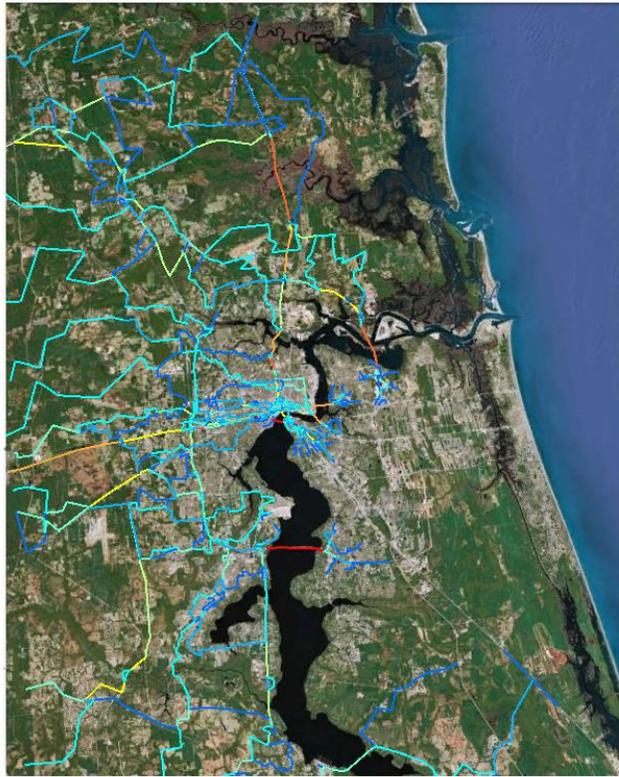
The output method for transportation network and model results has been updated due to addition of the NERPM4 network. The network has over 50,000 links and in order to efficiently show the numbers associated with flows and demands in the network the MTEVA now uses color coding with appropriate legends instead of number labels next to the traffic nodes and roads.

Webpage Screenshot



http://192.168.166.128/MTEVA/NEFlorida/

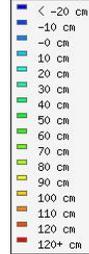
Figure 9 The updated input GUI for the northeast Florida scenario.



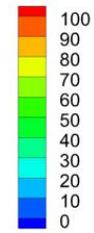
Base Layer:
 Transportation Network:
 Time:
 Storm Surge and Inundation:
 Optimized Traffic Solution:

[Simulations inventory](#) [MTEVA GUI](#)

Water level (cm)



Percent utilization



http://192.168.168.128/MTEVA/NEFlorida/plot.php?runID=MTEVA_20121005_200654

Figure 10 A snapshot of simulated evacuation traffic (percent of utilized capacity) in response to a Hurricane Katrina-sized storm making landfall in vicinity of the Lower St. Johns River (Northeast Florida).



MTEVA ONLINE CONTENT

The MTEVA is available online at <http://cseva.coastal.ufl.edu>. Content provided includes background on the individual models (storm surge and optimization) as well as how they are integrated and used within the appliance.

Storm Surge and Inundation Response Model

The simulation of storm surge and inundation is performed using the modeling system called [CH3D-SSMS](#). It includes a high resolution coastal surge model (CH3D), a coastal wave model (SWAN), along with large scale surge and wave models. In addition, a hypothetical analytic storm model has been implemented into the system.

CH3D-SSMS has been extensively validated with many hurricanes. Since 2004, it has also been used in order to predict and forecast hurricane wind, storm surge, wave and coastal inundation for several Florida and Gulf coasts. For the simulation purposes of the MTEVA, the modeling system has been further enhanced in order to include flooding-and-drying, current-wave interaction, variable bottom roughness for variable land use types and others.

Transportation Optimization Model

Evacuation planning is a vital part of the traffic assignment problem. Given a scenario of events that disrupt normal traffic flow and endanger the public safety, it is of utmost importance to determine the optimal flows for evacuating people and vehicles. The optimization model minimizes the **total travel costs** considering also the cost incurred when **reversing arcs** (counterflow). The formulated combinatorial optimization problem determines the optimal flows for evacuation, along with which arcs need to be reversed. The notation used is presented below:

N the set of all the network nodes
 A the set of all the network arcs
 c_{ij} the cost of reversing arc $(i,j) \in A$
 d_i the demand of node $i \in N$
 u_{ij} the capacity of arc (i,j)
 h_{ij} the travel cost (transportation cost) associated with arc (i,j)
 f_{ij} the flow variable determining the optimal vehicle flow at arc (i,j)
 β_{ij} binary variable defined as 1 if arc (i,j) is reversed and 0 otherwise.

The original minimization mathematical problem can be formulated as follows:

$$\begin{aligned} \min \quad & \sum_{(i,j) \in A} c_{ij} \beta_{ij} + \sum_{(i,j) \in A} h_{ij} |f_{ij}| \\ \text{s.t.} \quad & \sum_{j \in A_i^+} f_{ij} - \sum_{j \in A_i^-} f_{ji} = d_i, \quad \forall i \in N \\ & 0 \leq f_{ij} + u_{ij} \beta_{ij} \leq u_{ij}, \quad \forall (i,j) \in A \\ & -u_{ij} \leq f_{ij} \leq u_{ij}, \quad \forall (i,j) \in A \\ & \beta_{ij} \in \{0,1\} \end{aligned}$$

The formulation is, however, a mixed integer nonlinear problem, which is computationally very hard to solve. The absolute value though in the objective function can be easily linearized by introducing two auxiliary variables making the problem:

Figure 11 Web content describing the models incorporated into the MTEVA.



EDUCATION AND OUTREACH ACTIVITIES

Estuarine and Coastal Modeling 12 Conference (Nov. 7-9, 2011)

Through funding provided by Florida Sea Grant, the MTEVA was integrated with several other formerly independent coastal science applications into a single new appliance: The Coastal Science Educational Virtual Appliance (CSEVA). The applications included span a wide variety of coastal science applications and their integration enhances the user experience (less local storage requirements, easier to install, linked application scenarios, etc.) In addition to the MTEVA enhanced in this study, the CI-TEAM and SCOOP applications were included. The CI-TEAM application simulates the release of a tracer into the waters of the Indian River Lagoon estuarine system (northeast Florida). The SCOOP application simulates storm surge and inundation in two different domains: a simple domain being impacted by a hypothetical storm and Charlotte Harbor (southwest Florida) being impacted by various different wind forecasts for Hurricane Charley (2004). The development of the CSEVA was presented (along with a corresponding refereed publication) at the 12th International Conference on Estuarine and Coastal Modeling (Davis et al. 2011a). An abstract of this publication is shown in Appendix B.

Transportation Research Board Annual Meeting (Jan. 22-27th, 2012)

An oral presentation on the MTEVA was made at the Transportation Research Board (TRB) 91st Annual meeting in Washington, D. C.. The talk went well and particular interest was shown by David W. Jackson, a transportation industry analyst at the VOLPE National Transportation Systems Center. Per his request, more information on the project was sent to him. Although the corresponding TRB paper was not accepted, the referred conference proceeding now appears online through the TRB website. An abstract of this publication is shown in Appendix B.

University of Kentucky Statistics Department Seminar (Apr. 2012)

In April 2012, Chrysafis Vogiatzis, a PhD candidate working on the project, was invited to give a talk at the Statistics Department seminar of the University of Kentucky in Lexington, KY. In the talk, the Augmented Lagrange Heuristic was presented, receiving useful insight from students and staff of the department on potential improvements. In addition to that, while in Lexington, KY, Chrysafis Vogiatzis was invited to attend the State of Kentucky Department of Public Health meeting, where evacuation policies, and disaster management issues were discussed.

Unidata THREDDS Data Server (TDS) Workshop (Oct. 22-24, 2012)

A majority of the data access methods showcased in the CSEVA focus on customized web visualization interfaces. To provide a more interoperable appliance, a THREDDS server has been incorporated into the CSEVA. Thus, in October 2012, Justin R. Davis, a PI working on the project attended a THREDDS workshop sponsored by Unidata in Boulder, Colorado. At this meeting, he made an information presentation on the CSEVA showing examples of the bootable ISO and the Northeast Florida MTEVA application.



American Geophysical Union 2012 Fall Meeting (Dec. 3-7, 2012)

At the AGU meeting in San Francisco, a presentation was made on how the CSEVA can be used to perform weather and climate simulations using the WRF model and THREDDS interfaces. In addition, the latest version of the MTEVA will be highlighted in the presentation. An abstract of this presentation is shown in Appendix B.

Coastal Hazards Summit 2013 (Feb. 13-14, 2013)

Early in 2013, project PIs hosted a summit on Coastal Hazards to: bring together federal agencies, state agencies, researchers, and coastal communities to share the latest advances in coastal hazard research and planning/preparation/mitigation/response; to explore ways to apply the latest findings and products in coastal hazard research to assist stakeholders planning activities; and to identify critical research needs to enhance the stakeholders continued planning and preparation effort for a hazard resilient and resource sustainable coast. As part of this summit, a presentation was made on how Virtual Appliances can be used to help in the communication of coastal hazards. The main focus of this presentation will be the MTEVA application for Northeast Florida. An abstract of this presentation is shown in Appendix B.



4. CONCLUSIONS, RECOMMENDATIONS, AND SUGGESTED FUTURE RESEARCH

The enhancement of the unique, self-contained, software environment, the MTEVA has been completed. The MTEVA seeks to assist in coastal science, transportation and cyberinfrastructure research, education and outreach by creating a coupled modeling system capable of simulating the transportation network response in hypothetical and real physical domains to a system subject to high winds, storm surge, and inundation. The MTEVA use of VMs, allows individual science components to be brought together in a simple-to-use infrastructure where users can focus on learning the science instead of trying to setup and perform simulations.

While there are countless possible uses of the MTEVA, three will be highlighted. First, the MTEVA would be well suited for use by planners and organizers of emergency preparedness exercises who need to develop (in an easy-to-use fashion) realistic scenarios of conditions and transportation network conditions before (evacuation), during, and after (return) a storm. Second, the MTEVA is also well suited towards “real-time” use in an Emergency Operations Center (EOC) (ie after evacuation has occurred) to assist first responders in predicting specific transportation infrastructure which may be impassable. Finally, the MTEVA is ideally suited for deployment in educational environments where students of all skill levels can learn, through hands-on activities, about: storm surge and inundation, transportation engineering and optimization.

In summary, the MTEVA:

- contains a storm surge and inundation modeling system coupled with a traffic network optimization model capable of simulating lane reversal. The coupled modeling system is then applied to both hypothetical and real physical coastal domains and transportation network.
- incorporates both basic and advanced user interfaces and demonstrates interoperability through its use of a THREDDS Data Server (TDS) for distribution and visualization of results. At the most basic level, users can access the MTEVA through the web-based GUI. However, for more advanced users, terminal access can also be used to directly setup and perform simulations using the scheduling interfaces directly (e.g using the “condor_submit” command).
- is completely configurable, customizable and expandable. Because of the tools, scripts, web interfaces, etc. are located within the MTEVA; any individual component can be altered to meet and individual user’s need. For example, locations of nodes modified, additional network nodes/arcs can be added, or demands and capacities changed.



- is developed using publicly available technologies. All technologies used in the MTEVA are free and in the public domain; hence its use is unrestricted, thus making the technologies available to the widest possible audience.
- provides access to global computational resources. Once connected to the Internet, GAs automatically try to connect to other appliances and resource pools around the world; thus, providing the user the capability of running ensembles of simulations with ease. However, rather than access global resources, users can also setup their own “virtual clusters”. For example, resources within their own LAN can be connected through a secure virtual private network to provide a larger pool of resources without the need of travelling across potentially low bandwidth WAN connections.
- provides an educational environment useful for students of coastal science, cyberinfrastructure, and transportation engineering. For example, coastal science students can better understand how storm surge impacts a domain given storm strength, domain shape, etc. Cyberinfrastructure students can focus on the technical details of the GA itself along with the MTEVA’s web interfaces, databases and scripting technologies used behind the scenes. Transportation engineering students could investigate how the use of lane reversal can be optimized during a storm event. Finally, transportation practitioners in NE Florida could use the MTEVA to investigate how their domain responds to different hypothetical tropical storms.



APPENDIX A – MODEL INTERCHANGE FILES

INPUT/OUTPUT

- (input CH3D) Standard CH3D model input (fort.4, fort.15, fort.32)
- (input CH3D/Transp) transport_network.txt – describes the road network to be processed by the model, includes geographical coordinates as well as physical properties of the network such as types of roads
- (output CH3D) transport_network_state.txt – the state of the network at different timesteps, such as flooded/not flooded nodes and links of the transportation network
- (input Transp) transport_network_state.txt – see above
- (output Transp) transport_network_flow.txt – solution of the transportation problem defining the flows for the links in the network

FILE FORMATS

transport_network.txt

This file consists of the following:

Number_of_nodes Number_of_connections
i, Type(i), Demand(i), X(i), Y(i)

(one way roads)

(i=1,Number_of_nodes) – node type (0-virtual, 1-real), demand at the node, and coordinates of nodes.

i,Node1(i),Node2(i),Type(i),C1(i),C2(i)

(i=1,Number_of_connections) – establishes connection between two nodes and sets a type of the connection (1 = road, 2 = bridge, 0=virtual) and the capacity (C1 – capacity from Node1 to Node2 and C2 is the capacity from Node2 to Node1).

It should be noted that negative demand (any negative number) signifies a safety node. Currently it means that the node can be used as evacuation target. In the future the negative number could also signify “node capacity” – amount of cars it can handle / receive.

Roads are indestructible, while bridges can be destroyed, roads follow topography and road becomes unusable if at any location of the road the flood reaches FloodThreshold value (for this exercise FloodThreshold = 30cm) if at any point of time later on the flood retreats – the road becomes usable again. The bridges are considered to have their own elevation (set to 1 meter for this exercise), however, once the water level reaches the bridge not only it becomes unusable it’s also considered “destroyed” and cannot become operational again unlike the road can.



transport_network_status.txt

The file contains the time-dependent data which is output by CH3D model depending on the calculated flood and consists of the following:

Number_of_nodes, Number_of_links

Demand(i)

(i=1,Number_of_nodes) –demand at the node

Node1(j),Node2(j),C1(j),C2(j)

(j=1,Number_of_connections) – establishes connection between two nodes and the capacity (C1 – capacity from Node1 to Node2 and C2 is the capacity from Node2 to Node1).

TimeStep#, Time string

NodeStatus(i)

(i=1,Number_of_nodes)

- NodeStatus(i) = 1 if the node is connected to one or more nodes via available road
- NodeStatus(i) =2 if the node is isolated (no connections)
- NodeStatus(i) =3 if the node is destroyed (a node is considered to be destroyed once flood reached 0.5 meters)

LinkStatus(j)

(j=1,Number_of_links)

- LinkStatus(j) = 1 if the road is in service, 0 if the road is flooded

(the TimeStep/NodeStatus/LinkStatus block above is repeated MaxTimeStep times)

transport_network_flow.txt

The file contains a connectivity matrix at a given time, it consists a list of links with the flow (number of cars traveling) between the two nodes. This is a solution of the transportation model.

Number_of_links

TimeStep#, Time string

Remaining_demand(j)

(j=1,Number_of_nodes)

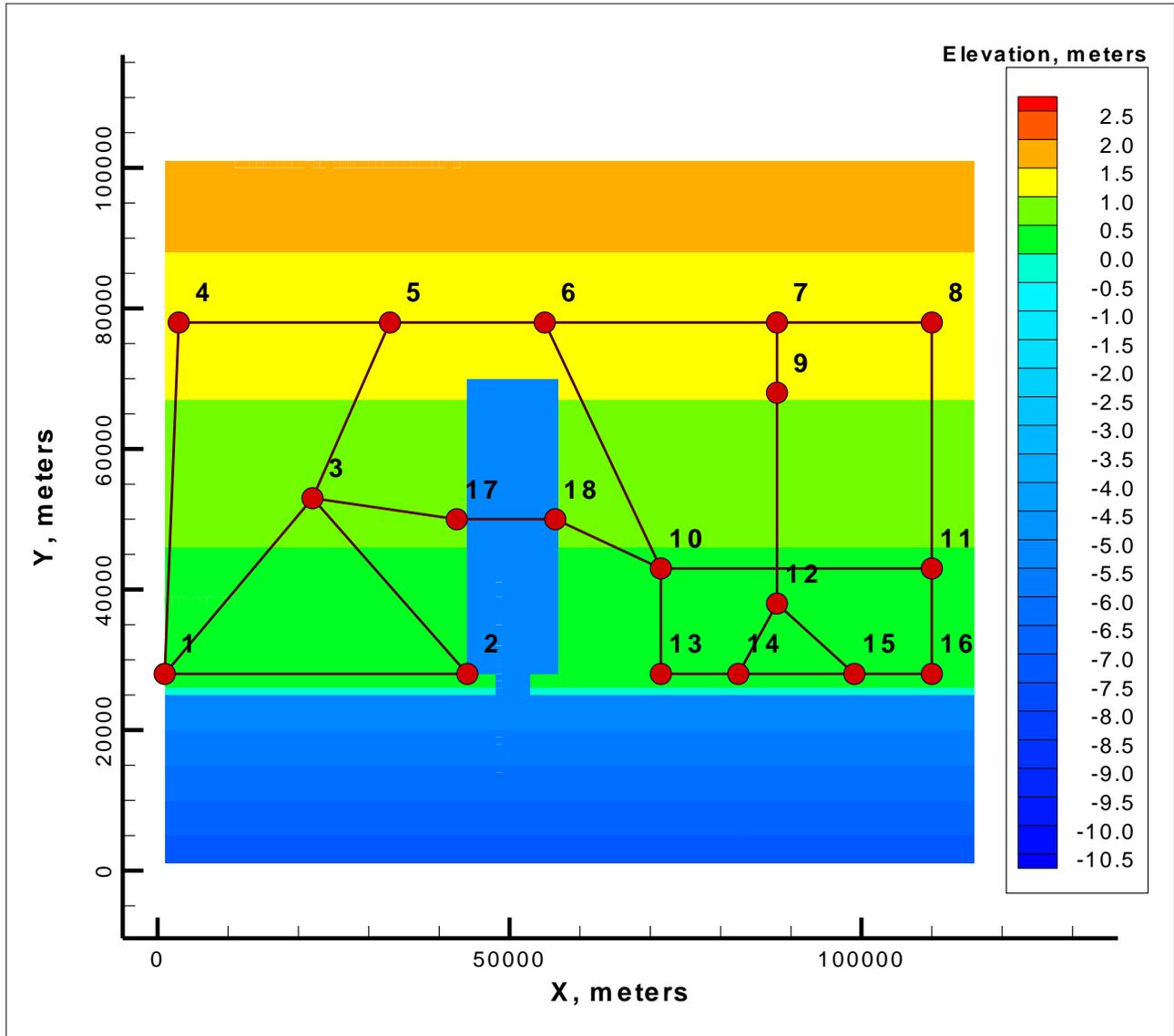
Flow(i)

(i=1,Number_of_links)

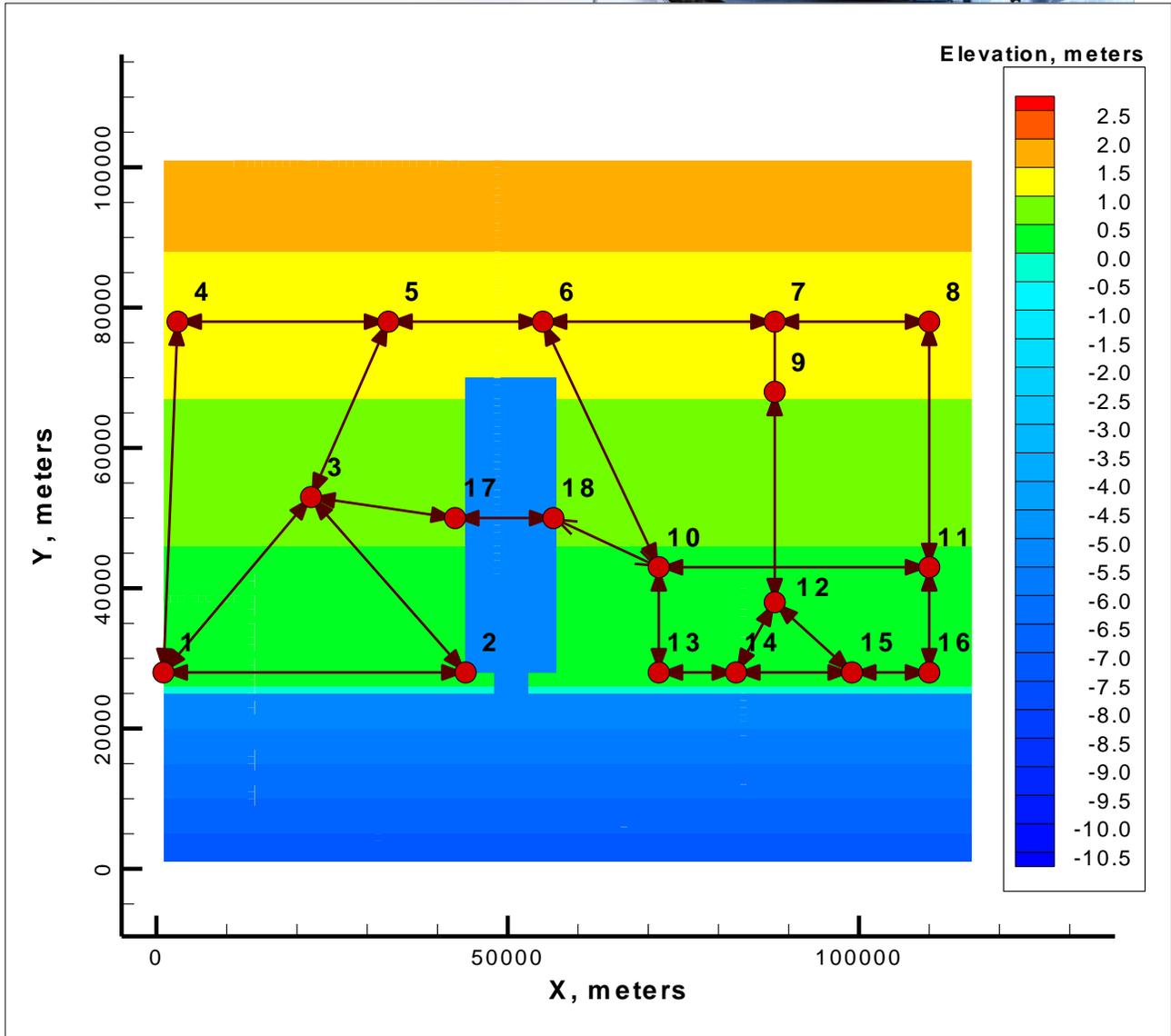
(the TimeStep/Demand/Flow block above is repeated MaxTimeStep times)



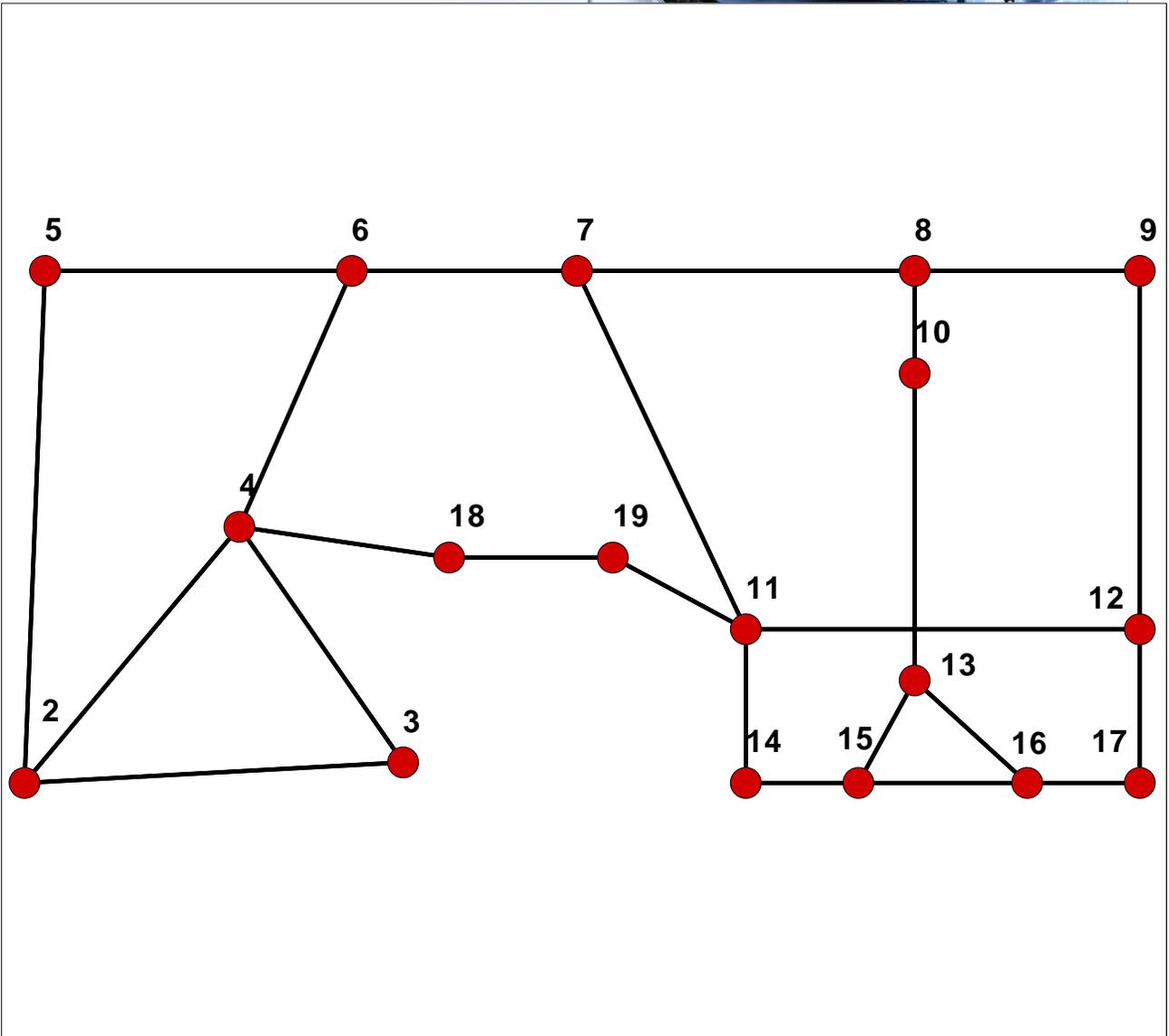
HYPOTHETICAL DOMAIN



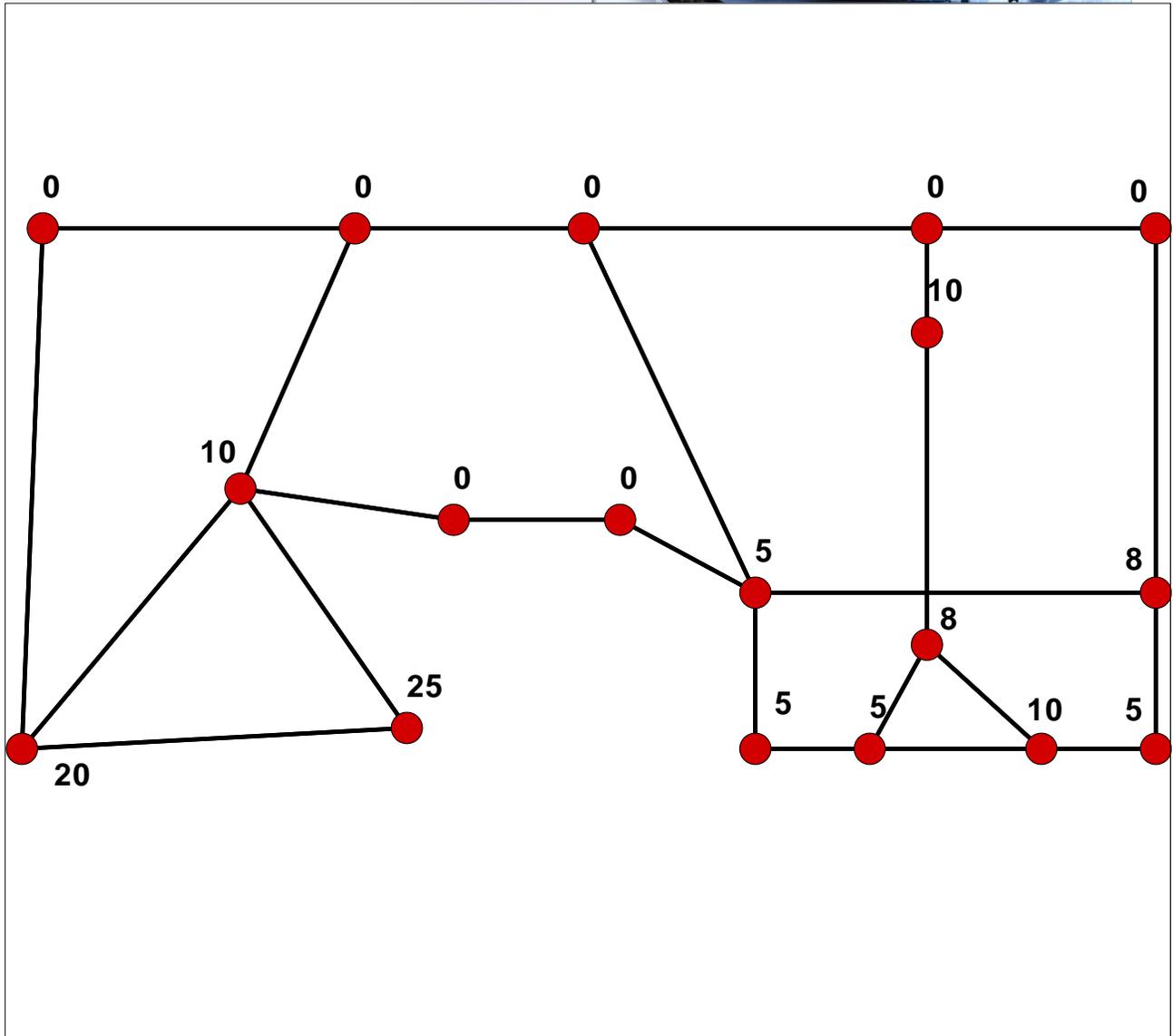
Domain, nodes and connections



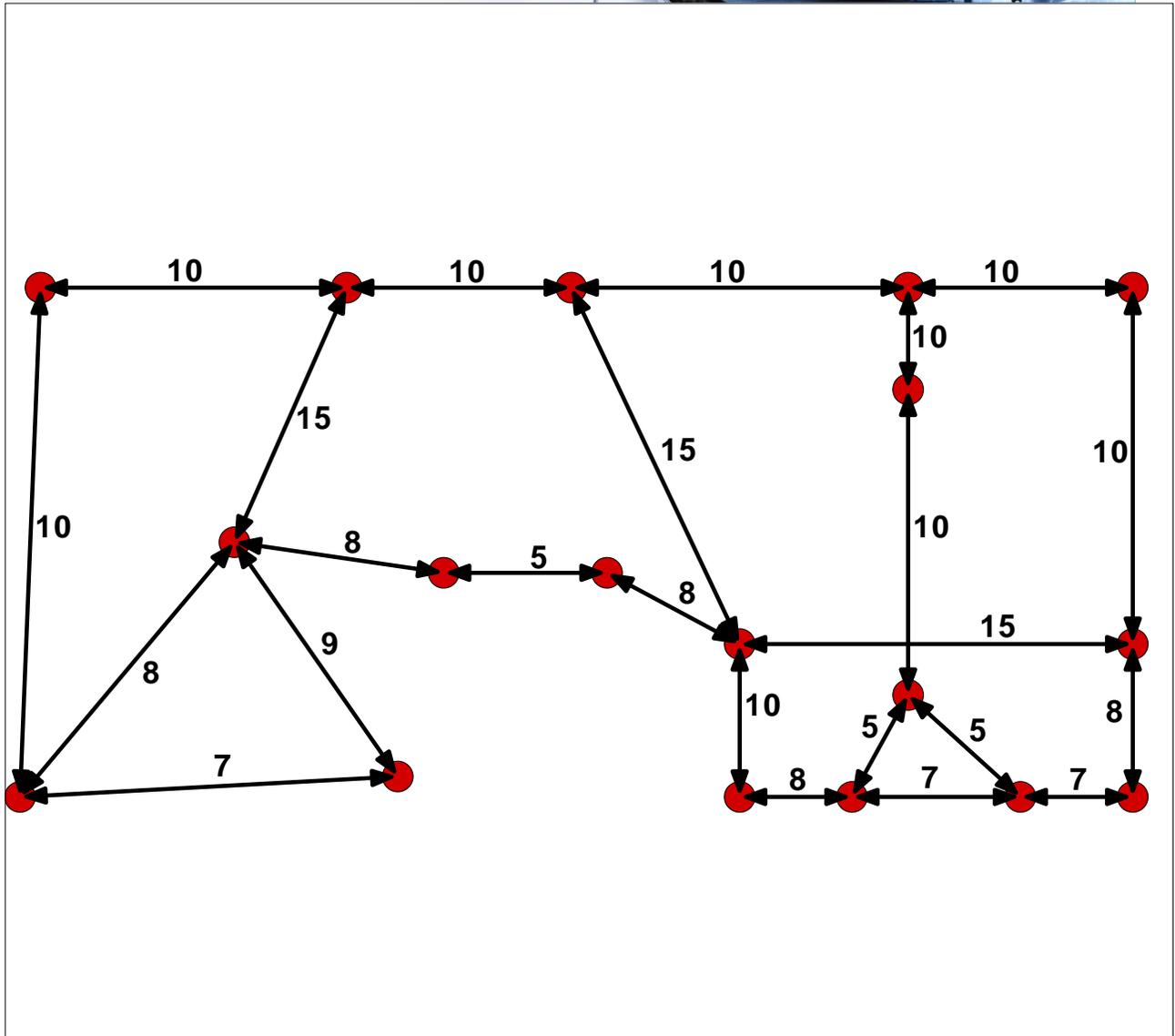
Domain, road network



Road network with nodes numbered



Road network with nodes demand



Road network with road capacities



JACKSONVILLE, FL TRANSPORTATION NETWORK + CH3D EASTCOAST GRID

Transportation network is based on the newest NERPM4 (NorthEast Regional Planning Model version 4, created for Northeast Florida) – “2005 base” scenario.

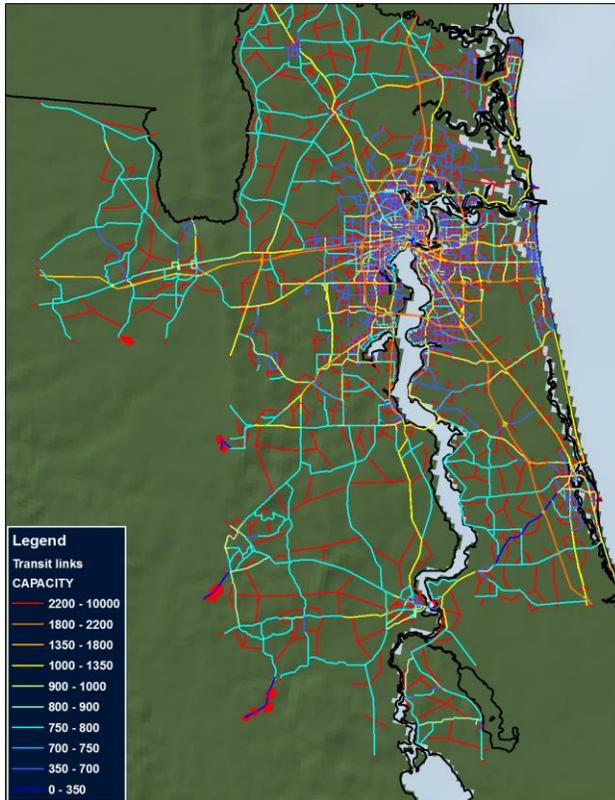


Figure 12 NERPM4 transit links loaded with road capacities

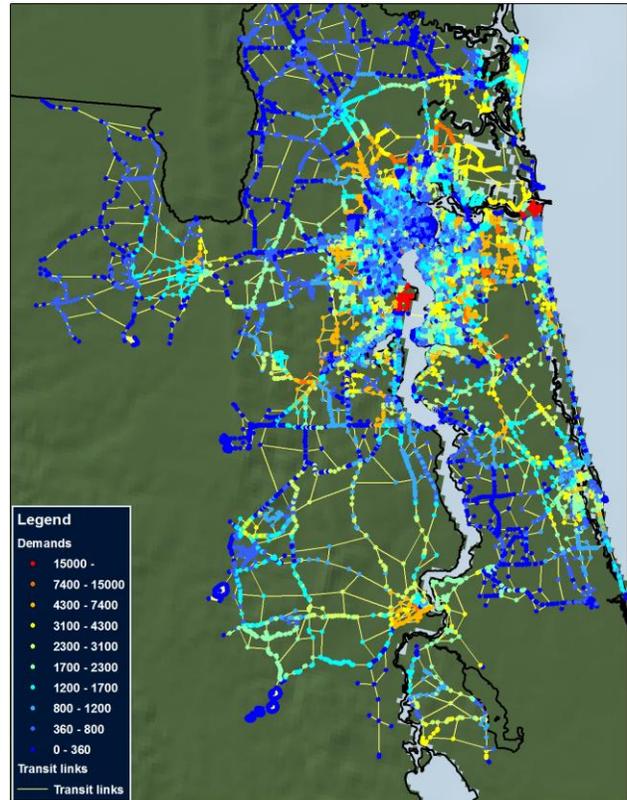


Figure 13 NERPM4 transit links and transportation model nodes, loaded with transit demands



APPENDIX B – PAPER/PRESENTATION ABSTRACTS

ESTUARINE AND COASTAL MODELING 12 CONFERENCE (NOV. 7-9, 2011)

The Coastal Science Educational Virtual Appliance (CSEVA)
Justin R. Davis, Vladimir A. Paramygin, Renato J. Figueiredo,
Y. Peter Sheng, Chrysafis Vogiatzis and Panos M. Pardalos

The Coastal Science Educational Virtual Appliance (CSEVA) is a unique tool designed to support interdisciplinary coastal science education and outreach activities, enabling active, hands-on, numerical modeling experiments by researchers, stakeholders and the general public. The CSEVA is a significant advancement over the prior Grid Appliance (GA) –based coastal science applications as it integrates formerly independent appliances: the CI-TEAM, SCOOP, and MTEVA into a single system. These applications span a wide variety of coastal science applications (conservative tracer release, storm surge and inundation, and transportation network assignment, respectively) and their integration greatly enhances the user experience in a variety of ways: less local storage requirements, easier to install, and linked application tools. In addition, the MTEVA application has been enhanced to include a simple idealized transportation network in northeast Florida being impacted by a hypothetical Katrina-like storm under various sea level rise scenarios as well as several new deterministic network assignment models. Finally, to facilitate even wider adoption of the CSEVA, a “Live” DVD/USB version of the GA has been developed. This version is much easier to use as it does not require any software to be installed locally as the GA is bootable directly off a DVD/USB device. The CSEVA along with corresponding documentation and tutorials are publically available on the Internet at <http://cseva.coastal.ufl.edu>.



TRANSPORTATION RESEARCH BOARD ANNUAL MEETING (JAN. 22-27TH, 2012)

Development of a Multimodal Transportation Educational Virtual Appliance (MTEVA)
to study congestion during extreme tropical events

Justin R. Davis , Qipeng P. Zheng, Vladimir A. Paramygin, Bilge Tutak,
Chrysafis Vogiatzis, Y. Peter Sheng, Panos M. Pardalos, and Renato J. Figueirido

A unique, self-contained software environment, the Multimodal Transportation Educational Virtual Appliance (MTEVA), has been developed to assist in coastal science, transportation, and cyberinfrastructure education, research and outreach. It is based on virtual machines which encapsulate the necessary models, pre- / post-processing routines and interfaces to enable users to perform simulations using an integrated inundation and transportation modeling system. By coupling models of coastal storm surge / inundation and the related transportation network response due to disconnected network links (e.g. flooded roads) in a simple-to-use infrastructure, users can focus on science instead of the complexities of configuring and performing simulations. In addition to being able to perform simulations locally, the MTEVA automatically connects to the “cloud”, enabling the user to perform an ensemble of scenarios via remote computing resources as well as on a local resource pool. This initial application of the MTEVA combines the CH3D Storm Surge Modeling System (CH3D-SSMS) with a transportation network model which supports lane reversal and applies this coupled modeling system to study the system’s response within an idealized domain being impacted by a hurricane. To assess the potential effectiveness of using the MTEVA for research and education, a preliminary user assessment was conducted with participation by graduate students. Survey results showed that the MTEVA is effective at helping graduate students understand key science topics and is viewed by them as a useful tool for undergraduate and graduate students.



AMERICAN GEOPHYSICAL UNION 2012 FALL MEETING (DEC. 3-7, 2012)

Using Virtualization to Integrate Weather, Climate, and Coastal Science Education

Davis, J. R., Paramygin, V. A., Figueiredo, R. J., and Sheng, Y. P.

To better understand and communicate the important roles of weather and climate on the coastal environment, a unique publically available tool is being developed to support research, education, and outreach activities. This tool uses virtualization technologies to facilitate an interactive, hands-on environment in which students, researchers, and general public can perform their own numerical modeling experiments. While prior efforts have focused solely on the study of the coastal and estuary environments, this effort incorporates the community supported weather and climate model (WRF-ARW) into the Coastal Science Educational Virtual Appliance (CSEVA), an education tool used to assist in the learning of coastal transport processes; storm surge and inundation; and evacuation modeling.

The Weather Research and Forecasting (WRF) Model is a next-generation, community developed and supported, mesoscale numerical weather prediction system designed to be used internationally for research, operations, and teaching. It includes two dynamical solvers (ARW – Advanced Research WRF and NMM – Nonhydrostatic Mesoscale Model) as well as a data assimilation system. WRF-ARW is the ARW dynamics solver combined with other components of the WRF system which was developed primarily at NCAR, community support provided by the Mesoscale and Microscale Meteorology (MMM) division of National Center for Atmospheric Research (NCAR). Included with WRF is the WRF Pre-processing System (WPS) which is a set of programs to prepare input for real-data simulations.

The CSEVA is based on the Grid Appliance (GA) framework and is built using virtual machine (VM) and virtual networking technologies. Virtualization supports integration of an operating system, libraries (e.g. Fortran, C, Perl, NetCDF, etc. necessary to build WRF), web server, numerical models/grids/inputs, pre-/post-processing tools (e.g. WPS / RIP4 or UPS), graphical user interfaces, “Cloud”-computing infrastructure and other tools into a single ready-to-use package. Thus, the previous onerous task of setting up and compiling these tools becomes obsolete and the research, educator or student can focus on using the tools to study the interactions between weather, climate and the coastal environment. The incorporation of WRF into the CSEVA has been designed to be synergistic with the extensive online tutorials and biannual tutorials hosted by NCAR. Included are working examples of the idealized test simulations provided with WRF (2D sea breeze and squalls, a large eddy simulation, a Held and Suarez simulation, etc.) To demonstrate the integration of weather, coastal and coastal science education, example applications are being developed to demonstrate how the system can be used to couple a coastal and estuarine circulation, transport and storm surge model with downscale reanalysis weather and future climate predictions. Documentation, tutorials and the enhanced CSEVA itself will be found on the web at: <http://cseva.coastal.ufl.edu>.



COASTAL HAZARDS SUMMIT 2013 (JAN. 31-FEB. 1, 2013)

Using Virtual Appliances to Communicate Coastal Hazard Risk
Justin R. Davis, Vladimir A. Paramygin, Chrysafis Vogiatzis,
Renato J. Figueiredo, Y. Peter Sheng, and Panos M. Pardalos

Communicating the risks of coastal hazards simultaneously to government agencies, researchers and coastal communities is especially challenging due to the wide variety of technical understanding among these diverse stakeholder groups. A typical approach to deal with this challenge is through the development of online web tools, such as Surging Seas: Sea Level Rise Analysis (Climate Central) or the Sea Level Rise and Coastal Flooding Impacts Viewer (NOAA Coastal Services Center,) or offline tools such as Hazus. While providing useful features, the online products typically use simplified approaches which cannot be modified / enhanced by the user, and offline approaches require potentially expensive software and / or are limited in their capabilities by the extent of local computational resources. To meet the challenge of developing a more adaptable education and outreach tool, the Coastal Science Educational Virtual Appliance (CSEVA) was developed. This unique tool supports interdisciplinary coastal science education and outreach activities, enabling active, hands-on, numerical modeling experiments by researchers, stakeholders and the general public. Using a newly developed application focusing on the transportation network in the Northeast Florida Regional Planning Model subject to the impact of a tropical storm under present and future climates, the capability of this system to communicate coastal hazard risk is highlighted.



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