Coastal Terrain Models: 
Considerations of Data and Applications

Introduction

Coastal Terrain Models (CTMs) combine terrestrial topography and estuarine or marine bathymetry data into a seamless elevation surface across the land / water interface. By providing an integrated surface model across this often complex transition zone, CTMs enhance the ability of coastal geomorphologists, research scientists, and GIS practitioners to explore the dynamic interactions of material and energy between land and sea (Li 2001, Hogrefe 2008). Historically, the shoreline has represented a sharp divide between coastal data sets, with topography and bathymetry being collected in different ways, by different people, to support different applications (Stock et al. 2010). Now, these disparate data sets can be merged in a GIS and NASA is making it possible to map both coastal topography and bathymetry at the same time with sensors such as their experimental advanced airborne research lidar (EAARL) (Nayegandhi 2009). This paper reviews CTM data inputs and recent advances in data collection and processing methods that are now enabling scientists to better integrate physical and biological measurements within a GIS to support decision making in the coastal zone.

In 2009, French and Burningham reported on the emerging trends and challenges in the field of coastal geomorphology and described the abilities to “predict meso-scale coastal behavior” and model “spatially distributed interactions between form and function” as a “grand challenge”. They reviewed current literature on an array of remote sensing and environmental instrumentation technologies for detecting coastal change and expressed a sense that multiple technologies are now converging toward complimentary data streams that will allow us to more precisely model and better predict coastal processes than ever before. The limiting factor they contend may be the ability of scientists from different disciplines to communicate well enough with each other to take advantage of these emerging capabilities. This paper will present CTMs as a bridge across this communication divide by providing a common geospatial framework on which to display a range of biophysical observations and support discussions about their mechanistic interactions.

In 2011, the U.S. Army Corps of Engineers (USACE), National Oceanic and Atmospheric Administration (NOAA), and the Federal Emergency Management Agency (FEMA) began discussions on a concept called SAGE or Systems Approach to Geomorphic Engineering. SAGE is a new interagency initiative to combine traditional “hard” shoreline protection with “green” or “soft” ecosystem based infrastructure design in an effort toward a holistic approach to protecting communities from coastal hazards (Chesnutt 2011). SAGE will rely on CTMs and the integration of a multitude of coastal environmental parameters to inform the hybrid
engineering process and for monitoring and evaluating the results of new engineering approaches and management actions. Klemas 2011 provides an updated review of remote sensing technology for coastal ecosystems and describes ground reference sampling approaches to calibrate and validate satellite and airborne remote sensing. The approaches discussed in French and Burningham 2009 and Klemas 2011, as well as the continued advances of geospatial technologies discussed in the other papers in the attached bibliography should prove quite useful as SAGE is implemented in the coming years.

Data Models, Applications, and Analytical Challenges

CTMs are primarily created using raster data sets of elevation values so that geospatial analyses and creation of related data sets such as slope, aspect, and flow paths can be computed efficiently. Triangulated Irregular Networks (TINs) are used in some cases where visualization of the model is of primary concern. Other vector data sets such as contour lines and spot elevations or depths can be used to generate the elevation values in the CTM, as described in Stock et al. GIS provides the analytical structure for CTMs within which the various data sources can be assembled, registered to same datum and projection, and merged. In addition, GIS functionality allows for the overlay of contextual data and other bio-physical and socio-economic data sources that can be analyzed within the coastal geospatial context (Li et al. 2001, Hogrefe et al. 2008). This process enables ecological and land use changes in monitoring data to be geo-statistically correlated to the physical changes in the coastal terrain model. It is this type correlation between coastal geomorphic form and ecosystem function that Marani et al. describe in their 2010 paper “The importance of being coupled: Stable states and catastrophic shifts in tidal biomorphodynamics”. While they used a point model rather than a CTM for their work, the authors explore the subtle interactions between coastal elevations, local sea level trends, and the marsh vegetation community. They describe the drivers of change between salt marshes, tidal flats, and sub-tidal platforms as being sediment supply, local subsidence, and sea level trends, all of which can be monitored and modeled for specific locations using CTMs.

As mentioned above, a variety of data sources can be used to create CTMs. It is critical for users of CTMs to understand the analytical limitations that are imposed by the spatial resolution and accuracy of the data that makes up their model. In their 2008 paper “Raster modeling of coastal flooding from sea level rise” Poulter and Halpin demonstrate the effect of various input elevation data sets on the predicted flooding extents of a hydrodynamic model. They show that using high resolution LiDAR data sets, which have enough spatial detail to resolve features like levies and canals, will significantly alter predicted flooding extents when compared to model runs using courser resolution data in which the levies and canals are not identifiable. Obviously, water control structures are important features to be able to include in flood modeling, so Poulter and Halpin suggest that older sea level rise studies done with course data be re-done with LiDAR data where it’s available.

Coastal salt marshes in particular are difficult places to obtain elevation data, primarily due to soft, wet substrates, surface water, and vegetation. However these types of coastal systems are of particular importance due to their high biological productivity and the water quality and flood buffering services they provide. Consequently, there is much interest in monitoring, modeling, and predicting their responses to changing environmental stressors such
as land use change, nutrient run-off, and sea level rise (Carbognin et al. 2004, Marani et al. 2010, Schmid et al. 2011). Given the small spatial scale of sea level rise, on the order of millimeters per year, the accuracy of the elevation data used is critical for determining the amount of confidence that should be placed on models results (Gesch 2009). Schmid et al. provide solid background information on the technical limitations of LiDAR data in coastal marshes and present data to show that stated elevation accuracies on many delivered LiDAR products do not hold for marsh areas. They caution coastal decision makers who are using LiDAR derived information in marshes that it may not be as accurate as they think it is, and they should check it themselves if they can.

Another major challenge presented by the variety of data sources used to create CTMs is that of matching vertical datums. A datum is a reference surface, or zero point, from which heights or depths are measured. Bathymetry is generally referenced to a tidal datum such as mean lower low water (MLLW) which is the average of all low waters measured at a particular location. This zero point is used so that it is very unlikely that the water would ever be shallower than the depths recorded on a nautical chart, because most of the time the actual water level is higher than MLLW. Topography on the other hand is generally referenced to a geodetic datum, related either to a gravity model or a mathematical ellipsoid model of the earth. Reconciling the differences between these different possible zero points for the various elevation data sets going into a CTM can be difficult. However, NOAA has developed a tool called VDatum, or the vertical datum transformation tool which uses modeled and observed relationships between these reference surfaces to transform elevation data sets between vertical datums, thus making the creation of CTMs much easier (Marcy et al.. 2011)

A Look to the Future

The geospatial infrastructure for monitoring subsidence and local sea level rise documented in Carbognin et al. (2004) appears to be what is needed to support adaptation planning for sea level rise in low lying coastal cities around the world. The robust leveling network, continuous GPS near tide stations, lagoon bathymetry, and the Synthetic Aperature Radar change detection efforts they describe will all be essential tools in the years to come for many places beginning to experience coastal flooding the way Venice Italy has for centuries. Advances in small footprint full waveform resolving LiDAR (Nayegandhi et al. 2009) and data processing schemes for existing topographic LiDAR (Schmid et al. 2011) will continue to improve the input elevation data sets for CTMs, as will expanded use of multi-beam and side-scan sonar (Klemas 2011). The biggest step remaining in the future may again be one of communicating what science is discovering about our coastal systems to the communities who live there and have to make decisions to manage the resources and risks of life in the coastal zone. Coastal Terrain Models provide a visually appealing and analytically powerful framework that can be used to communicate these complex interactions and help to understand the impacts and effectiveness of the innovative coastal management and protection strategies of the future.
Annotated Bibliography


This paper discusses the geodetic and tidal infrastructure implemented in and around the city of Venice, Italy and the Venice lagoon, where 23 cm of relative sea level rise has been measured over the past century. The authors explain how long-term geodetic leveling observations connecting the stable uplands and the subsiding coastline to tide station records were used to separate this trend into sea level rise and land subsidence components. Using comparisons between Venice and Triest, Italy, the authors differentiated human-induced and naturally occurring subsidence based on historic ground water withdrawal practices. More recent synthetic aperture radar (SAR) observations of land subsidence were corroborated by the leveling surveys showing promise for less expensive subsidence monitoring. This integration of high accuracy land elevations and water levels is then used in GIS to connect hydrodynamic models of the lagoon and Adriatic Sea to coastal infrastructure and socio-economic data to inform the adaptation and mitigation strategies that are being implemented to protect Venice and the Venice lagoon ecosystem from rising seas. The paper correlates the local sea level rise rates with an increase in the number of coastal flooding events over the past two decades. It also documents decadal patterns of relative sea level change alternating between longer periods of flat trends punctuated with steep rises in sea level over short periods of time. Due to the potential catastrophic impacts of rising seas and inundation on the people and cultural patrimony of Venice, the authors make a strong case for enhancing local and national government investment in the geospatial infrastructure, surveying, remote sensing and GIS applications to inform decision-making.


This paper provides an excellent overview of the process of building a coastal terrain model for the island of Tutuila in American Samoa. The authors explain the role of CTMs in understanding the complex interaction between terrestrial ecosystems, the island’s inhabitants, and the surrounding coral reefs, as well as how CTMs are used to support local land management decisions. Of note, the authors document a novel approach to filling a data gap in the complex intertidal system between the 0-15m bathymetry contours by using a combination of blue and green spectral bands from IKONOS imagery to extract depth information. To assist other practitioners, the authors provide a link to a detailed “cookbook” with their recipe for GIS and remote sensing processing steps to integrate USGS DEMs, IKONOS imagery, and bathymetry data to create CTMs. The paper concludes with an in-depth accuracy assessment of the mosaiced terrain model by presenting robust error analysis techniques, including statistical approaches as well as visualization and graphical representations of the data. The authors make a strong case for the use of CTMs in modeling human impacts to coral reefs and providing a scientific foundation for developing protection and management strategies.

This overview article details recent advances with several geospatial technologies, including those used for acquiring data for CTMs or data that can inform models based on CTMs. The article reviews and synthesizes more in-depth articles from the journal on multi-and hyper-spectral spectral imagery, thermal infrared scanners, microwave radiometers, radar imagers, scatterometers, altimeters, and LiDAR. The author makes a strong case for how the increasing power of advanced satellite and airborne systems and the ability to combine their data streams with robust field reference data schemes to calibrate and validate the remote-sensing information are now enabling scientists to derive much more detailed information about coastal systems than has previously been possible. These new sensors and processing methods are making available data with higher spatial, spectral, and temporal resolution than ever before. The article highlights the fact that while these cutting edge technologies are providing a wealth of new and better data, they are not yet fully supported by mature and robust processing algorithms required to derive the most information from the data the sensors provide. Detailed in this article are advances in techniques for improving the accuracy or bathymetry and coastal topography, as well as classification of imagery, and change detection strategies and algorithms. Of note, the author specifically mentions the value of co-locating continuous GPS receivers with long-term tide stations to differentiate local sea level trends from land elevation changes. Looking to the future the author predicts an acceleration of advances through the combination of new technologies and techniques for generating and analyzing spatial information and applying them to a range of important issues from watershed hydrodynamics to water quality in living resource models, ultimately providing a coastal early warning system to help prioritize management decisions.


This paper lays out a strong framework for using CTMs as the foundation for models predicting coastal erosion rates and using GIS to investigate impacts to coastal infrastructure. The paper documents the process of coastal erosion within the Great Lakes and describes the different data streams necessary to model stressors and responses. The paper stresses the importance of evolving the shoreline data model away from regular line and polygon data structure to a dynamic segmentation and digital shoreline structure. Using this new approach the authors can model existing and predicted future shorelines by intersecting the CTM with predicted water level surfaces. In this case, CTM is derived from aerial photos and satellite imagery's and USGS DEM's as well as acoustic sounding systems for bathymetry. Water levels were obtained from the output from local hydrodynamic models and operational forecast systems for the Great Lakes. Overlying the CTM with infrastructure data and predicted water levels, the authors can make predictions of erosion hazard to infrastructure and use GIS to explore erosion impacts on various segments of society. In the end, the paper strikes an exciting geospatial populist tone by invoking the prospect of local community web-based coastal erosion awareness projects bringing tools to the people to support decision-making by property
owners and local governments concerned with protecting their shorelines and providing strategies for them to get the information they need.


In this paper Marani et al. describe a mechanism for the process by which subtle changes in land and water elevations can drive tidal landforms to alternate between three stable states: subtitle platforms, tidal flats, and salt marshes. They state the process is primarily governed by three overarching controls: sediment availability, local subsidence, and the rate of sea level change. The paper builds on similar works that have described this mechanism for switching between alternate stable states for a variety of other ecosystems. The authors lay claim to being the first to create a fully integrated model that describes this biogeomorphodynamic behavior in tidal systems. Of importance, they highlight model results suggesting the role of marsh vegetation as primarily that of wave suppression and related reduction of erosion rather than having a major role in trapping suspended sediment. They stress the importance of vegetation in contributing biomass for organic deposition on the surface to help the system keep pace with sea level rise. The authors described well the management implications of their new model results, specifically that due to different historical elevation trajectories, different coastal areas may respond differently to the same rates of sea level rise. The paper was a good piece on how different scientific disciplines must come together to model complex spatial processes and predict ecosystem responses to changing stressors. This paper represents the type of advances in the understanding of coastal processes that are being enabled by new technologies and maturing GIS, GPS, and remote sensing methodologies being used to spatially relate physical and ecological patterns and change.


In this paper Poulter and Halpin investigate the impacts of spatial resolution and hydrologic connectivity rules in the creation of digital elevation models and the resulting implications for their use in modeling sea level rise and coastal inundation. The authors used LiDAR data collected in coastal counties of North Carolina (NC) to assess various combinations of different data processing routines, scales of data, and choices about the way water flows within the inundation model. By comparing the modeled extents of coastal flooding produced using their different procedures to predictions from previous sea level rise models, the authors show that large differences in flooding extents and predicted impacts can result by using updated data and techniques. The authors point out that the advent of high resolution digital elevation data has increased the ability to resolve topographic complexity such as canals and
levies, that impact water movement and were not identifiable in the coarser resolution data used in the past. Their results indicated that lower resolution elevation data sets produce larger areas of inundation due to this inability to resolve features that would affect water movement in the coastal zone. The authors suggest that due to the low slope of the land from the shoreline inland across the coastal NC region that there are multiple thresholds of sea level rise that could each inundate large areas of land, resulting in episodic accelerations in the rate of land loss, rather than it being a steady continuous process. These model results are important for coastal managers as they indicate that larger areas of inundation may occur earlier on due to the low elevation and slope, essentially frontloading the impacts from sea level rise to coastal communities in that region.


This excellent paper details how LiDAR accuracy is impacted by the complex environmental conditions within coastal salt marshes and presents multiple avenues for accuracy improvement. The article reviews recent literature documenting the technical aspects of the difficulty that LiDAR has in resolving surface elevations under varying plant heights and densities and surface water conditions within marshes. Through extensive error analysis of LiDAR data sets within coastal South Carolina, the paper shows that while LiDAR datasets may meet FEMA's floodplain mapping accuracy requirements, the errors in marshes are significantly higher and are not represented within the accuracy assessment category of weeds, tall grasses and crops as many users may assume. Having explained the limitations of current LiDAR technologies in marshes, the authors propose innovative processing and filtering strategies to ameliorate those errors. This documented difference between LiDAR accuracy in marshes and the reported accuracy statements is important information for coastal resource managers to know when they are planning to use LiDAR to support their decision making. In the end, the paper looks toward the future where the authors see promise in the ability of smaller footprint, full waveform resolving LiDAR and more refined processing and filtering algorithms that will make LiDAR data more accurate and more useful in measuring inundation and sea level rise impacts across the spectrum of coastal landforms.


This paper described the authors’ efforts to produce a CTM using the best available topography, bathymetry, and shoreline data for very complex terrain along the coast of Finland. The authors digitized contour lines from topographic maps and nautical charts, merged them and calibrated the results using ground reference transects collected across the shoreline. The paper serves as a good example of what’s possible even in areas without new high-resolution elevation and bathymetry data, while at the same time making clear the limitations on the
applications of the model given the coarseness of the underlying data. They did a very good job at describing the complexities involved in developing the model due to different data collection methods on the land and marine sides, as well as different data requirements based on differing responsibilities of the agencies collecting the data. The paper highlights the ability of GIS software to integrate these various data types and to derive important new insights by overlaying them with other data layers to explore meaningful spatial relationships. The paper made it clear that bathy-topo data integration using coarse spatial resolution data should not be used for vulnerability assessments for storm surge and sea level rise, but could be used to distinguish flat shores from steep ones. Where this is the only type of data available, important management information can be gleaned by overlaying infrastructure data in buffered areas around identified flat shores. It was of interest because it addressing it addresses modeling capabilities for the coastal zone for areas in the world that lack the high spatial resolution of lidar data that is now becoming widely available in the United States.
Citations not included in annotated Bibliography:


