

THE DEVELOPMENT OF A PROBABILISTIC APPROACH TO FORECAST COASTAL CHANGE

ERIKA E. LENTZ^{1,2}, CHERYL J. HAPKE³

1. *University of Rhode Island, Department of Geosciences, Kingston, RI 02881*
2. *U.S. Geological Survey, Woods Hole Coastal and Marine Sciences Center, Woods Hole, MA 02543, USA, elentz@usgs.gov*
3. *U.S. Geological Survey, Woods Hole Coastal and Marine Sciences Center, Woods Hole, MA 02543, USA, chapke@usgs.gov*

Abstract: This study demonstrates the applicability of a Bayesian probabilistic model as an effective tool in predicting post-storm beach changes along sandy coastlines. Volume change and net shoreline movement are modeled for two study sites at Fire Island, New York in response to two extratropical storms in 2007 and 2009. Both study areas include modified areas adjacent to unmodified areas in morphologically different segments of coast. Predicted outcomes are evaluated against observed changes to test model accuracy and uncertainty along 163 cross-shore transects. Results show strong agreement in the cross validation of predictions vs. observations, with 70-82% accuracies reported. Although no consistent spatial pattern in inaccurate predictions could be determined, the highest prediction uncertainties appeared in locations that had been recently replenished. Further testing and model refinement are needed; however, these initial results show that Bayesian networks have the potential to serve as important decision-support tools in forecasting coastal change.

Introduction

Sandy beaches are dynamic environments that often change rapidly and dramatically in response to storm events. Beaches serve as the first line of defense between storm waves and dunes, as well as structures located further landward. As extreme beach erosion frequently prompts calls for rapid intervention, understanding not only how rapidly beaches may change, but also to what degree and where change is most likely to occur is critical. Forecast scenarios frequently rely on geometric models and projections of historical rates that lack the spatial and temporal resolution necessary to determine specified changes along coast (Bruun, 1962; Fenster *et al.*, 1993). Other forecast efforts focus on along-coast vulnerability to extreme events such as hurricanes (Stockdon *et al.*, 2009). The research presented here predicts post-storm changes to oceanfront beaches in two study areas at Fire Island, New York using Bayesian networks. The prediction scenarios resulting from this work can provide managers with essential information to protect human and natural resource interests alike.

Bayesian networks have a host of applications in a variety of disciplines, from marketing to ecology (Ellison, 1996; Rossi *et al.*, 2003). Although their applicability in the geosciences has been demonstrated in areas such as seismology and hydrology (Katz *et al.*, 2002; Tsapanos *et al.*, 2003), using networks as predictive tools in the coastal zone is fairly new (Plant and Holland, *in press*; Hapke and Plant, 2010). Bayesian networks allow an array of factors that influence coastal change to be considered, such as wave climate, existing geomorphology, and past behavior. Because inductive reasoning underlies Bayes theorem, the ways in which these factors influence each other as well as the ways in which they influence the outcome are also taken into account. This study assesses the ability of Bayesian networks to predict net shoreline movement and volume change in response to storms. High resolution DEMs using historical topography, lidar, and recent field data have been used to provide a local assessment of morphologic change to beaches and dunes at Fire Island (Lentz and Hapke, 2010). Due to this work, there is now sufficient data available to develop models that predict change in morphology to a specific event (such as storm) using real data.

Study Area

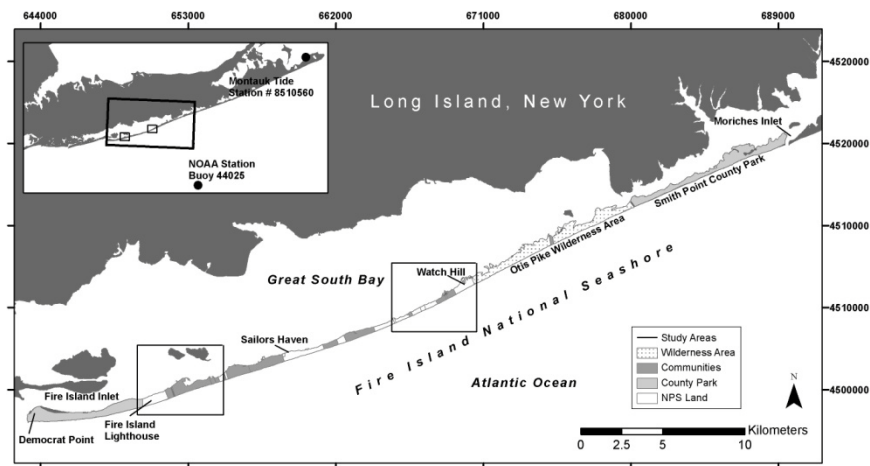


Fig. 1. Location map of Fire Island (inset) and of study areas used in the analysis.

Fire Island is a 50 km-long barrier island located along the south shore of Long Island, New York (Fig. 1). This study focuses on two, approximately 4-km-long study sites that each contain private communities and undeveloped land, and are located in western and central reaches of the island. The western study area is the

more heavily developed and anthropogenically modified (replenishment and beach scraping, which transports sand from the subaerial beach to enhance the primary dune line) of the two, and has on average lower dunes, wider beaches, and a more gradual profile slope than the eastern site (Lentz and Hapke, 2010). The western site is also more sediment-rich, with an offshore source in the form of sand ridges which are thought to contribute sediment to the system (Schwab *et al.*, 2000; Hapke *et al.*, 2010). The more sediment-limited eastern site occurs at point of inflection in the island where the long-term evolution of the island varies. East of this point the barrier has experienced more overwash and inlet formation as it migrates landward. Further west, the island has evolved as a prograding spit. Several communities in the eastern site have experienced chronic erosion over the last several decades, and are areas for which improved predictive capabilities of beach change are critical.

Methods

Bayesian networks are used to evaluate causal relationships between a host of user determined input parameters. An advantage of Bayesian networks is that they allow the inclusion of prior knowledge of a system, as well as conditional probabilities in the predictive model. Bayesian networks are based on Bayes rule which states:

$$P(F_i|O_j) = p(O_j|F_i)p(F_i)/p(O_j) \quad (1)$$

The left hand term is the updated conditional probability (the posterior probability) of the forecast (F_i) given a particular set of observations, O_j . Here we are forecasting the probability distributions of net shoreline movement and beach volume change on a set number of transects along coast. The term $P(F_i|O_j)$ is the likelihood of the observation if the forecast is known. This term reflects the input variables (initial states, historical rates) described below, and includes also the uncertainties of these measures. The term $p(F_i)$ is what is known about the parameter before new or additional information is available, or the prior probability. The term $p(O_j)$ is a sum of the joint probabilities, and introduces a normalizing factor independent of F .

In this study the prediction developed in the Bayesian networks was used to determine net shoreline movement and volume loss in response to storm events: the April 2007 “Patriot’s Day” nor’easter and the November 2009 “Nor’Ida” storm, an extratropical storm that formed from the remnants of Hurricane Ida. These storms were selected because pre-storm topographic surveys were collected within several months prior to each event and post-storm lidar was available. In

addition to storm activity, a major replenishment project was completed among communities in both sites in April of 2009.

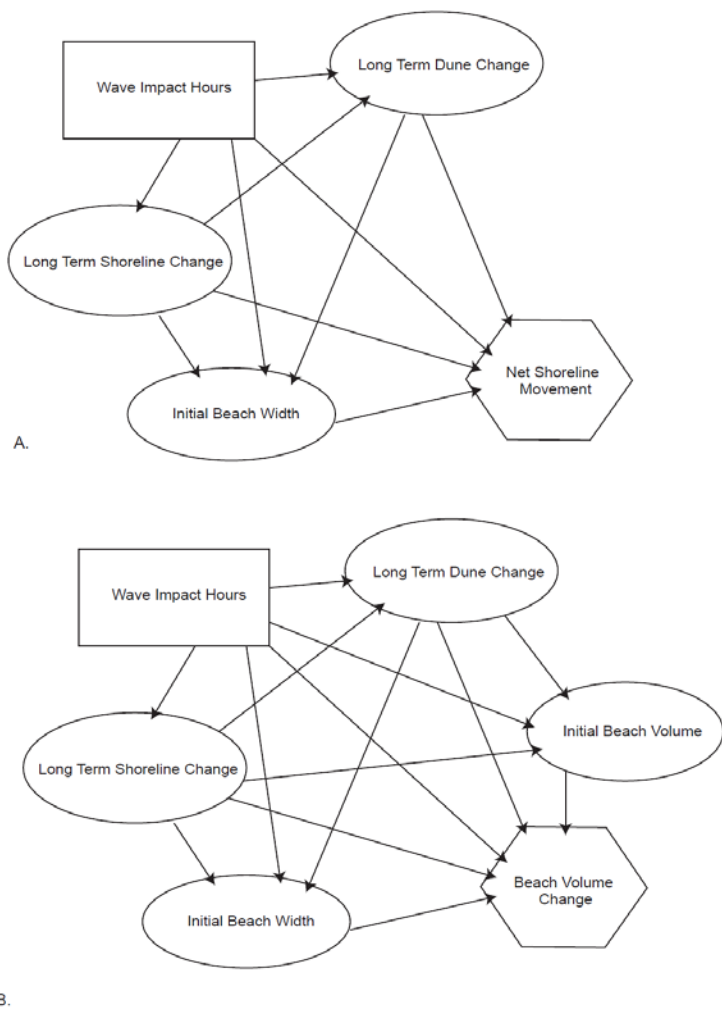


Fig. 2. Conceptual Bayesian network showing driving forces (rectangle), historical change rates and initial states of the system (ovals), and the predicted outcome (polygon). Arrows indicate causal relationships between parameters and illustrate the complex interplay of these parameters in net shoreline movement (A) and volume change (B) models.

The Bayesian network developed for this analysis includes three main components: 1) driving forces; 2) historic change rates and the initial state of the system; and 3) the outcome or likelihood prediction, with causal relationships linking them (Fig. 2). Results predict the most probable outcome of net shoreline movement and volume change along a defined segment of shoreline in response to a storm event (Table 1), and are then independently verified with existing post-storm data. Both inputs and outputs are discretized into a finite number of possible values (bins). Bin divisions are specific to the pre-storm morphology and event conditions, and allow the model to account for the range and uncertainty in the measurement of parameters provided.

Table 1. Individual bin boundary values for each model parameter.

Model Parameter	Bin Boundary Values	
	Patriot's Day Storm (2007)	Nor'Ida (2009)
Impact Hours (hrs)	0 1 10 50 100 250	0 1 2 10 25 70
Long-term dune toe change (m/yr)*	-1 -0.5 0 1 1.5	-1 -0.5 0 0.6
Long-term shoreline change (m/yr)*	-5 -2 0 2 4	-1 0 0.25 0.7 1.8
Beach width (m)	0 40 65 80 90 100 120	0 25 40 55 75 90
Total volume (m ³)	0 35 50 70 90 140	0 40 60 80 100 150
Volume change (m ³ /m)	-70 -50 -20 0 20 50 70	-115 -50 -20 0 20 50 100
Net shoreline movement (m)	-20 -10 -5 5 10 20	-55 -30 -10 10 30 55

*Long-term change rates for the Patriot's Day Storm are determined from 9 delineated features (April 1969 to March 2007); long-term change rates for Nor'Ida are from 17 delineated features (April 1969 to September 2009)

Metrics describing the initial state of the system were derived from high resolution topographic surfaces spanning 1969 through 2009 (Lentz and Hapke, 2010). Shorelines and dune toe positions were manually delineated from slope and elevation surfaces at 1 m grid resolution and imported into the Digital Shoreline Analysis System (DSAS) (Thieler *et al.*, 2009) where linear regression rates were determined along 50 m transects. It is important to note that long-term change rate calculations only extend from oldest date available in the dataset to the date of the surface prior to the storm; in the case of the Patriot's Day storm, temporal coverage was from April 1969 to March 2007, and for

Nor’Ida coverage was from April 1969 to September 2009. Change rates were calculated for 89 transects in the western site, and 75 transects in the eastern site.

The initial state of the beach is determined by measuring beach slope, width, maximum elevation, and volume along each transect. Slope and volume were determined from mean high water (MHW) to the dune toe, and the maximum beach elevation was extracted along each transect. Beach width is defined as the total length of the transect between MHW and the dune toe. Several dates within the topographic dataset capture pre- and post-storm data (March and April 2007 for the Patriot’s Day Northeaster; September and December 2009 for Nor’Ida), and these events serve as a primary focus for model development.

Using methods developed by Ruggiero *et al.* (2001), wave and tidal information were used to determine total water level (TWL) along each transect. Wave and tidal data were downloaded from NOAA (<http://www.ndbc.noaa.gov>, accessed September 2, 2010) buoy #44025 and the Montauk tidal station #8510560 (Fig. 1). These methods use the wave run up calculations from Stockdon *et al.* (2006) in conjunction with tidal measurements to determine the wave impact hours, or the number of hours waves exceeded the maximum elevation of the beach. The period of study in for each event began on the date of the pre-storm survey and ended on the date of the post-storm survey so as to ensure the temporal span accurately reflected the topography measured

Results

Results show very good agreement between predicted versus observed post-storm net shoreline movement and volume change. Predictions of the most probable net shoreline movement were slightly less accurate than those of volume change, and in each case, predictions of parameters from the Patriot’s Day storm were more accurate than those from Nor’Ida (Table 2).

Table 2. Model accuracy results determined by cross validation of predicted outcomes vs. observed change. The uncertainty column indicates the percentage of predictions where more than one bin was deemed equally probable.

Storm	Parameter	Accuracy	Higher uncertainty
Patriot’s Day 2007	Beach Volume Change	82%	15%
Nor’Ida 2009	Beach Volume Change	79%	7%
Patriot’s Day 2007	Net Shoreline Movement	75%	23%
Nor’Ida 2009	Net Shoreline Movement	70%	16%

The outcome of the net shoreline movement prediction was correct at 75% of the transects for the Patriot's Day storm (Table 2, Fig. 3). Uncertainties were higher at 23% of these transects, wherein the most probable outcome was equal in more than one bin (worst case was three bins). Confidence in the remaining transects (one bin deemed most probable) was high. Results were also evaluated for their ability to predict extreme events. Because bin values varied for each parameter predicted (Table 1), the parameters defining extreme events for each storm also varied. In the case of the Patriot's Day storm net shoreline movement, extreme events were defined as more than 10 m of shoreline accretion, or more than 10 m of shoreline erosion at any given transect alongshore. Model results from the Patriot's Day storm had greater than 65% accuracy in predicting events of extreme erosion and accretion along coast.

For the Nor'Ida storm, the Bayesian network correctly predicted net shoreline movement at 70% of transects (Table 2, Fig. 3). Of these predictions, 16% had higher uncertainties with equally high probabilities in two or three bins. The net shoreline movement models had greater than 80% accuracy in predicting extreme shoreline erosion (Table 1), with extreme events in this case defined as reflected as 30 m of shoreline erosion or accretion.

Predictions from the volume change models were slightly better than those for the net shoreline movement. The volume change parameter had six bins as opposed to five for the net shoreline movement (Table 1). In general, the narrower the bins, the more skill by the model required to accurately predict the correct outcome. The Patriot's Day storm volume change predictions were 82% accurate, the best prediction of any of the models (Table 2, Fig. 4). Confidence in the predictions was quite high, wherein the highest probabilities were spread over 2 to 3 bins at only 15% of the transects. In addition, this network had 70% accuracy in predicting extreme events ($60 \text{ m}^3/\text{m}$ of volume loss or gain) along transects.

Although Nor'Ida volume change predictions were less accurate than those of the Patriot's Day storm (79% vs. 82%), uncertainties in model predictions were only 7%, the highest confidence in predictions of any of the models in this study. Extreme volume loss (more than $50 \text{ m}^3/\text{m}$) was the most accurately predicted outcome (greater than 90% accurate).

In addition to analyzing the outcomes from the Bayesian networks, a sensitivity analysis was run on the results to determine the relative importance of the various parameters included in the network (Fig. 5). Results of the sensitivity analysis for shoreline movement showed that for both storms, the long-term shoreline change rate had the greatest influence on the model outcome, followed

by initial beach width and the wave impact hours. The rate of long-term dune toe change had the least importance in shoreline network development.

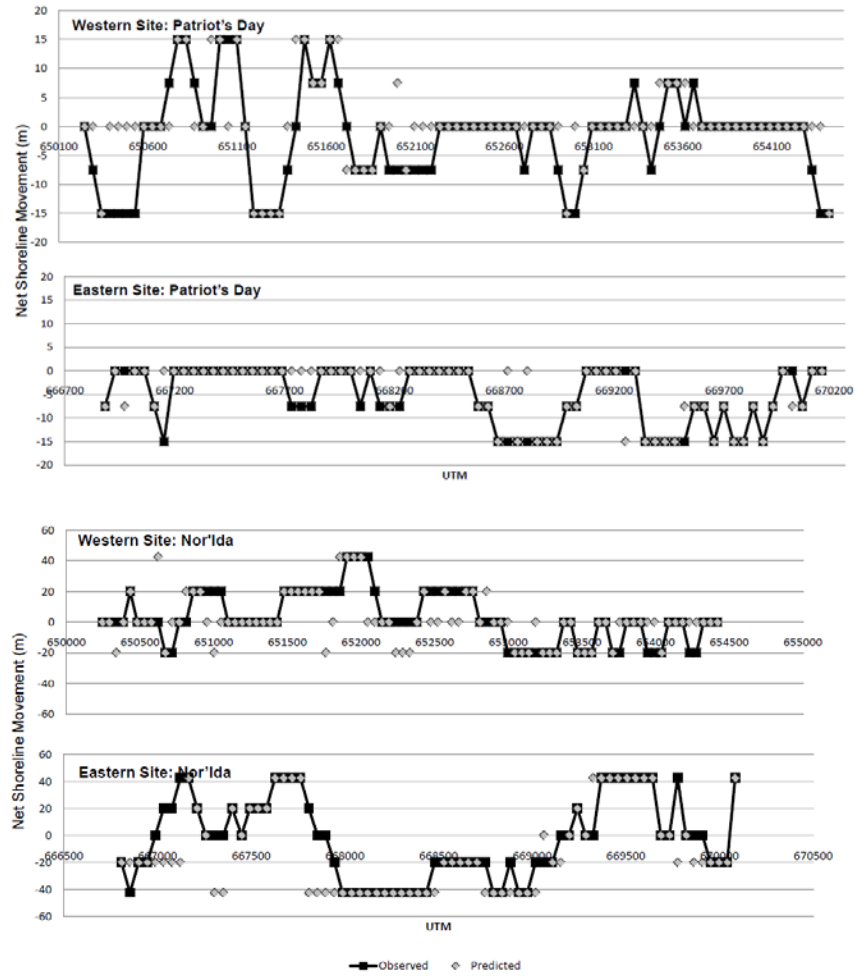


Fig. 3. Cross validation results showing the observed (squares) and predicted (diamonds) outcomes from the net shoreline movement model alongshore. The plotted values are the center values of the highest probability bin for each transect location.

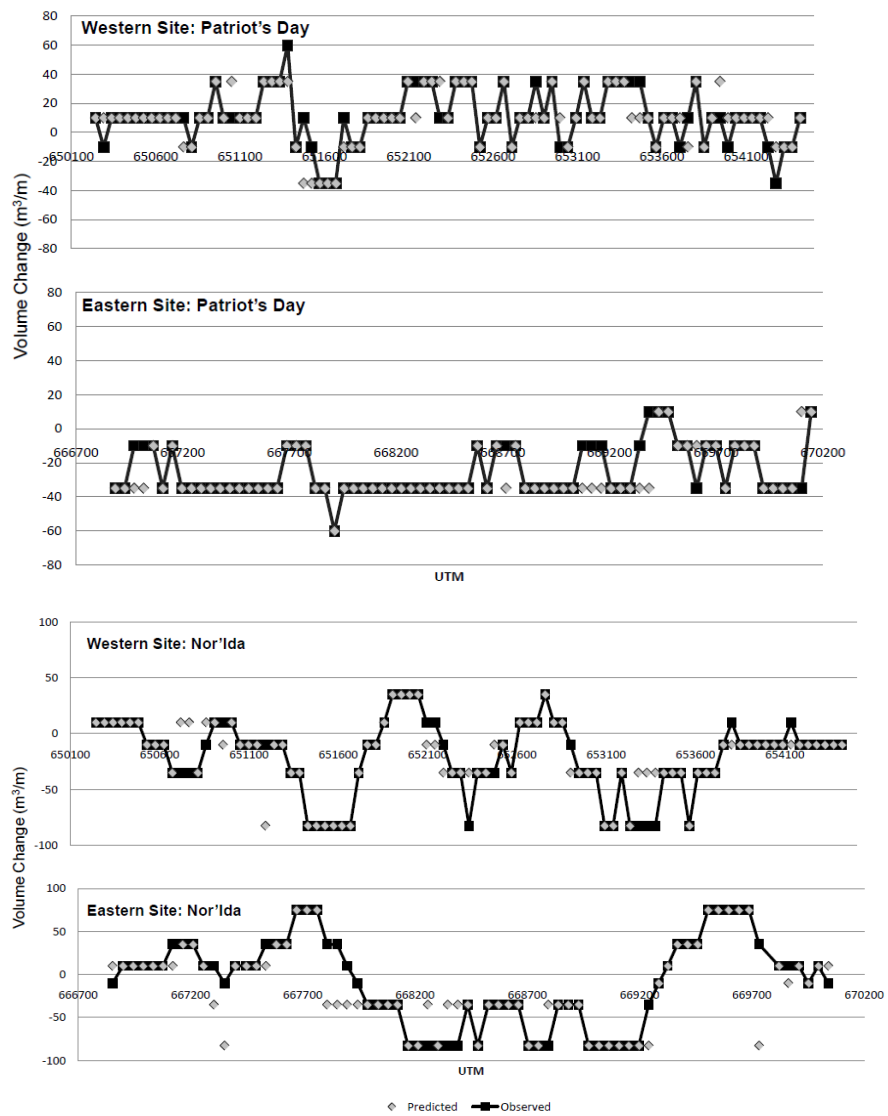


Fig. 4. Cross validation results showing the observed (squares) and predicted (diamonds) outcomes from the beach volume change model alongshore. The plotted values are the center values of the highest probability bin for each transect location.

The shoreline movement sensitivity analysis showed the relative influence of the parameters was consistent between storms. Historical change rates were most influential in the Patriot's Day storm followed by the long-term dune toe change rate, wave impact hours, initial volume, and beach width (Fig. 5). In contrast, sensitivity analysis results for volume change were variable between the two storms. The volume change network for Nor'Ida was most sensitive to initial states: initial volume was most important, followed by beach width, long-term shoreline change, wave impact hours, and long-term dune toe change.

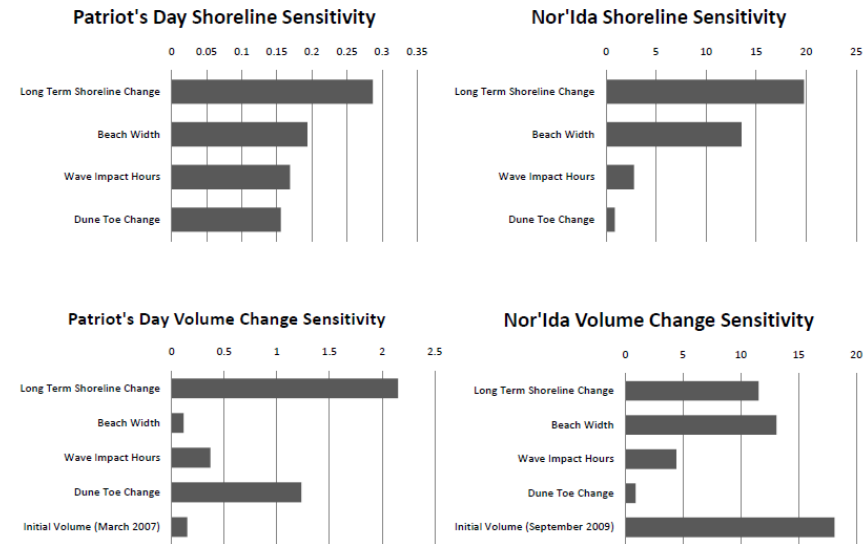


Fig. 5. Sensitivity analysis results showing results for models of net shoreline movement and volume change for each storm. Plotted results are the percentages of variance reduction (unitless ratios) and show the relative influence of the parameters incorporated in the model on the predicted outcomes.

Discussion

The results from this study show that the Bayesian networks can be used to accurately determine volume change and net shoreline movement in the recovery period following a storm event. In locales such as Fire Island, where development and threats to existing structures can prompt calls for rapid intervention or mitigation, such means of prediction are of particular use to resource managers. While many forecasting tools are focused on the vulnerability of the coast to only the most extreme storm events (hurricanes), this study is unique both in its modeling approach and in its effort to predict change related to less intense but longer duration storms.

Results show strong agreement between predicted outcomes and observations and the models successfully predicted net shoreline movement and beach volume change 70-82% of the time. The inherent variability of some parameters may also explain why some predictions are more accurate than others (volume change vs. net shoreline movement). In addition, an exploration of modification impacts may explain differences in the accuracies of the predictions around storm events (Patriot's Day vs. Nor'Ida).

A preliminary look at predictions of net shoreline movement shows that these predictions were lower in accuracy when compared with those of volume change (Table 2). Unlike beach volume change which reflects sediment movement along the transect, net shoreline movement represents a feature's position and can show substantial variability, particularly in a post-storm recovery period, making accurate predictions difficult (Psuty and Silveira, 2009). The similarity in model sensitivities for shoreline movement indicates that initial state and long-term shoreline change are both key parameters, with the historic shoreline change rate being the most influential parameter in shoreline model predictions. These findings are similar to those of Hapke and Plant (2010) which found that the prediction of coastal cliff failures was most sensitive to the historic cliff erosion along the California coastline. The lack of influence of historic dune toe change may suggest that this is a parameter less important in accurate model development of net shoreline movement, which would be expected given its distance and minimal control on the shoreline feature being measured.

Additionally, lower prediction accuracies for both net shoreline movement and volume change were observed for Nor'Ida. Again, these results are not surprising as a large beach replenishment project completed six months before the storm added considerable sediment to the subaerial system, a substantial amount of which was still present prior to the storm event. At Fire Island, where communities are interspersed with unmodified segments of coast, the addition of material to the beach increases along-coast variability: wider beaches and accreting shorelines in replenished sites versus unaltered states in non-replenished locales. This variability is reflected in the input parameters, and results in a lowering of the skill of the model such that the correct outcome is not as easily predicted or anticipated. The sensitivity tests appear to verify the impacts of the 2009 replenishment on modeling beach volume change, which showed parameters of initial state (beach width and the initial volume of the beach) were most important to the Nor'Ida network predictions. Interestingly, the Nor'Ida volume change model was better at correctly predicting the most probable outcome including substantial human influences. These results suggest the variability in the initial state of the beach between replenished and non-replenished areas was a critical component in developing a model and producing

accurate outcomes. In contrast, sensitivity results for the Patriot's Day storms indicated the historic shoreline change rate was the most important parameter in predicting the volume change outcomes, indicating that in areas not recently modified, long-term behavior is a sufficient parameter in model building.

In an effort to explore human modification and development influences on how well the model performed, inaccurate predictions (Fig. 3 and 4) were tallied in both modified and non-modified areas. In the Nor'Ida predictions, the average failure rate for shorelines was 29% and 21% for beach volume change. Modified areas had the higher inaccuracies in both net shoreline movement and volume change (31% and 25% respectively), which may suggest that change in recently modified areas is more difficult to predict than unaltered areas.

The results from this study highlight the potential for Bayesian networks to serve as forecasting tools of morphologic change on sandy shorelines. While relatively small segments of coast were the focus of this study, the increasing availability of temporally dense coastal lidar data may make more regional analyses of change possible. The success in predictions of net shoreline movement and beach volume change suggests that Bayesian networks may have broader applicability for other measures of coastal morphologic change. Given the uncertainty surrounding many of the anticipated climate change impacts, having adaptable coastal forecasting models that can be continually updated with new information as scenarios unfold may prove to be an invaluable management and research tool.

Conclusions

Decision support models, or Bayesian networks, have been shown to accurately predict the post-storm morphodynamic response of select beaches on Fire Island. In this demonstration study, net shoreline movement and beach volume change resulting from two of the most extreme storms to impact the region in the 2000s were predicted with accuracies ranging from 70-82%. Prediction uncertainties are highest in areas that were replenished in the same year as the storm. Sensitivity analyses verify that when beaches have recently been modified, predictions are governed mostly by changes to beach morphology directly related to replenishment (i.e. beach width, beach volume). These results indicate that additional parameters and model refinement may be needed to better forecast changes in areas that have been anthropogenically modified. The overall accuracy of the predictions, despite their applications in areas known to vary morphologically and that are intermittently modified, demonstrates potential for Bayesian networks to be utilized as effective forecasting tools in sandy environments. Furthermore, the increasing availability of regional lidar coverage offers the potential for the construction of broad spatial prediction

models. In a changing climate, the flexibility and adaptability of these models, coupled with the ease of integrating new information as it becomes available, make their continued development and exploration an area of high interest in coastal change research.

Acknowledgments

Funding for this research was provided by the National Park Service and was supported in part by NSF IGERT grant DGE-0504103. We are grateful to NPS staff, Meredith Kratzmann, Rachel Hehre, and Mike Bradley at URI for field assistance and technical expertise, as well as Amar Nayegandhi, Emily Klipp, and Jaime Bonisteel for making the post-storm 2009 lidar rapidly available. We thank Peter Ruggiero for assistance with the wave run-up calculations, as well as Ben Gutierrez, Rob Thieler, and Nathaniel Plant for helpful feedback on preliminary results.

References

- Bruun, P., 1962, Sea level rise as a cause of shore erosion. *Journal of the Waterways and Harbors Division*, 88: 117-130.
- Ellison, A.M., 1996, An introduction to Bayesian inference for ecological research and environmental decision-making. *Ecological Applications*, 6(4): 1036-1046.
- Fenster, M.S., Dolan, R., and Elder, J.F., 1993, A new method for predicting shoreline positions from historical data. *Journal of Coastal Research*, 9(1): 147-171.
- Hapke, C.J. and Plant, N.P., 2010, Predicting coastal cliff erosion using a Bayesian probabilistic model. *Marine Geology*, 278: 140-149.
- Hapke, C.J., Lentz, E.E., Gayes, P.T., McCoy, C.A., Hehre, R.E., Schwab, W.C., and Williams, S.J., 2010, A review of sediment budget imbalances along Fire Island, New York: Can nearshore geologic framework and patterns of shoreline change explain the deficit?: *Journal of Coastal Research*, v. 26, p. 510-522.
- Katz, R.W., Partange, M.B., and Naveau, P., 2002, Statistics of extremes in hydrology. *Advances in Water Resources*, 25: 1287-1304.
- Lentz, E.E. and Hapke, C.J., 2010, Geologic framework influences on the geomorphology of an anthropogenically modified barrier island:

Assessment of dune/beach changes at Fire Island, New York. *Geomorphology* In-Press.

Plant, N.G. and Holland, K.T., *in press*, Prediction and assimilation of surfzone processes using a Bayesian network – Part I: Forward models. *Coastal Engineering*.

Psuty, N.P. and Silveira, T.M., 2009, Trend in foredune crestline displacement, Fire Island National Seashore, New York, USA, 1976-2005. *Journal of Coastal Research*, SI 56: 15-19.

Rossi, P.E., and Allenby, G.M., 2003, Bayesian statistics and marketing. *Marketing Science*, 22(3):304-328.

Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J., and Beach, R.A., 1996, Wave runup, extreme water levels, and the erosion of properties backing beaches. *Journal of Coastal Research* 17: 401-419.

Schwab, W.C., Thieler, E.R., Allen, J.R., Foster, D.S., Swift, B.A., and Denny, J.F., 2000, Influence of Inner-Continental Shelf Geologic Framework on the Evolution and Behavior of the Barrier-Island System Between Fire Island Inlet and Shinnecock Inlet, Long Island, New York: *Journal of Coastal Research*, v. 16, p. 408-422.

Stockdon, H.F., Holman, R.A., Howd, P.A., and Sallenger, A.H., 2006, Empirical parameterization of setup, swash, and runup. *Coastal Engineering*: 53(7): 573-588.

Stockdon, H.F., Doran, K.S., and Sallenger, A., 2009, Extraction of lidar-based dune-crest elevations for use in examining the vulnerability of beaches to inundation during hurricanes. *Journal of Coastal Research*, SI 53: 59-65.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., and Ergul, A., 2009, Digital Shoreline Analysis System (DSAS) version 4.0: An ArcGIS extension for calculating shoreline change, *U.S. Geological Survey Open File Report* 2008-1278.

Tsapanos, T.M., Papadopoulos, G.A., and Galanis, O.Ch., 2003, Time independent seismic hazard analysis of Greece deduced from Bayesian statistics. *Natural Hazards and Earth Systems Sciences*, 3: 129-134.