
A GIS-based Approach for Estimating Soil Loss Volume Due to Water Erosion

by

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Abstract: The procedures to mathematically estimate the erosion and sedimentation rates in coastal areas require knowledge of the magnitude and direction of the energy flux due to waves breaking along the coast of the area where the study is performed. These procedures need the estimation of several input variables that necessitate the carry out of extensive field studies, which are both expensive and time-consuming. Furthermore the models employed by these procedures have poor prediction capability due to the fact that the input variables are themselves random scattered events in the time and space frame. In this paper we present a GIS-based approach for estimating shoreline erosion based on a discrete representation of the coastal terrain surface to estimate coastal erosion rates, which is more accurate, reliable, and effective than the traditional hydrodynamic-based approaches. To implement this method, we have created a Digital Elevation Model (DEM) for our study area along the Ohio Lake Erie shoreline using a set of aerial-photographs acquired by the U. S. National Oceanic and Atmospheric Administration (NOAA) coupled with a GPS survey conducted to obtain ground control points (GCP's). To create a Coastal Terrain Model (CTM) for the study area, we have integrated the DEM with the bathymetry produced by NOAA. The results of implementing this method in the study area for a time period from 1979 to 1997 are presented and discussed in this paper.

I. Introduction

Shoreline change results from coastal erosion and the effect of the breaking waves in the near-shore zone as well as the near-shore currents. The breaking waves in the near-shore zone and the near-shore currents are responsible for the transportation of beach sediments that results in shoreline change. This is part of a larger-scale process known as littoral transport, which is the movement of material by waves and currents in the coastal zone. With respect to sand supply, a given length of coastline may have a surplus, be in balance, or have a deficit in its sand supply budget. The sand supply would be in balance for a particular area if the amount of sand leaving the area were being replaced by an equal amount of sand arriving from adjoining areas. Over a short time period, shoreline erosion may occur in an area followed by a build-up of sand supplied by the longshore

transport of sediment, even though over the long term, the area will be in a state of dynamic equilibrium. A large reduction in the sand supply, or a long-term reduction in supply to an area, creates a deficit in the sand budget that must be balanced, usually by increased shoreline erosion (U.S. Corps. of Engineers, 1992).

To quantify the longshore transported sediment, a wave climate representative of the annual wave conditions measured or experienced in offshore waters must be established. The wave climate is in the form of a set of wave heights with different periods and directions, which must be routed towards the shore by a wave refraction model until the waves break on or near the beach. Information on their breaking angles relative to the beach orientation, breaking wave heights, and wave speed at breaking should be determined and used to establish the longshore components of the energy flux for the two directions along the shore. To establish a representative wave climate, proper understanding of the directional distribution of wave height and wave period is needed, since the distribution of wave heights is converted to an equivalent distribution of wave energy that is a function of the longshore sediment transportation rate (U.S. Corps. of Engineers, 1992).

This model has been employed intensively over the years to compute the long-term shoreline change. Although the one-line model has been extended to deal with the cross-shore sediment transport as well, the issue of grain-size sorting has never been addressed by any of these extended versions. On the other hand, the mathematical models proposed for sediment transport in rivers and channels do incorporate the grain-size sorting aspect. One may ask why do we care about the grain-size sorting issue in coastal areas. It is because grain-size sorting is important for several coastal engineering applications and for identifying an eroding section of the shore that is characterized by a specific grain-size. We must also note that sand supplies influence shoreline erosion by supplying the material that builds and maintains beaches, offshore bars, and the general beach profile. The presence of these features dissipates wave energy and their absence usually results in increased shoreline erosion rates. Hitoshi and Suzuki (1982) have presented a unique longshore sediment transport model that combines both shoreline prediction and grain-size sorting. It should be mentioned at this point that grain-size sorting and the distribution of coastal sediment patterns are used to determine the sediment transport direction and the sources of sedimentation. It is therefore important when studying shoreline change in a specific coastal area to collect and analyze samples for the grain-size distribution, median grain size, and the settling velocity.

One of the research directions being followed to assess shoreline change and predict future change use successive aerial photos to quantify the shoreline change. We have quantified shoreline change due to erosion in a Lake Erie coastal area based on the fact that the change is an indication of either a period of erosion or accretion (Li et al., 2001). The cross-shore displacement of any point on the beach, as observed from comparing one photo to another, is the excursion distance for that point for the period between the photos. On an accreting beach, the excursion distance of a point relative to its initial position is positive, and on an eroding beach, it is negative.

II. Models of Shoreline Erosion

Although the near-shore processes are of a complex nature and most of the existing shoreline prediction models are based on a lot of assumptions that make them only approximate models, people still employ them but do so with careful interpretation of predictive results. This is because a model that describes the near-shore waves, circulation, and shoreline evolution with sufficient accuracy needs to be spatio-temporal in 4D space. Therefore the development of such equations is still an area of active research and study. Among the famous shoreline prediction models are the one-line models that have been used successfully in various studies to calculate longshore sediment transport rates and long-term shoreline changes.

These models are based on the assumption that the geometric shape of the shoreline doesn't change and that the displacement occurs only at right angles to the shore. This implies that the sediment transport is uniformly distributed over the moving portion of the shoreline profile. Therefore the incremental volume of sediment in a reach is simply $(D_B + D_C) Dx Dy$, where Dx is the cross-shore displacement of the profile and Dy is the reach length. The conservation of sediment mass principle may be written as:

$$\frac{\Delta x}{\Delta t} + \frac{1}{D_B + D_C} \left(\frac{\Delta Q_l}{\Delta y} \pm q \right) = 0 \quad (1)$$

In which Q_l is the longshore transport rate, D_C is the offshore closure depth, D_B is the berm crest elevation, q is a line source such as rivers and coastal bluffs or sink that might be caused by sand mining, and t is time.

It is clear that the above shoreline prediction model is a function of the longshore transport rate, which could be computed using the longshore sediment models presented in the first part of this section. This requires the determination of the breaking wave angle relative to the beach. The wave model presented by Hitoshi and Suzuki (1982), unlike that of the U.S. Army Corps of Engineers, uses a modified model to obtain the wave angle, however it is a complicated model that is computationally intensive. The U.S. Army Corps of Engineers on the other hand proposed the following approximation to estimate the breaking wave angle, which is simpler:

$$\alpha_b = \alpha_{bg} - \alpha_{sg} = \alpha_{bg} - \tan^{-1} \left(\frac{dy}{dx} \right) \quad (2)$$

Where α_b is the local wave angle relative to the beach, α_{bg} is the wave angle relative to a model baseline, α_{sg} is the shoreline angle relative to the model baseline, y is the shoreline position, and x is the distance longshore.

Hitoshi and Suzuki (1982) have derived and solved a separate conservation equation for each fraction of the sediment so as to simulate the temporal variation of the gain-size long the beach. They further modified a conservation equation proposed by Hirano in 1971 to predict the grain-size sorting on a beach in the longshore direction for shoreline advance and shoreline recession that may be stated as follows:

$$\frac{\partial i_b}{\partial t} = \frac{m}{AD} \left[i_b \frac{\partial Q_y}{\partial y} - i_b \frac{\partial Q_y}{\partial y} \right] \tag{3}$$

Where i_b is the fraction of the sand-grain of the i^{th} rank contained in the surface bed layer, i_b is the transported sand, and A is the thickness of the surface bed layer.

Hitoshi and Suzuki (1982) have further presented the following shoreline change model which basically a mass conservation equation:

$$\frac{\partial x_s}{\partial t} = -\frac{1}{D} \frac{\partial Q_y}{\partial y} \tag{4}$$

Where x_s is the position of the shoreline from a reference line, t the time, Q_y the longshore sediment transport rate, D the depth of the sediment transportation zone and y the coordinate along the shoreline. D could also be thought off, as $D_C + D_B$, where D_C is the offshore closure depth and D_B is the berm crest elevation.

III. The GIS-based Approach

This method uses the best available spatial information about the coastal terrain surface under study to generate a Coastal Terrain Model (CTM) and further produce accurate shorelines. This approach is spatially comprehensive in view of the fact that the modeling frame is the four-dimensional (4D) coordinate system, which generates better modeling results than the existing shoreline change prediction modes that are mostly two-dimensional models (2D). By four-dimensional frame we mean the XYZ and time frame. Once we generate the CTM and extract the shorelines at time t_1 and t_2 from the orthophotos, we could overlay them in the GIS environment and further extract the depth of the sediment-transport-zone D for every grid-cell in our square-cell CTM. The incremental volume of sediment in a reach will simply be $D.Dx.Dy$, where Dx and Dy are the CTM-cell dimensions. Note that the direction of x and/or y is unnecessary to exactly be identified in this case since we are only computing the volume of shoreline lost since time t_1 . Our goal now is to predict the longshore sediment transport rate using information about the shoreline change. The conservation of sediment mass principle in the differential form is as follows:

$$\partial Q_y = -\frac{\partial x \cdot \partial y}{\partial t} \cdot D \tag{5}$$

For a square-cell CTM we have; $Dx = Dy = C$. Furthermore Δt is the time elapse during which the shoreline at t_1 changes to the shape at time t_2 . Re-writing the sediment mass conservation equation solving for Q_y and approximating we will have a discrete representation of the coastal sedimentation:

$$Q_y = \frac{1}{\Delta t} \cdot \sum_{i=1}^n C^2_i \cdot D_i \tag{6}$$

Where Q_y is the volumetric longshore sediment transport rate, n is the number of the grid cells that lie between the two shorelines; D_i is the sediment transport zone depth for the i^{th} CTM cell, which could be estimated using the following relation:

$$D_i = Z(i)_{CTM} - Z_b(i) \tag{7}$$

Where $Z(i)_{CTM}$ and $Z(i)_b$ are the terrain elevation and the bathymetric height corresponds to the i^{th} CTM cell respectively.

For estimating the volume of shoreline soil loss from time t_1 to time t_2 , and the longshore sediment transport rate, we have employed a shoreline erosion concept illustrated by the schematic shoreline profile of Figure 1, which represents the action of the energy flux caused by the breaking waves and currents on the shoreline profile.

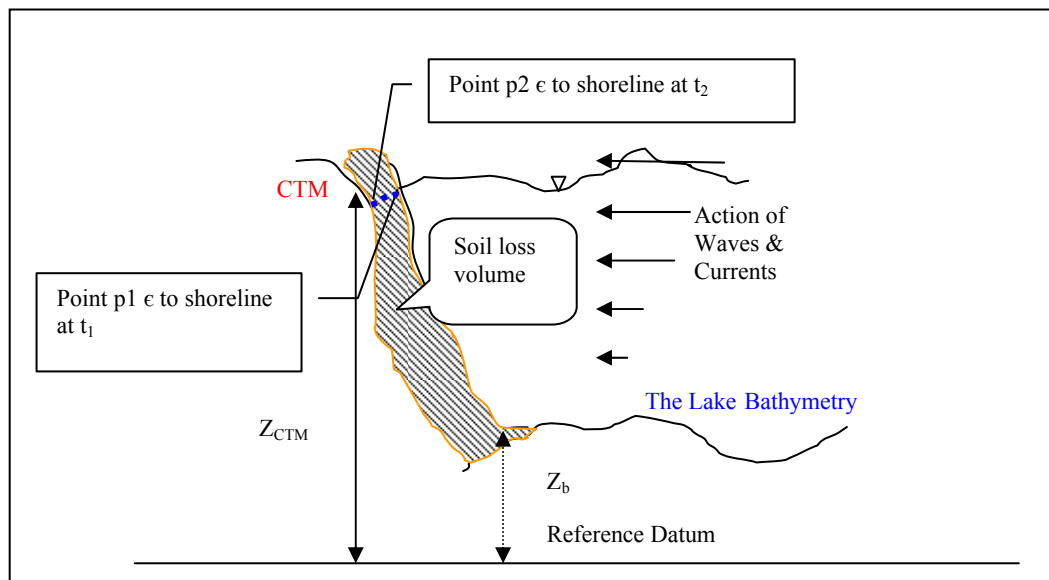


Figure 1. Schematic shoreline profile to depict the effect of waves and currents on the shoreline

To implement this procedure, a high-resolution CTM was created using a set of aerial photos acquired by the National Oceanic and Atmospheric Administration (NOAA) in 1997 that was coupled with a Global Positioning System (GPS) survey for ground control points (GCP's) in a study area that extends 11-km from Sheldon Marsh to Vermillion along the Ohio Lake Erie shoreline. To look deeply into the coastal zone topography in the study area, several spatial cross-shore profiles were generated to study the effect of the spatial pattern on shoreline erosion. As illustrated in Figure 2, the shoreline topography for the study area ranges from steep bluffs with abrupt elevation change to

gently inclined terrain toward the Lake surface. This complex topography explains the huge soil-loss volume of shoreline due to erosion by the combined energy flux of waves and currents. This is because the energy flux acts on the toe of the high-rise bluffs resulting in huge shoreline loss. The shorelines for 1979 and 1997, the study period, were extracted from the United States Geological Survey (USGS) Digital Line Graph files and the rectified aerial photos of NOAA-1997 respectively. The USGS Digital Elevation Model (DEM) for 1979 was resampled to the same resolution of the CTM of 1997.

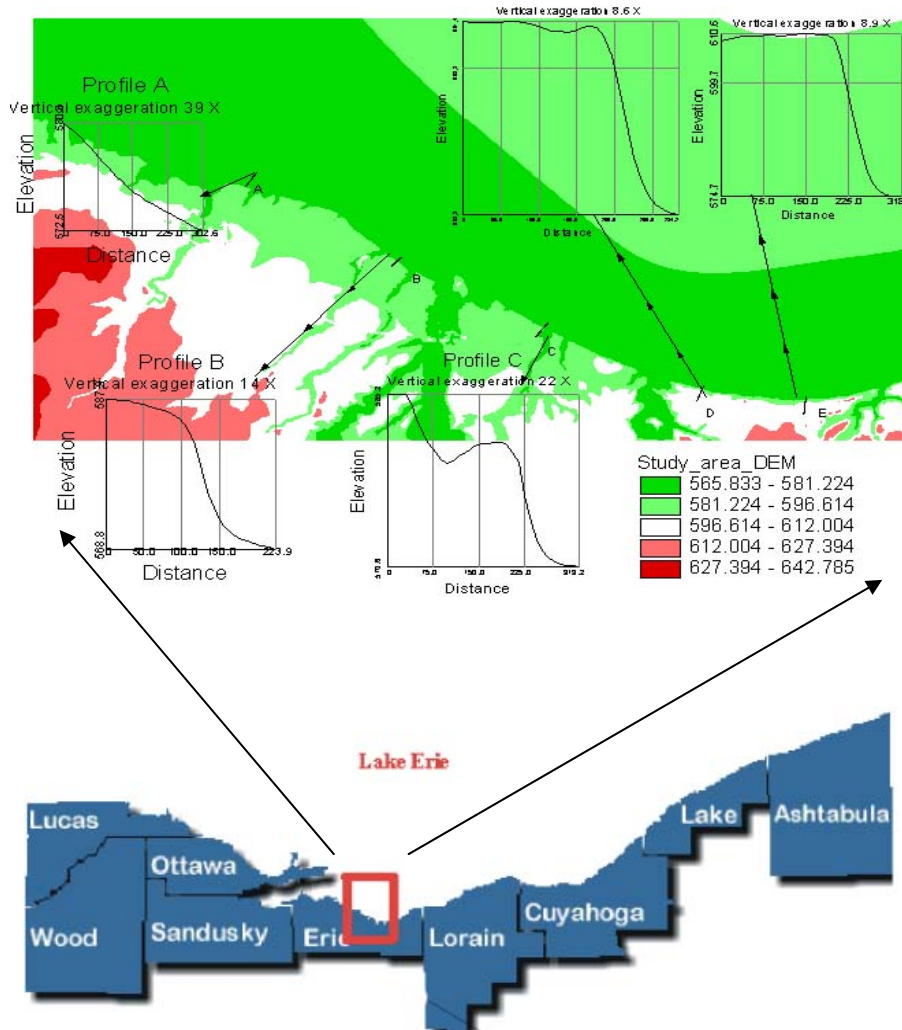


Figure 2. The study area and its coastal and bluff's topography

Using Arc/Info[®] GIS system, we have overlaid the coastal loss area CTM, the lake bathymetry produced by NOAA, and the newly produced CTM from the NOAA aerial photos to obtain the volumetric shoreline soil loss rate and further the volumetric sedimentation transport rate. Figures 3 below illustrates the volumetric shoreline soil loss rate in the study area.

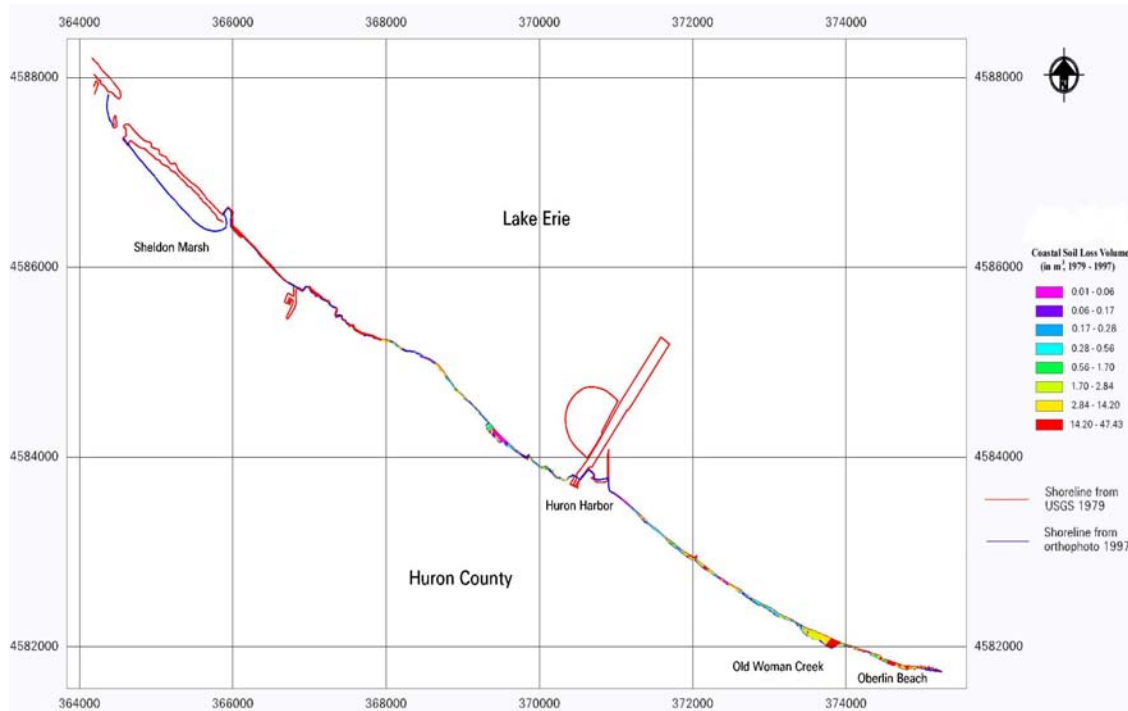


Figure 3. The volumetric coastal soil loss in the study area from 1979 to 1997

IV. Results and Analysis

Spatial autocorrelation analysis was then performed to test whether the discrete representation of the volumetric sediment transport rates on the local scale of the CTM cell-by-cell level is independent of the values of the neighboring cells. Spatial autocorrelation measures the level of interdependence between the variables, and the nature and strength of that interdependence. We were basically interested in this analysis because it would show us if we could derive correctly information about longshore component of wave energy flux such as the energy flux factor, P_{ls} using the longshore sediment transport rates, Q obtained by the method presented in this paper. Spatial autocorrelation may be classified as either positive, where all similar variable values appear together, or negative, where all unrelated values appear in close association. To obtain the spatial autocorrelation coefficients for the longshore sediment transport rates, which are basically interval data, we used Moran's I method, which is a widely used spatial autocorrelation method based on cross-products to measure the cell-values association (Sokal and Thomson, 1987) where the spatial autocorrelation coefficient I is estimated as follows:

$$I = \frac{\sum_i \sum_j w_{ij} \cdot c_{ij}}{s^2 \sum_i \sum_j w_{ij}} \tag{8}$$

Where $w_{ij} = 1$ if cell i and cell j are neighbors and $w_{ij} = 0$ otherwise, z_i and z_j are the longshore sediment transport rates of cell i and cell j , $c_{ij} = (z_i - \text{mean}(z))(z_j - \text{mean}(z))$, and $s^2 = \sum_j (z_j - \text{mean}(z))^2 / n$. Moran's coefficient, I values that are greater than zero show similar correlated cluster of neighbors whereas values less than zero reflects either uncorrelated, random, or dissimilar spatial neighbors. We have computed Moran's I coefficient for the grid of the longshore sediment transport rates shown in Figure 3 above. The resulted Moran's coefficient we have obtained reflects high spatial autocorrelation among the cells of the grid of the longshore sediment transport rates as Figure 4 shows. This high correlation found among the cells of the longshore sediment transport rate grid may indicate the existence of the same wave climate conditions in the study area. Based on this we could estimate the energy flux factor from equation 12 using the values we obtained for the longshore sediment transport rates, Q confidently and we could further establish a wave climate that represents the action of waves in the study area.

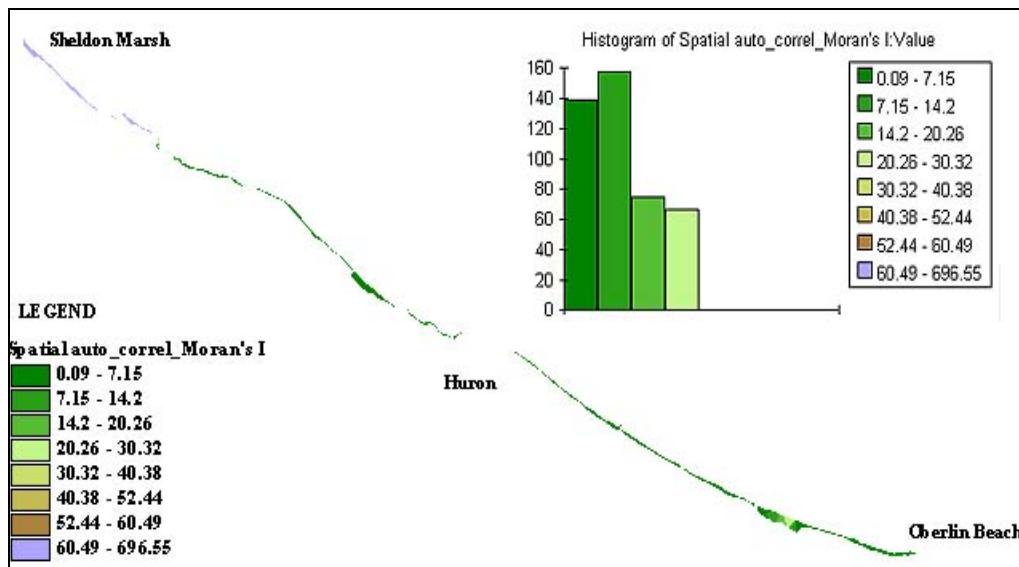


Figure 4. The spatial autocorrelation of the longshore sediment transport rates grid

V. Conclusion

This GIS-based shoreline-erosion estimation method, which has been introduced in this paper, is based on a discrete representation of the coastal terrain to estimate the longshore sediment transport rate, which is more accurate, certain, reliable, effective, and economic than the traditional approaches. The advantage of this approach is that we only need shorelines at time t_1 and t_2 and a CTM. In small-scale studies we can even just use geo-referenced low-resolution satellite data like Thematic Mapper data. This will save time and money spent to perform the traditional procedure of longshore sediment transport estimation and in the same time produce better results. The longshore sediment transport rates estimated by this approach would have better accuracy than those obtained using the traditional longshore sediment transport models, because the input variables have better

accuracy. Furthermore, the estimated longshore sediment transport rates obtained by this approach include the effect of the coastal storms and currents on shoreline change, which are usually not easy to be incorporated in any coastal sedimentation model. The spatial autocorrelation results obtained in this study indicates high correlation among the coastal sedimentation rate grid cells, which point out that the longshore sediment transport rate, Q could be used confidently to estimate the energy flux factor and further to establish a representative wave climate in the study area.

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Dr. Tarig Ali has a doctorate from the Department of Civil and Environmental Engineering and Geodetic Science at the Ohio State University, with a specialization in Geodetic and Geo-information Science and Surveying Engineering. Dr. Ali's research interests include GIScience, LiDAR Mapping, Wide-Area GPS Networks, Mobile and Internet-based GIS, Coastal Mapping and GIS, and Applications of GIS & Remote Sensing in Environmental & Transportation Engineering. Dr. Ali is the recipient of the 2006 ESRI Award for Best Scientific Paper in GIS 3rd Place (with N. Xutong, R. Ma, and R. Li), the 2005 Faculty Excellence Award by East Tennessee State University, the 2004 Murrough O'Brien Educational Award by the American Shore & Beach Preservation Association, and the 2003 Duane C. Brown Jr. Award by the Ohio State University - Department of Civil and Environmental Engineering and Geodetic Science.