Appendix H. Basic Approaches for Shoreline Change and Land Loss Projections: Application to Fire Island, New York

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While the factors that influence coastal change in response to sea-level rise are well known, our ability to incorporate this understanding into quantitative approaches that can be used to assess land loss over long time periods, such as 50-100 years, is limited. Part of the reason for this is the complexity of quantifying the influence of a range factors on shoreline change (*e.g.*, geologic framework, sediment supply, and hydrodynamic climate). In many settings, the human action to control the coast also adds to the complexity. This appendix reviews some of the basic approaches that have been applied to predict shoreline changes over 50-100 year time scales. One method which examines the vulnerability of a region to inundation (EPA, 1989; Titus and Richman, 2001; Rowley *et al.*, 2007) is used described previously in this report (See Chapter 1). This appendix is divided into two parts. First, three approaches that are used to predict shoreline change and land loss are reviewed. Next, three of the methods are applied to the shores of Fire Island, New York to provide examples of how these techniques are used and their limitations.

H.1 REVIEW OF SHORELINE CHANGE/SEA-LEVEL RISE IMPACT MODELS

The Bruun Model. One of the most widely known models developed for predicting shoreline change driven by sea-level rise on sandy coasts was formulated by Bruun (1962; 1988). This model is often referred to as the 'Bruun rule' and considers the two dimensional shoreline response (vertical and horizontal) to a rise in sea level (Schwartz, 1967). A fundamental assumption of this model is that the cross-shore shape of the beach, or beach profile, assumes an equilibrium shape that translates upward and landward as sea level rises. Four additional assumptions of this model are that:

- The upper beach is eroded due to landward translation of the profile
- The material eroded from the upper beach is transported offshore and deposited so that the volume eroded from the upper beach equals the volume deposited seaward of the shoreline
- The rise in the nearshore seabed as a result of deposition is equal to the rise in sea level, maintaining a constant water depth
- Gradients in longshore transport are negligible.

Mathematically, the model is depicted as:

$$R = \frac{L_*}{B + h_*} \cdot S \qquad \text{(Eqn H.1)}$$

where R is the horizontal retreat of the shore, h is the depth of closure or depth where sediment exchange between the shore face and inner shelf is assumed to be minimal, B is the height of the berm, and S is the vertical rise in sea level. This relationship can also be evaluated based on the slope of the shore face, Θ, as:

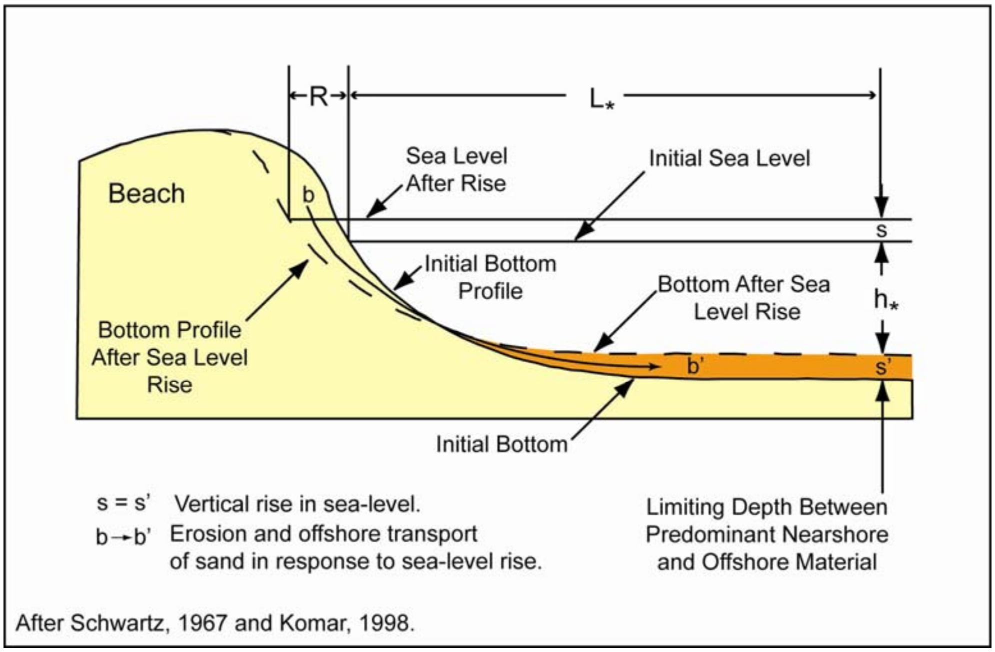
$$R = \frac{1}{\tan\Theta} \cdot S \qquad \text{(Eqn H.2)}$$

For most sites, it has been found that general values of Θ and R are approximately 0.01-0.02 and 50S–100S respectively (Wright, 1995; Komar, 1998; Zhang, 1998).

A few studies have been conducted to verify the Bruun Model to actual beach settings (Schwartz, 1967; Hands, 1980; also see SCOR, 1991; Komar, 1998; and Dean and Dalrymple, 2002 for a review). In other cases, some have advocated that there are several uncertainties with this approach which limit its use in practical application (Thieler *et al.*, 2000; Cooper and Pilkey, 2004). Field evaluations have also shown that the assumption of profile equilibrium can be difficult to meet (Riggs *et al.*, 1995, List *et al.*, 1997). Moreover, the Bruun relationship neglects the contribution of longshore transport which is a primary mechanism of sediment transport in the beach environment (Thieler *et al.*, 2000) and there have been relatively few attempts to incorporate longshore transport rates into this approach (Everts, 1985).

Even though the Bruun model has been in use for the last four decades no clear consensus exists regarding its validity as a quantitative predictive tool. Some studies have validated the approach (Bruun, 1962; Dubois, 1976; Hands, 1983; See review in SCOR, 1991; and Komar, 1998) while others have questioned several aspects of this method (Thieler *et al.*, 2000; Cooper and Pilkey, 2004).

A number of investigators have expanded upon the Bruun rule or developed other models that simulate sea-level rise driven shoreline changes. Dean and Maurmeyer (1983) adapted and modified the Bruun rule to apply to barrier islands (*e.g.*, the Generalized Bruun Rule). Cowell *et al.* (1992) developed the Shoreline Translation Model (STM) which incorporated several parameters that characterize the influence of geological framework to sea-level rise driven shoreline change. Stolper *et al.* (2005) developed a rules-based geomorphic shoreline change model (GEOMBEST) that simulates barrier island evolution in response to sea-level rise. While these models can achieve results consistent with our general understanding of sea-level rise driven changes to barrier island systems there is still the need for more research and testing against both the geologic record and present-day processes are needed to advance scientific understanding and inform management.



After Schwartz, 1967 and Komar, 1998.

Figure H.1 Illustration showing the Bruun Model and the basic dimensions of the shore that are used as model inputs.

Historical Trend Extrapolation. Another commonly used approach to evaluate potential shoreline change in the future relies on the calculation shoreline change rates based on changes in shoreline position over time. The shoreline change rates can then be used to extrapolate future shoreline positions at a specific location. In this approach a series of shorelines is assembled from maps for a particular area. In most cases these maps are either National Ocean Service T-sheets, aerial photographs, or derived from GPS surveys (Shalowitz, 1964; Leatherman, 1983; Dolan *et al.*, 1991; Anders and Byrnes, 1991). The historical shorelines are then used to estimate rates of change over the time period covered by the different shorelines. Several statistical methods are used to calculate the shoreline change rates with the most commonly used being end-point rate calculations or linear regression (Dolan *et al.*, 1991; Crowell *et al.*, 1997). End-point rate calculations are simply the rates determined based on the change in position between the oldest and most recent shorelines in a given dataset. Linear-regression rates are the result of estimating the average rate of change using a number of shoreline positions over time. The shoreline change rates can then be used to extrapolate future changes in the shoreline (Crowell *et al.*, 1997).

Because past shorelines positions are readily available from maps that have been produced through time and the relatively straightforward approach, the extrapolation of historical trends to predict future shoreline position has been applied widely for coastal management and planning (Crowell and Leatherman, 1999). In particular, this method is used to estimate building set-backs (Fenster, 2005). Estimation of future shoreline positions is often the result of multiplying the observed rate of change by the number of years to of the projection. More specific assumptions can be incorporated that address the rate of sea-level rise or geological characteristics of an area (Leatherman, 1990; Komar *et al.*, 1999).

Historical trend analysis has evolved over the last few decades based on earlier efforts to investigate shoreline change (described in Crowell *et al.*, 2005). Since the early 1980s computer based GIS software has been developed to digitally catalogue shoreline data and facilitate the quantification of shoreline change rates (May *et al.*, 1982, Leatherman, 1983, Thieler *et al.*, 2005). At the same time, thorough review and critique of the procedures that are employed to make these estimates have been conducted (Dolan *et al.*, 1991; Crowell *et al.*, 1991; 1993; 1997; Douglas *et al.*, 1998, Douglas and Crowell, 2000; Honeycutt et al, 2001; Fenster *et al.*, 2001; Ruggiero *et al.*, 2003; Moore *et al.*, 2006; Genz *et al.*, 2007).

Recently, national scale assessment of shoreline change has been carried out by the U.S. Geological Survey (Gulf Coast: Morton *et al.*, 2004; southeastern U.S. coast: Morton and Miller, 2005; the California coast: Hapke *et al.*, 2006). In addition, efforts are ongoing to complete similar analyses for the Northeastern, mid-Atlantic, Pacific Northwest, and Alaskan coasts.

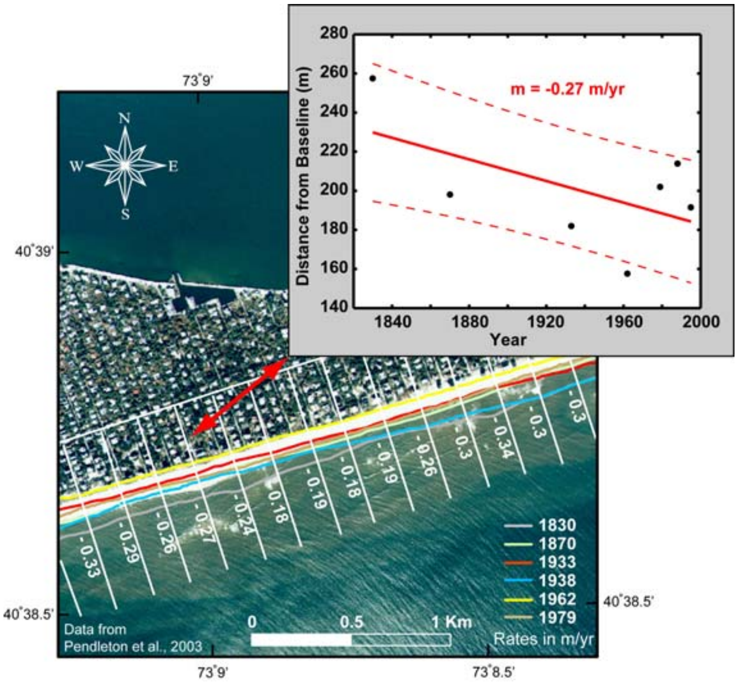


Figure H.2 Aerial photograph of Fire Island, New York showing former shoreline positions and how they are used to calculate long-term shoreline change rates using linear regression. The inset box shows the shoreline positions at several points in time over the last 170 years. From the change in position with time, an average rate of retreat can be calculated. This is noted by the slope of the line, *m*. The red line in the inset box indicates the best fit line while the dashed lines specify the 95% confidence interval for this fit. Photo source: State of New York GIS.

The Sediment Budget. Another approach to shoreline change assessment involves evaluating the sediment mass balance, or sediment budget, for a given portion of the coast (Bowen and Inman, 1966; Komar, 1996; List, 2005). In this method, the gains and losses of sediment to a portion of the shore, often referred to as a control volume, are quantified and evaluated in based on estimates of beach volume change. Changes in the volume of sand for a particular setting can be identified and evaluated with respect to adjacent portions of the shore and to changes in shoreline position over time.

One challenge related to this method is obtaining precise measurements that minimize error since small vertical changes over these relatively low gradient shoreline areas can result in large volumes of material (NRC, 1987). To apply this approach, accurate measurements of coastal landforms such as beach profiles, dunes, or cliff positions, are needed. Collection of such data, especially those on the under-water portions of the beach profile are difficult. In addition, high-density measurements are needed to evaluate changes from one section of the beach to the next. While the results can be useful to understand where sediment volume changes occur, the paucity of quality data and the expense of collecting it limit the application of this method in many areas.

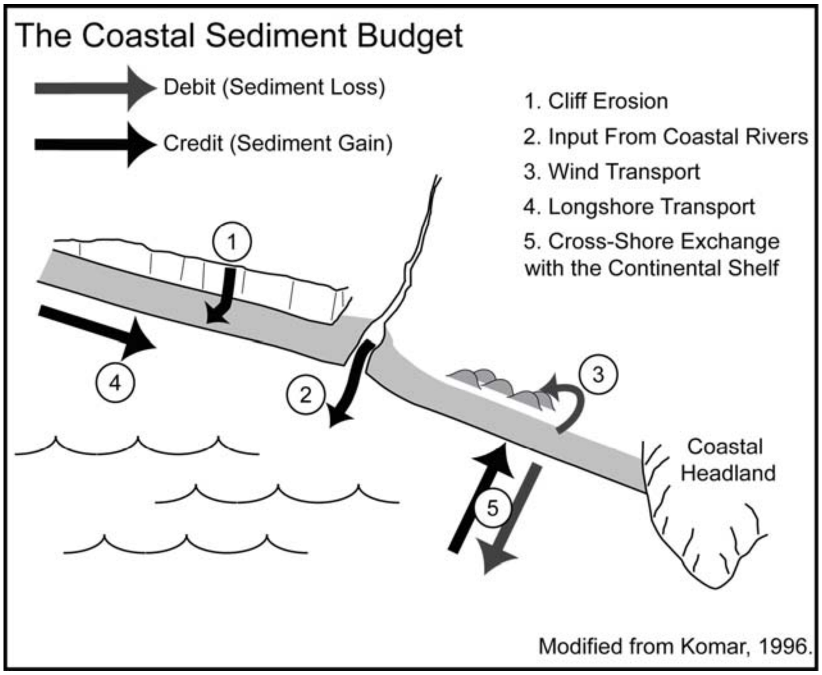


Figure H.3 A schematic of the coastal sediment budget (modified from Komar, 1996). In this approach the gains and losses of sediment from the beach and nearshore regions are evaluated to identify possible underlying causes for shoreline changes. In this schematic the main sediment sources are: 1) cliff erosion, 2) coastal rivers, 3) alongshore transport, and 4) cross-shore sediment transport from the continental shelf. The main sediment sinks are: 1) offshore transport from the beach to the shelf and 2) wind transport from the beach to coastal dunes.

Monte Carlo Simulation. One approach that has been applied to simple shoreline change models is the use of Monte Carlo simulations (Vrijling and Meijer, 1992, Reeve and Fleming, 1997). In this approach, a probability density function of some measure of shoreline change or position can be generated from a simple shoreline change model. A random number generator is used to generate a wide range of values for the respective input variables that are used to calculate the results. This approach is commonly applied using straightforward one-line models that relate shoreline change to wave height and sediment characteristics such as Pelnard-Considere’s (1956) shoreline evolution equation or the U.S. Army Corps of Engineers CERC equation (CERC, 1984). This approach has been applied to address shoreline changes over time spans of 5 years (Dong and Chen, 1999), 12 years (Reeve and Fleming, 1997) and 25 years (Ruggiero *et al.*, 2006) but has not been attempted over longer scales approaching centuries and incorporated changes in sea level.

The Coastal Vulnerability Index. One approach to parameterize the potential for coastal changes is through the development of a Coastal Vulnerability Index (CVI). This technique was first applied by Gornitz *et al.* (1989; 1990; 1994) to evaluate coastal hazards along portions of the United States coast. In this approach, 13 variables that influence coastline change and morphology were identified. Each risk factor is ranked according to a numerical scheme. The magnitude of the combined factors is then computed to determine the CVI for a given section of coast. The resulting index provides a qualitative measure of potential vulnerability at a particular location.

Recently, the U.S. Geological Survey (USGS) used this approach to evaluate the potential vulnerability of the U.S. coastline on a national scale (Thieler and Hammar-Klose, 1999) and on a more detailed scale for the U.S. National Park Service (Thieler *et al.*, 2002). The USGS approach reduced the index to include six variables (geomorphology, shoreline change, coastal slope, relative sea-level change, significant wave height, and tidal range) which were considered to be the most important in determining a shoreline's susceptibility to sea-level rise (Thieler and Hammar-Klose, 1999). The CVI is calculated as:

$$CVI = \sqrt{\frac{a \times b \times c \times d \times e \times f}{6}} \qquad \text{(Eqn H.3)}$$

where a = geomorphology, b = rate of shoreline change, c = coastal slope, d = relative sea-level change, e = mean significant wave height, and f = mean tidal range.

The CVI provides a relatively simple numerical basis for ranking sections of coastline in terms of their potential for change that can be used by managers to identify regions where risks may be relatively high. The CVI results are displayed on maps to highlight regions where the physical effects of coastal change may be the greatest.

H.2 CASE STUDY: PROJECTING POTENTIAL FUTURE SHORELINE CHANGE, FIRE ISLAND, NEW YORK

H.2.1 Introduction

The southern coast of Long Island, including the offshore continental shelf, exhibits complex geomorphology and geology due to several factors including: the underlying glacial geology, mobile sandy deposits comprising Long Island, characteristics of waves and tides in the region, and frequent impacts by major storms. The result is that Long Island beaches and dunes are dynamic landforms constantly changing due to complex physical forcing agents. Fire Island, which forms the central portion of the southern Long Island coast (Figure H.4), is a barrier island system where shoreline changes and the processes driving, including the vulnerability to sea-level rise, them have been studied for the last several decades (See reviews in Leatherman and Allen, 1985; Pendleton *et al.*, 2004; Psuty, 2005). Shoreline retreat due to the long-term effects of diminished sand supply and storm erosion has threatened residential development and coastal habitat. In addition, rising relative sea level is also influencing shoreline and dune changes on Fire

Island (McCormick *et al.*, 1984; Leatherman and Allen, 1985; Zhang, 1998; Psuty, 2005). At the same time, these processes are natural phenomena inherent to barrier islands such as Fire Island. Even with the scientific knowledge gained from the research that has been conducted, it remains difficult to predict quantitatively with high confidence how the Fire Island system is likely to change in response to future sea-level rise over the next century and beyond. In addition, human action to control shoreline changes, tidal inlets, and rare storm related breaches of the barrier island system have had an impact on the barrier island's behavior. The following discussion reviews briefly the three basic methods that are currently used to assess potential shoreline changes driven by sea-level rise. The goal of this discussion is to illustrate the limitations of these shoreline change approaches that arise due to their simplicity and inability to capture the dynamic nature of the system.

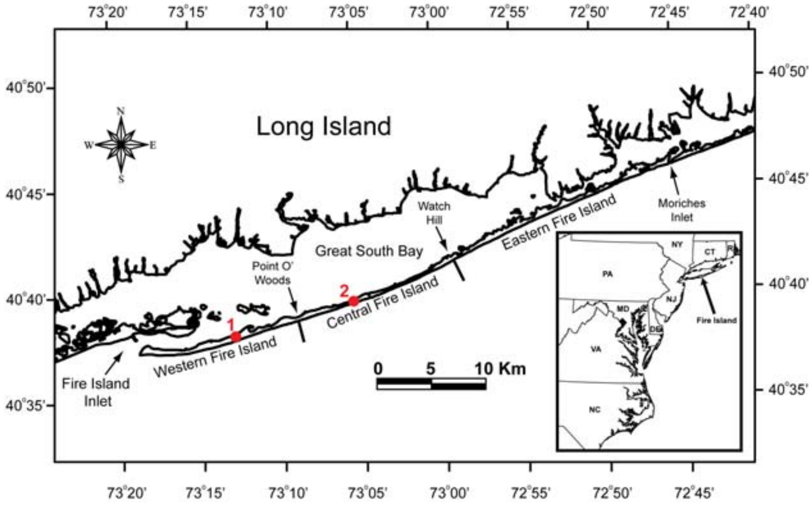


Figure H.4 Map of Fire Island, NY showing the three sections (western, central, eastern) that are discussed in this assessment. Red circles 1 and 2 denote the locations in Figures H.5 and H.6.

H.2.2 Potential Future Sea-level Rise Impacts: Established Concepts

Current scientific understanding suggests that Fire Island should migrate landward and upward over the long term through the process of ‘barrier island roll-over’ in response to rising sea level, the effects of storms, and sand feeding the barriers from a combination of erosion of the adjacent coast and the inner shelf (Hoyt and Henry, 1967; McCormick and Toscano, 1981; Leatherman and Allen, 1985; Williams and Meisburger, 1987; Schwab *et al.*, 2000). For this process to continue in the future, the evolution of the Fire Island system will depend on the continuing availability of sand to the barrier system from erosion of the adjacent coast as well as offshore areas. In addition, future storms will alter the Fire Island barrier. Some of these events could be large resulting in overwash and shoreline erosion whose effects may persist for a number of years. The formation of breaches and inlets during the most severe events is also possible, but it is difficult to predict when and where storm breaches might occur and how they might evolve (Williams and Foley, 2007). Historical records indicate that inlet formation and overwash have had large influences on these portions of the barrier and such risks are likely to remain in the future (Allen *et al.*, 2002 and Psuty, 2005). While there are some numerical models have been developed to predict barrier island migration and evolution in response to sea-level rise (Dean and Maurmeyer, 1983; Cowell *et al.*, 1992, 1995; Stolper *et al.*, 2005; Moore *et al.*, 2007), modeling approaches are still being developed and generally not yet suitable to inform management and policy decisions. Instead, the simpler approaches discussed in this case study are often used.

H.2.3 Projection of Future Shoreline Change Due to Sea-Level Rise Using Simple Quantitative Approaches

Three simple, commonly-used approaches are considered to predict future shoreline change and land loss due to sea-level rise along Fire Island. The three methods are: 1) the Bruun Rule model 2) extrapolation of historical shoreline change rates and 3) assessment of areas susceptible to inundation based on land elevation. The future shoreline changes were predicted for four sea-level rise scenarios which assumed that global sea levels would increase by 0.25 m, 0.5 m, 1 m, and 2 m by 2100. Long-term observations from a nearby tide gauge at the Battery in southern Manhattan indicated that relative sea level has risen at a rate of 2.88 mm/yr while the global rate over the last century was 1.7 mm/yr (Bindoff *et al.*, 2007). Based on this difference it is assumed that the local subsidence will occur at the same rate over the remainder of this century such that the total rise by 2100 is expected to be 0.11 m greater than the global rise. As a result, the future relative sea-level rise targets for this Fire Island assessment are: 0.36 m, 0.61 m, 1.11 m, and 2.11 m. In the following examples, the 1995 shoreline was used as a starting point for all of the projections and serves as a reference point from which all projections are discussed.

It is important to note that these three approaches are typically applied to different applications. While Bruun model is often applied to academic problems where researchers are either attempting to prove the validity of the concept (*e.g.*, Schwartz, 1967; Hands, 1983) or attempting to quantify the relationship between sea-level rise and shoreline change (Zhang *et al.*, 2002), it has also been used in coastal management applications (Komar, 1998). Historical shoreline change rate extrapolations are used most often in coastal management to inform coastal managers and as a basis for setback calculations (Crowell and Leatherman, 1999; Fenster, 2005). Inundation susceptibility assessments have been used for statewide or national scale assessment of sea-level rise impacts to provide estimates of land areas at risk from a specific rise in sea level (EPA, 1989; Najjar *et al.*, 2000).

The Bruun Model. The input parameters for this model, *L*, *B*, and *h* (See Figure H.1) were determined from a data base of beach profiles from the U.S. Army Corps of Engineers and State of New York between 1979 and 2003. The berm height, *B,* was determined from average profile estimated for each beach profile location. The depth of closure, *h*, was determined as the depth at which the standard deviation of beach profile change became constant following Morang *et al.*, (1999).

Historical Trend Extrapolation. In the second approach, shoreline change rates were used to extrapolate future shoreline positions to the year 2100. For this projection, shoreline change data were taken from Pendleton *et al.*, 2004. These shoreline change rates were calculated based on 10 historical shorelines spanning 1830 to 1995. The shoreline change rates were computed every 200 m along the shoreline and then averaged alongshore in 1 km bins. To extrapolate a future shoreline positions for the year 2100, the historical shoreline change rates calculated at the 200 m spacing were multiplied by 105; the number of years between the most recent shoreline (1995) and 2100. In taking this approach, it is assumed that all processes that contribute to long-term shoreline changes are reflected in the historical rate, including the effect of sea-level rise, and will remain more or less constant over the period of interest.

It is important to note that while the other two shoreline change methods are used to depict potential shoreline changes due to sea-level rise, extrapolation of shoreline change rates may not apply to sea-level rise scenarios that exceed those that occurred in the time periods corresponding to the historical shorelines that are used. During time span of the shorelines that were used in these calculations, relative sea level rose between 30-40 cm in the vicinity of Fire Island. These shoreline change projections, therefore, are best considered for the 0.36 m sea-level rise scenario. In some instances, a ratio can be established between sea-level rise and shoreline change such that an increased rise in sea-level can be considered (See Leatherman, 1990). Yet for these cases, the roll of sediment losses from the shore should also be considered carefully.

Inundation Susceptibility. The other approach which is used to evaluate potential land loss due to sea-level rise involves quantifying or specifying which land areas lie below a given elevation which corresponds to a particular rise in sea level. This approach is straight forward and can be determined using a variety of data (*e.g.*, Lidar elevations) to depict the topography of the landscape, however it does not consider any dynamic processes (*e.g.*, erosion, accretion, barrier rollover). Here, the elevation contours corresponding to the four sea-level rise scenarios were determined. The elevation contours used in this example were based on Lidar elevations acquired in the year 2000.

Using these data, elevation contours corresponding to the four sea-level rise scenarios were identified (Figures H.5 and H.6).

H.2.4 Comparison of Shoreline Change Results

The application of these three methods is discussed below based on the following figures (Figures H.5 and H.6).

Figure H.5 Site 1 comparison of shoreline change projections for a portion of Fire Island, NY (See Figure H.1 for location). Aerial photograph obtained from the state of New York.

Inundation. Here, the contours corresponding to the first three sea-level rise cases occupy a narrow portion of the barrier where the slope of the shoreface is relatively steep. Only the elevation corresponding to the 2.11 m rise scenario clearly occurs landward of the 1995 shoreline. At site 1, the elevation contours corresponding to the first three sea-level rise scenarios (0.36, 0.61, and 1.11 m) occur seaward of the 1995 shoreline (starting point for the projections) and the results for the Bruun model and historical extrapolations. At site 2, elevation contours corresponding to the first three sea-level rise scenarios (0.36, 0.61, and 1.11 m) occur both landward and seaward of the 1995 shoreline (starting point for the projections).

These results indicate the difficulty in attempting to apply this approach to a barrier island setting. First, the elevation data that were used for this example were acquired in 2000-five years after the 1995 shoreline that was used as a baseline and as part of the historical shoreline data set. Second, the geological understanding of barrier island systems indicates that barrier islands can be expected to migrate upward and landward in response to sea-level rise, so it cannot be assumed that the Lidar based topography of the barrier island will remain static as sea level rises.

Historical rate extrapolation. At Site 1, the historical extrapolation, depicted by the orange line, occurs farther inland than most of the scenarios displayed here even though this applies only to the smallest sea-level rise scenario (0.36 m). Here, the shoreline extrapolated based on shoreline change rates is 100-150 m landward of the position estimated using the Bruun Rule for the 0.36 m scenario (Figure H.5). At Site 2, the historical extrapolation occurs either even with or slightly offshore of the 1995 shoreline indicating that the shoreline position would remain static or migrate offshore by the end of this century (Figure H.6).

The differences in the projected shoreline changes rates between the two locations may be related to differences in the sediment budget between locations. At site 1, analyses of the sediment budget and shoreline change trends suggest that there has been a net loss of material from the beach leading to net erosion of the shoreline (Allen *et al.*, 2002; Psuty, 2005). On the other hand, site 2 occurs in a region where it has been suggested that the sediment budget is balanced or even augmented by accumulation of material transported onshore from the continental shelf (Williams and Meisburger, 1987; Kana, 1995; Rosati *et al.*, 1999; Schwab *et al.*, 2000).

Bruun Model. Results based on the Bruun model project a landward migration of the shoreline for each respective sea-level rise scenario. Given that sediment budget analyses indicate a long-term loss of material from the shore at site 1 and a possible abundance of sediment at site 2, it is likely that the sediment budget at each site is not balanced. Because of this, a simple application of the Bruun model neglects the sediment budget contribution to long-term shoreline change and may underestimate the magnitude and direction of future shoreline changes.

Storm Overwash. Lastly, at site 1 historical evidence has shown that storm surges from severe storms can penetrate up to 300 m inland. In Figure H.5, based on overwash maps complied by Johnson (1982) it can be seen that overwash from the Ash Wednesday 1962 Nor’easter penetrated nearly 250 m inland. It is difficult to predict when or in some cases where these incursions may occur in the future, but it is clear that the penetration distance of these events, which occurred over 40 years ago, exceeded the shoreline changes projected in this case study (*e.g.* Douglas *et al.*, 1998). Historically, storm overwash has been most prevalent along the eastern and western portions of Fire Island where dune heights are lower than those of the central portion of the island.

Figure H.6 Site 2. Comparison of shoreline change projections for a portion of Fire Island, NY (see Figure H.1 for location). Aerial photos from the state of New York.

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