Appendix 2. Basic Approaches for Shoreline Change Projections

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While the factors that influence changes in shoreline position in response to sea-level rise are well known, it has been difficult to incorporate this understanding into quantitative approaches that can be used to assess land loss over long time periods (*e.g.*, 50 to 100 years). The validity of some of the more common approaches discussed in this Appendix has been a source of debate in the scientific community (see Section 3.1). This Appendix reviews some basic approaches that have been applied to evaluate the potential for shoreline changes over these time scales.

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. A fundamental assumption of this model is that over time 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:

1. The upper beach is eroded due to landward translation of the profile.

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

Mathematically, the model is depicted as:

$$R = \frac{L_*}{B + h_*} \cdot S \qquad \text{(A2.1)}$$

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, L_* is the length of the beach profile to h_*, and S is the vertical rise in sea level (Figure A2.1). This relationship can also be evaluated based on the slope of the shore face, Θ, as:

$$R = \frac{1}{\tan \Theta} \cdot S \qquad \text{(A2.2)}$$

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

A few studies have been conducted to verify the Bruun Model (Schwartz, 1967; Hands, 1980; also reviewed in SCOR, 1991; Komar, 1998; and Dean and Dalrymple, 2002). In other cases, some researchers have advocated that there are several uncertainties with this approach, which limit its use in real-world applications (Thieler *et al.*, 2000; Cooper and Pilkey, 2004, also reviewed in Dubois, 2002). 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).

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 the geological framework into sea-level rise driven shoreline change for barrier islands. 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 the current understanding of sea-level rise driven changes to barrier island systems, there is still need for more research and testing against both the geologic record and present-day observations to advance scientific understanding and inform management.

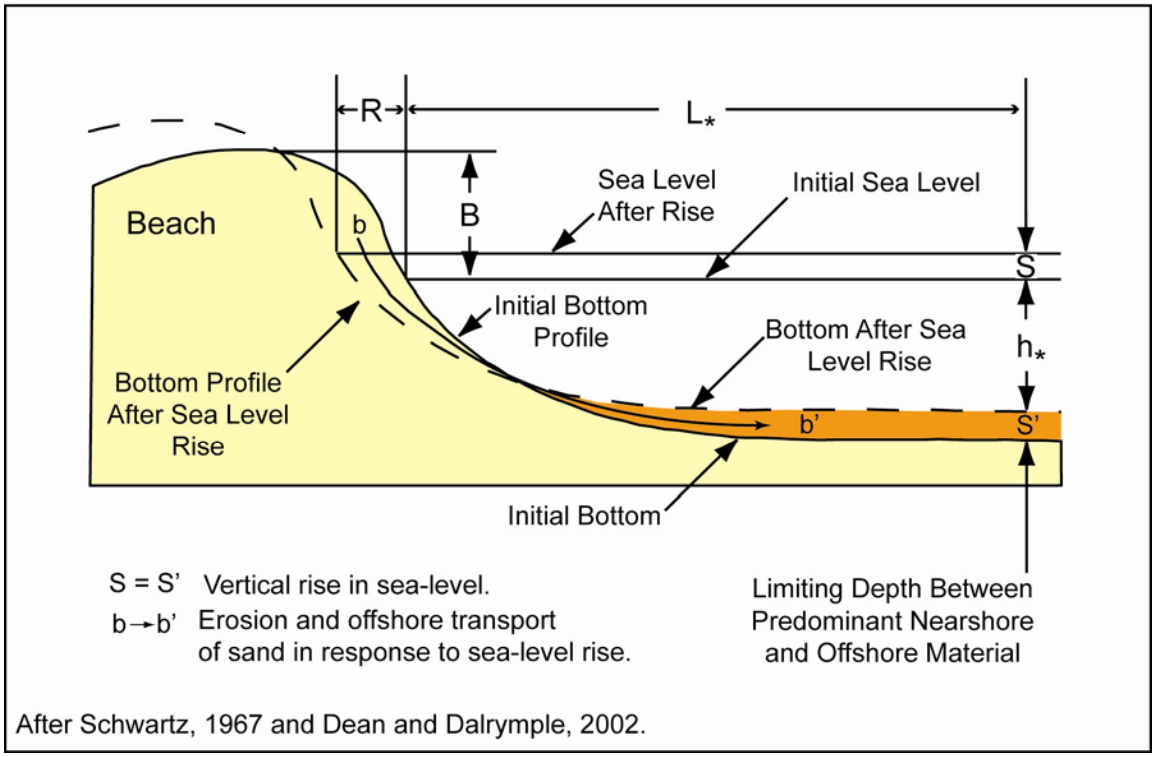

Figure A2.1 Illustration showing the Bruun Model and the basic dimensions of the shore that are used as model inputs.

Historical Trend Extrapolation. Another commonly used approach to evaluate potential shoreline change in the future relies on the calculation of shoreline change rates based on changes in shoreline position over time. In this approach, a series of shorelines from different time periods are assembled from maps for a particular area. In most cases, these shorelines are derived from either National Ocean Service T-sheets, aerial photographs, from Global Positioning System (GPS) surveys, or lidar surveys (Shalowitz, 1964; Leatherman, 1983; Dolan *et al*., 1991; Anders and Byrnes, 1991; Stockdon *et al*., 2002). The historical shorelines are then used to estimate rates of change over the time period covered by the different shorelines (Figure A2.2). 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). The shoreline change rates can then be used to extrapolate future changes in the shoreline by multiplying the observed rate of change by a specific amount of time, typically in terms of years (Leatherman, 1990; Crowell *et al.*, 1997). More specific assumptions can be incorporated that include other factors such as the rate of sea-level rise or geological characteristics of an area (Leatherman, 1990; Komar *et al.*, 1999).

Because past shoreline positions are readily available from maps that have been produced over time, 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 setbacks (Fenster, 2005). Despite this, relatively few studies have incorporated shoreline change rates into long-term shoreline change predictions to evaluate sea-level rise impacts, particularly for cases involving accelerated rates of sea-level rise (Kana *et al*., 1984; Leatherman, 1984).

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 Geographical Information System (GIS) software has been developed to digitally catalog 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, a national scale assessment of shoreline changes that have occurred over the last century has been carried out by the U.S. Geological Survey (Gulf Coast: Morton *et al.*, 2004; southeastern U.S. coast: Morton and Miller, 2005; 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.

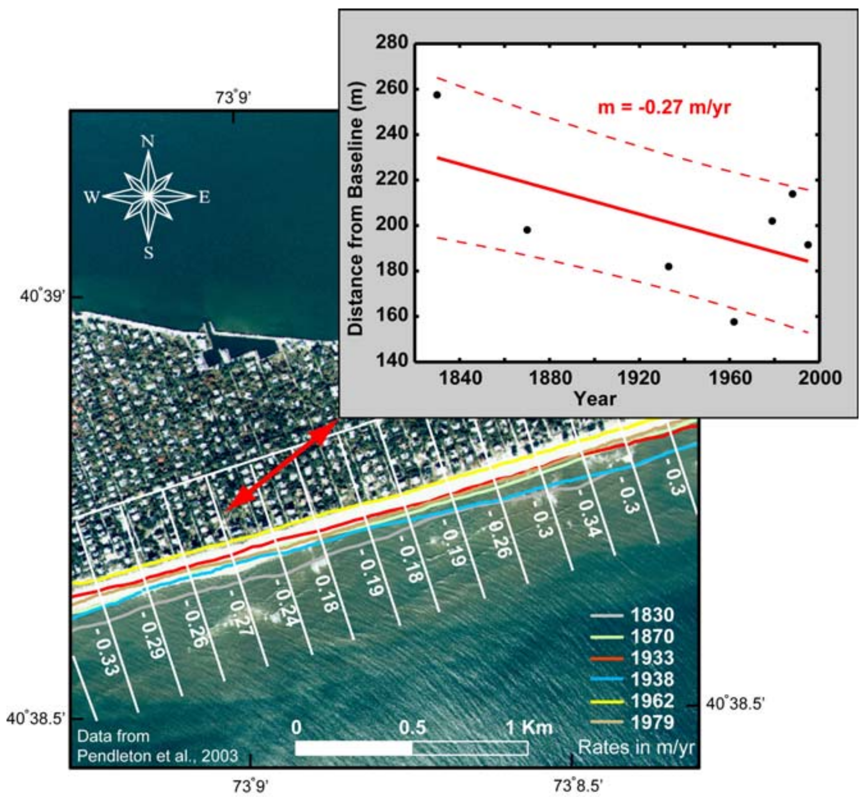

Figure A2.2 Aerial photograph of Fire Island, New York showing former shoreline positions and how these positions are used to calculate long-term shoreline change rates using linear regression. The inset box shows the shoreline positions at several points in time over the last 170 years. From the change 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 percent 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; Rosati, 2005), as shown in Figure A2.3. Using 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 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 underwater portions of the beach profile, is 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 lack of quality data and the expense of collecting the data limit the application of this method in many areas.

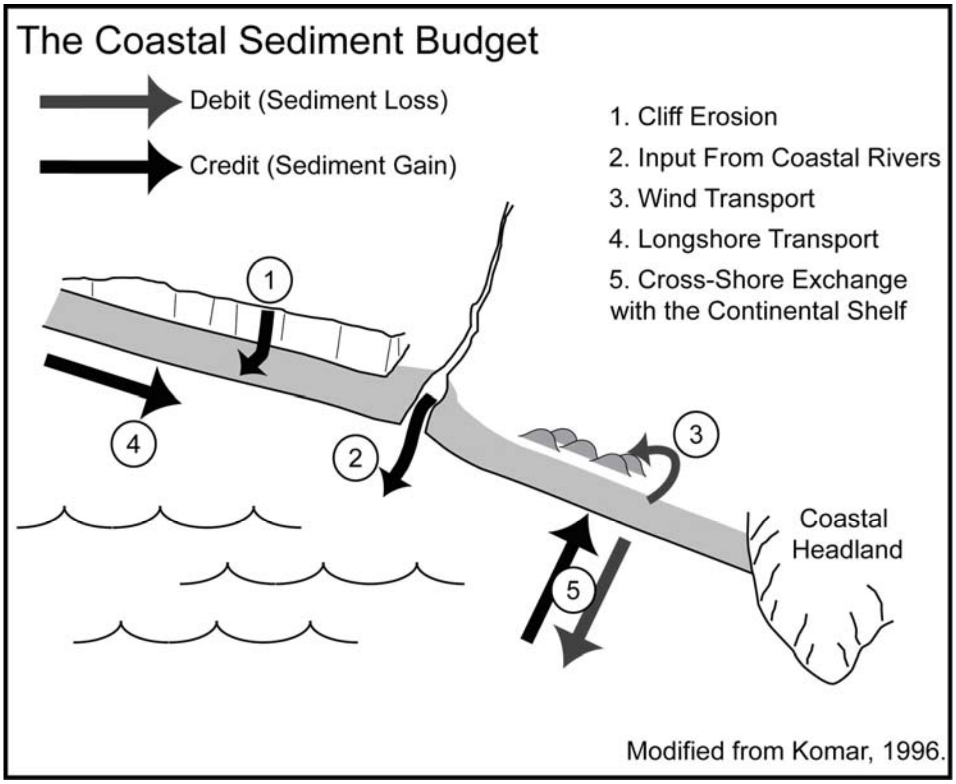

Figure A2.3 Schematic of the coastal sediment budget (modified from Komar, 1996). Using the sediment budget approach, the gains and losses of sediment from the beach and nearshore regions are evaluated to identify possible underlying causes for shoreline changes. In this schematic the main sediment gains are from: cliff erosion, coastal rivers, longshore transport, and cross-shore sediment transport from the continental shelf. The main sediment losses are due to: offshore transport from the beach to the shelf and wind transport from the beach to coastal dunes.

The Coastal Vulnerability Index. One approach that has been developed to evaluate the potential for coastal changes is through the development of a Coastal Vulnerability Index (CVI, Gornitz and Kanciruk, 1989; Gornitz, 1990; Gornitz *et al*., 1994; Thieler and Hammar-Klose, 1999). 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:

$$CVI = \sqrt{\frac{a \times b \times c \times d \times e \times f}{6}} \tag{A2.3}$$

where *a* is the geomorphology, *b* is the rate of shoreline change, *c* is the coastal slope, *d* is the relative sea-level change, *e* is the mean significant wave height, and *f* is the 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 factors that contribute to shoreline changes may have the greatest potential to contribute to changes to shoreline retreat (Figure A2.4).

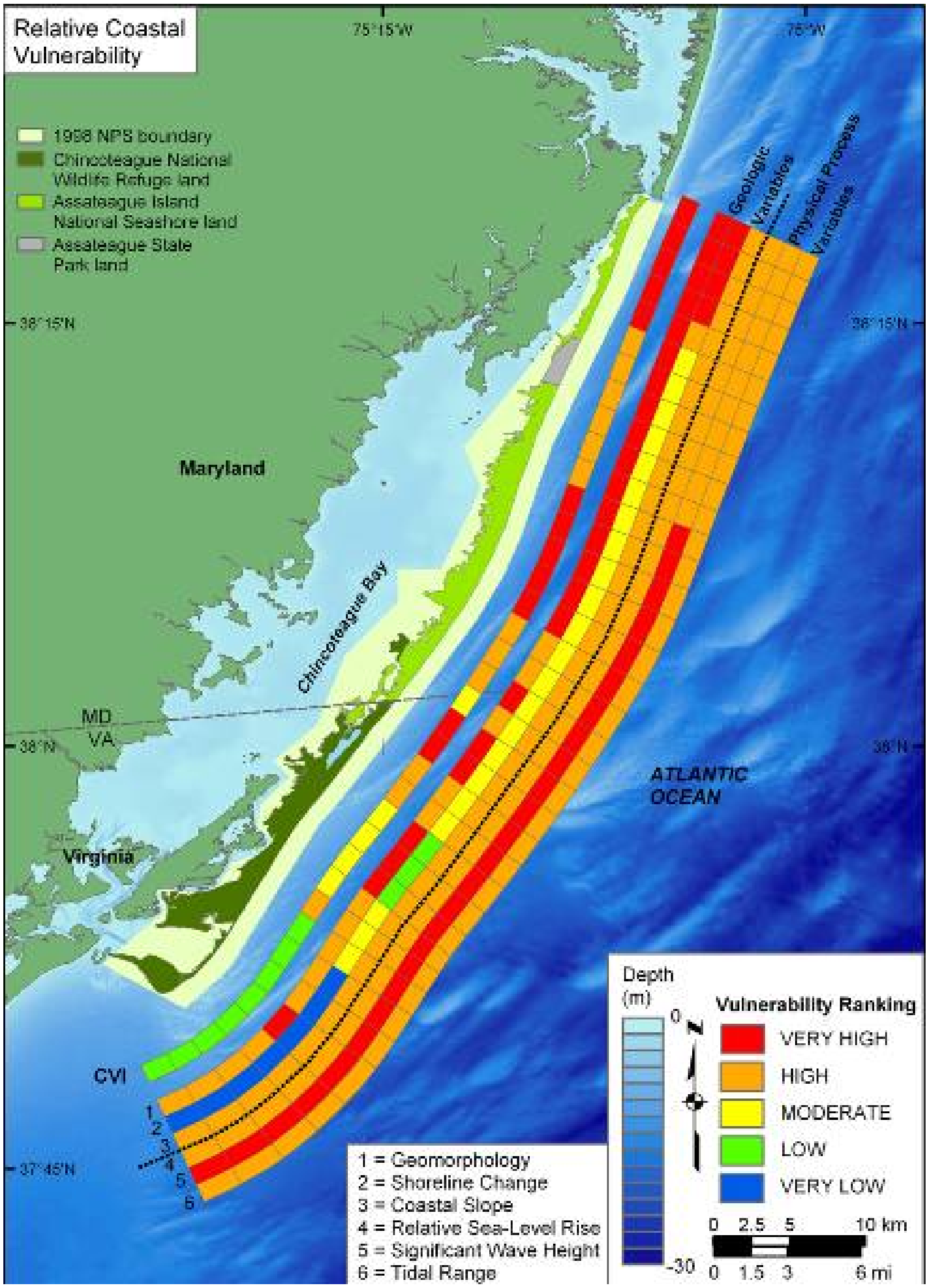

Figure A2.4 Coastal Vulnerability Index (CVI) calculated for Assateague Island National Seashore in Maryland. The inner most color-coded bar is the CVI estimate based on the other input factors (1 through 6). From Pendleton *et al*. (2004).

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