Beaches Response to Sea-Level Rise in Northern Puget Sound, Washington

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Abstract: The threat of global sea-level rise and beach recession is an important issue that coastal managers all over the world must address. Sea-level rise in northern Puget Sound is estimated by the University of Washington Climate Impacts Group to be between 8 and 55 cm by 2050. Close to unrestricted development along much of the coast of Puget Sound has left a large number of developments susceptible to changing beach conditions. To better understand beaches response to sea-level rise I intent to apply a model, developed by Bruun (1962) and modified by Nicholls (1998) which predicts the coastlines response to sea-level rise. The model holds inherent assumptions, such as a closed sediment budget which must be accounted for when applying the model. Model results will be measured as order of magnitude values based on recommendations by the Scientific Committee on Ocean Research. The model will be applied on a scale of 50 and 100 years using sea-level rise values developed by the Climate Impacts Group.

Keywords: Sea-Level Rise, Beaches, Puget Sound, Coastal Modeling

INTRODUCTION

Significant effects of sea-level rise (SLR) on beaches include transgression of the shoreline, and erosion of the backshore (Healy, 1996). There is a strong possibility that SLR is the cause of 70% of the worlds sandy beaches becoming recessional (Zhang, Douglas, & Leatherman, 2004). The global threat of SLR and coastline recession is an important management issue to any coastal country, for example low-lying atolls whose sovereignty may be entirely undermined by the inundation of their land (Barnett & Adger, 2003).

The University of Washington Climate Impacts Group (CIG) places 2050 estimates of SLR in Puget Sound from 8 to 55 cm above current levels (Mote, Peterson, Reeder, Shipman, & Binder, 2008). The CIG places moderate estimates of SLR around 15 cm by 2050. Mote, et al. (2008) determined SLR values for the course of 50 and 100 years based on the intended impact lengths of management decisions. 100 year values are estimated at 16, 34, 128 cm. Thermal expansion, land-based ice melting, and local movement of the land are factors that Mote, et al. (2008) contributed to SLR values in Puget Sound.

Erosion of the backshore and transgression of the shoreline due to SLR will threaten human developments and structures along the coast. Current U.S. coastal zone management strategies allow for a great deal of state and local control over shoreline development. Unfortunately state and local controls have been lax, allowing much of the coast to have close to unrestricted development (Beatley, Brower, & Schwab, 1994). Komar (1998) outlines numerous cases along the coasts of Washington and Oregon when erosion has undermined coastal development because of poor management strategies.

Coastline erosion due to SLR must be distinguished from coastal inundation. Low lying areas such as salt marshes and mangrove swamps are susceptible to slight changes in SLR leading to their eventual destruction because the ecosystem cannot adapt quickly enough to the rise in sea level (Zhang, et al., 2004). In the previous example, inundation takes place due to the lack of variation of topography and low angle slopes. Erosion on the other hand, is the actual "removal of sedimentary materials which form the shoreline" (Wells, 1995, p. 111).

To better understand the effects of coastline response to SLR, beyond inundation predictions, I intend to determine the change to Puget Sound beaches by applying a model, developed by Bruun (1962) and modified by Nicholls (1998), which predicts the coastlines response due to SLR. Nicholls' modified model will be applied to selected sections of the Puget Sound coast at a temporal scale of 50 and 100 years using the CIG's SLR values for Northern Puget Sound.

COASTLINE RESPONSE MODELS

In 1962, P. Bruun developed a model that described shoreline change on beaches due to SLR. Bruun developed the 2-dimensional model utilizing the equilibrium beach profile concept (Dubois, 1992). Figure 1 (Cooper & Pilkey, 2004) provides a simplified illustration of the Bruun model. Bruun's model assumes erosion of backshore sediment and deposition of eroded sediment in the nearshore up to a closure depth, or the seaward limit of morphologic change (Hennecke & Cowell, 2004). Broad acceptance and application of the Bruun model in coastal engineering has resulted in over half a century of its dominance as the normative model of coastline response to SLR (Davidson-Arnott, 2005). More recently however, Cooper & Pilkey (2004) critically examine a number of assumptions associated with the Bruun model including a closed sediment budget based on the equilibrium beach profile theory.

One inherent assumption associated with the Bruun model is the equilibrium beach profile theory and subsequent closed sediment budget. The equilibrium beach profile theory states that the beach profile is maintained after SLR; the profile is only translated landward and upward by the magnitude of SLR (Bruun P. , 1988). A closed sediment budget eliminates sediment input and output, such as longshore transport. A majority of coastal environments include the exchange of sediment between external sources. Therefore, Zhang, et al. (2004) applied the model to shorelines with no net longshore transport in an effort to minimize error introduced by closed sediment budget assumptions. Zhang, et al. (2004) discovered how the closed sediment budget severely limited possible application sites when trying to apply the model to dynamic coastlines. Application of the model is therefore limited by the sediment budget controls placed on the model. Still, sites were able to selected by Zhang, et al. (2004) for application of the model.

Variations to the Bruun model have been developed in an attempt to more accurately capture the dynamics of coastal processes. Dean & Maurmeyer (1983) adjusted the Bruun rule to incorporate the migration of barrier islands. Hands (1983) included sediment budget variables to the models equations. Kriebel & Dean (1985) developed a model for predicting erosion during severe storms and elevated water levels. Dubois (1992) suggested that the offshore is abandoned by wave action allowing for complete onshore movement of sediment and subsequent transgression of barrier islands. Healy (1996) developed a model, based on Bruun's model, to fit previously recorded sea-level conditions concerning dune and shelf erosion facilitating the modeling of future shore profiles. Kont, Ratas, & Puurmann (1997) made corrections for variations in sediment size for impact studies in Estonia. Zhang, Douglas, & Leatherman (2004) and Hennecke, Greve, Cowell, & Thom (2004) used complex statistics and geographic information systems (GIS) respectively to increase accuracy and applicability of the model. Davidson-Arnott (2005) proposed the conceptual RD-A model which included beach-dune interaction.

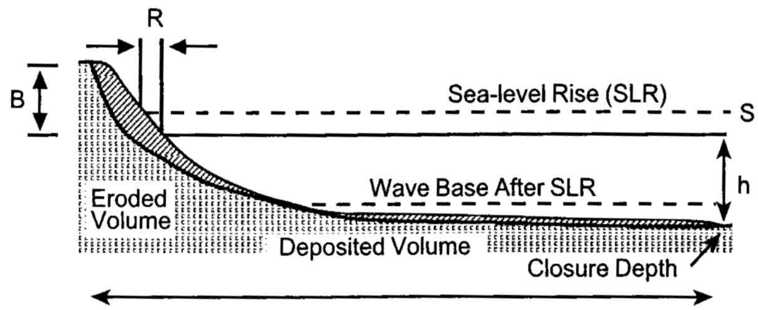

Figure 1 - Simplified Representation of Bruun's Model

Hennecke & Cowell (2004) and Hennecke, Greve, Cowell, & Thom (2004) applied coastline response models in GIS. Using GIS to apply coastline response models along a section of coast allows for increased applicability of the results. Multiple shoreline profiles are selected along a stretch of coast, and then recession rates are interpolated for a wide area instead of a simple 2-dimensional profile. Model results that show beach profile change along a stretch of coast, instead of a single 2-dimensional profile, provides a better interpretation of the changes to the beach's profile.

The Scientific Committee on Ocean Research (SCOR) Working Group 89 (1991) recommended a number of guidelines when employing coastline response models. SCOR suggested an application of an order-of-magnitude assessment to the model output; meaning, the results of the model are not definite and should be accepted and applied with this knowledge. Accepting a model output as absolute is inconclusive; as with any predictive model, the results may vary from the actual occurrence due to randomness of natural processes. Mote, et al. (2008) similarly stressed that their SLR calculations for Puget Sound were not exact predictions, and should be used for advisory purposes only. Applying an order-of-magnitude assessment acknowledges the existence of the assumptions inherent to predictive models.

Bruun (1988), The SCOR working group (1991), Pilkey, Young, Riggs, Smith, Wu, & Pilkey (1993), and Cooper & Pilkey (2004) have demonstrated that modeling is not a perfect representation of reality; however, it provides an approximation of reality. My research will apply a coastline response model to selected beaches of Puget Sound. While the model I intend to apply will not provide exact coastline recession rates, due to the nature of modeling, it will provide coastal managers and decision-makers with important information on the implications of SLR to the beaches of Puget Sound.

METHODS

I aim to better understand Puget Sound beaches response to SLR by applying a model that predicts the morphological response to SLR. I will be applying Robert J. Nicholls (1998) modification of Bruun's model to selected beaches within Puget Sound.

Study sites for this research must account for assumptions in the models to minimize error. Because the model I intend to apply is 2-dimensional and assumes a closed sediment budget, study areas must be selected that minimize sediment transport, such as longshore drift. Zhang, et al. (2004) followed similar site selection procedures to minimize error in their study on the U.S. East Coast due to longshore drift. The study area for this research will be in northern Puget Sound. Sufficient sediment transport data exist in three northern Puget Sound counties, Whatcom, Skagit, and Island, to select sections of coast that minimize sediment transport. Possible study sites will be identified, then specific sites selected for modeling based on availability.

I will be applying Nicholls' model (1998) to selected beach profiles in Puget Sound. Similar to the Bruun model, Nicholls' model assumes an equilibrium beach profile; meaning, the beaches profile is preserved and translated landward and upward relative to sea-level. The model assumes a 2-dimensional closed sediment budget and can be calculated as (Figure 2):

Equation 1 – Beach recession due to SLR

$$R = G\left(\frac{L}{H}\right)S$$

where

Equation 2 – Elevation change between the offshore and onshore boundaries

$$H = B + h_s$$

R is the shoreline recession due to SLR, S. G is the inverse of an overfill ratio (US Army Corps of Engineers, 1984) and represents grain size of the eroded material. L is the active profile width between the onshore and offshore boundaries. H is the elevation change between the onshore and the offshore boundaries, B is the land elevation at the onshore boundary, and h_s is the depth at the offshore boundary.

Nicholls' (1998) variation better defined the onshore and offshore boundaries of Bruun's model. Bruun's model defines the onshore boundary as the beach crest or dune crest. However, Nicholls (1998) states that as the dune profile is translated its height will change. Therefore, it is better to represent the average elevation of the land, B, as the elevation behind the crest. Reducing the height of B, and adding the width of the dune (W) to the profile allows the crest to maintain its height relative to sea level and migrate onshore. The relationship of B to H is shown in Equation 2. The addition of the dune width (W) to Equation 1 adjusts the beach recession formula to:

Equation 3 – Adjusted recession equation

$$R = G\left(\frac{(L+W)}{H}\right)S$$

Nicholls (1998) notes that the recession rates will be a bit higher than Equation 1, but given the fact that W is markedly less than L, and H is only slightly affected, the change in recession is minimal. Only a scenario where the dunes are exceptionally high would the change in recession from the original equation be large. Nicholls continues to note that preservation of the dune maintains the standard of protection against storms that existed before SLR.

The offshore boundary has also been modified from Bruun's original design. Nicholls (1998) defines the depth of closure, or the offshore boundary, by the range of possible time-scales considered. Nicholls considers the low estimate time scale as the annual depth of closure, $d_{L,1}$:

Equation 4 – Low estimate annual depth of closure

$$d_{L,1} = 2.28H_s - 68.5\left(\frac{H_s^2}{gT_s^2}\right)$$

where H_s is the wave height in a 12h period, and T_s is the associated wave period. The high estimate time scale is the depth of closure over the course of a century:

Equation 5 – High estimate depth of closure typical of a century

$$d_{L,100} = 1.75d_{L,1}$$

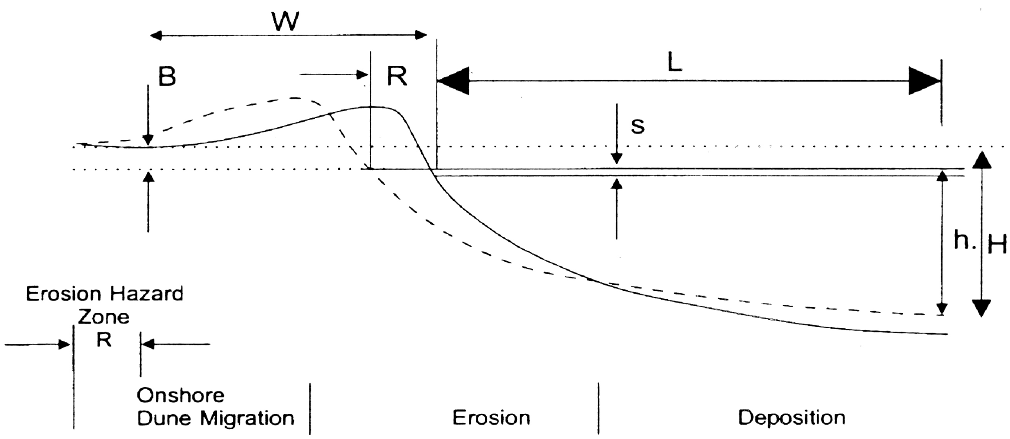

Figure 2 – Illustration of beach morphology change due to SLR

Nicholls (1998) notes that an appropriate reference depth for the depth of closure appears to be around one meter above low water. Given the fact that a larger depth of closure predicts a lower beach slope, the $d_{L,100}$ will predict a larger recession then $d_{L,1}$.

The profile corresponding to the boundary locations must be determined upon establishment of the onshore and offshore boundaries. Determining the profile requires bathymetry and digital elevation model data. GIS will assist in the development of the beach profiles. Inputting bathymetry data and DEM data in GIS will allow profiles to be extracted to exacting measurements. The resulting profiles will be used for the recession calculations. Multiple recession calculations will be performed for the low, moderate, and high estimates of SLR in Puget Sound.

Rising sea-level producing changes in Puget Sound beach morphology is important to state and local coastal zone managers and property owners because they have a vested interest in the coastline and its longevity. Whether that interest is for example, economic or ecological, is a matter of circumstance and not relative to this project. Regardless of individual interest SLR will affect beaches morphology and consequently any manmade structure adjacent to the beach, for example, residential structures. Coastal managers must be aware of how beaches will react to SLR in order to properly develop management plans. Additionally, property owners should be aware of SLR consequences on their property to allow for appropriate planning or possible hazard mitigation. Modeling beaches response to SLR will assist any related coastal effort by providing advisory shoreline recession and profile response values.

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