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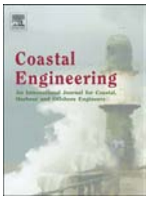

Determining shoreline response to sea level rise

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ABSTRACT

The Bruun rule is the most widely used method for determining shoreline response to sea level rise. It assumes that the active portion of an offshore profile rises with rising sea level, and the sand required to raise the profile is transported from the shoreline. It is difficult to evaluate the efficacy of the Bruun rule because sea level rise often has a lesser effect on shoreline change than that produced by sand sources, sinks, and longshore transport gradients. In addition, some shorelines have advanced seaward with rising sea level. Dean (1987) showed that equilibrium profile theory predicts that rising sea levels produce landward sand movement forced by nonlinear waves. This paper presents an equation with terms representing all phenomena affecting shoreline change including Bruun-rule recession, onshore sand transport, sand sources and sinks, and longshore transport gradients. As an example of its use, rates of onshore transport are determined along the 275-km Florida southwest coast, USA, and a 19-km portion of this coast using known values for sand sources, sinks, and longshore transport gradients. Then future shoreline changes are projected for both coasts from 2015 to 2065 and for the southwest coast from 2015 to 2100, using sea level rise projections from the Intergovernmental Panel on Climate Change. Beach nourishment is shown to be a very effective adaptation strategy for sea level rise with shoreline change projections useful to estimate required rates of beach nourishment to counter sea level rise.

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1. Introduction

1.1. Bruun rule

The Bruun rule (Bruun, 1954, 1962, 1988), named by Schwartz (1967), is the most widely used method for determining shoreline response to sea level rise. It assumes that over the long term the "active" portion of a profile perpendicular to the shoreline maintains a constant form known as an equilibrium profile. Characteristics of the profile depend primarily on sand size (assumed constant) and secondarily on wave parameters (Dean, 1987). The active profile extends to a water depth known as "closure depth", beyond which there is little sand motion and, according to the Bruun rule, there is no movement of sand onto the active profile. The Bruun rule assumes that the active profile maintains its shape over the long term, rising with sea level rise. In order for the profile to move upward, there must be a source of sand, and the Bruun rule assumes that all of the sand is transported from the shoreline, and this loss of sand causes shoreline recession. Therefore, as shown in Fig. 1, the shoreline change, ΔX, due to sea level rise of ΔS for the active profile extending a distance of W_* from the beach berm with height, B, to closure depth, h_*, is

$$\Delta X = -\Delta S\left(\frac{W_*}{h_* + B}\right). \tag{1}$$

The notation of W_*, B, and h_* was used by Dean (1987) and others. It is assumed that $\Delta X \ll W_*$ and $\Delta S \ll h_*$.

Closure depth is an important parameter of the Bruun rule. Dean and Malakar (2002) said closure depth was an estimate of the average annual depth limit at which sediment motion was active to a significant degree, and that this was the approximate depth at which a nourished beach would "equilibriate". This definition will be used for closure depth. Nicholls et al. (1996) noted that closure depth separated a landward active zone from a seaward less active zone, and it was a "morphodynamic" boundary and not a cross-shore sand transport boundary, so sand could flow onshore from beyond closure depth. Nicholls et al. (1996, 1998) noted further that closure depth depended on the time frame considered, as will be discussed later.

There have been conflicting accounts of how well the Bruun rule predicts shoreline response to sea level rise. Schwartz (1967) concluded from two small-scale laboratory experiments and field observations at Cape Cod, USA, that the Bruun rule concept was a good first-order approximation of shoreline response to sea level rise. Citing several

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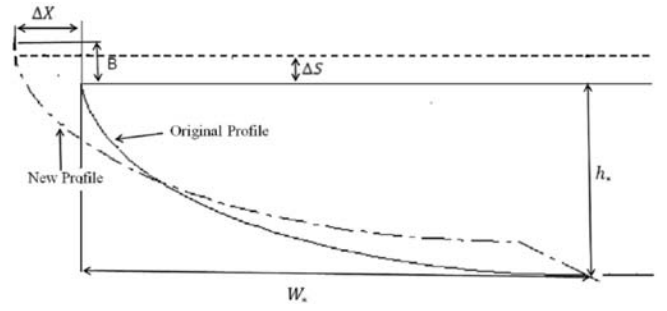

Fig. 1. Active profile change due to sea level rise according to the Bruun rule.

studies, the Scientific Committee on Ocean Research (1991) concluded that the Bruun rule had been confirmed in its "basic patterns" by both laboratory and field experiments, but recommended that it be used only for order-of-magnitude projections of shoreline recession. Zhang et al. (2004) analyzed sea level rise and shoreline change from New York to South Carolina, USA, and concluded that there was good agreement between the Bruun rule and observed erosional trends. Cooper and Pilkey (2004) argued against the efficacy of the Bruun rule and recommended it be abandoned, but they did not offer an alternative. Rosati et al. (2013) presented evidence of the efficacy of the Bruun rule if it were modified to not only include seaward transport of sand, but also landward transport if a profile had an excess of sand relative to the equilibrium profile.

It is difficult to determine the efficacy of the Bruun rule because there are other factors affecting shoreline change. Zhang et al. (2004) could only use 24% of the shoreline they considered to evaluate the Bruun rule because the remainder of the shoreline was influenced by inlets and coastal engineering projects. Passeri et al. (2014) analyzed shoreline response to sea level rise along the south Atlantic Bight and northern Gulf of Mexico, USA, and concluded that the Bruun rule could be used effectively to determine shoreline recession only in areas where there was little to no background erosion caused by other factors. Stive (2004) noted that on most shorelines sea level rise has a lesser effect than that produced by sand sources and sinks, longshore gradients, and onshore-offshore sand transport. Sea level rise has produced only about 5–10% of the recession along the Netherlands shoreline with breaks such as inlets (Stive et al., 1990) and about 20% of the recession on the Outer Bank barrier islands of North Carolina, USA (Inman and Dolan, 1989). Houston and Dean (2015) determined that inlets modified for navigation caused 70% of shoreline recession on the 575-km long east coast of Florida, USA. Stive (2004) showed that natural longshore transport gradients on the USA east coast and Netherlands coast had a comparable effect on shorelines as sea level rise, and human-induced longshore transport gradients could be an order of magnitude greater. Many shorelines also have had extensive placement of beach nourishment, masking shoreline recession caused by sea level rise.

1.2. Onshore sand transport

Dean (1987) noted that the Bruun rule assumed that sand on the active profile was a uniform size, but sand size is varied along profiles, generally becoming finer in the offshore direction (as acknowledged by Bruun, 1983). Dean proposed an equilibrium profile concept that included sand-size variability along the active profile. For a particular wave climate, a sand particle of a particular size will be in equilibrium when resting at a particular water depth. Following sea level rise, the sand particle must move to shallower water to be back to the water depth at which it is in equilibrium. Therefore, in response to sea level rise, sand particles should move landward over time to re-achieve the equilibrium profile. It should be noted that Bruun (1983, p. 88) said of the Bruun rule, "And the theory is first of all an erosion and not an accretion theory."

Dean (1987) and Davidson-Arnott (2005) postulated that shorelines advancing seaward received sand from beyond closure depth, and this sand raised active profiles with sea level rise. Using a nonlinear wave model, Dean (1987) showed that wave asymmetry produced a landward average shear stress that he said would tend to cause shoreward sediment motion across the continental shelf. Roelvink and Stive (1990) also noted increasing wave-induced streaming and short-wave asymmetry as one moved from beyond closure depth to the active profile on the Netherlands coast. The annual volume of sand moving landward can be small, but Cowell et al. (2003a) noted that systematic residual fluxes that are small on sub-decadal time scales can eventually accumulate such that they produce measurable morphological changes.

Landward movement of substantial quantities of sand was postulated by the de Beaumont (1895) theory of barrier island formation. This theory said that during Holocene sea level rise there was an excess of sand in offshore profiles that was transported landward and formed and/or widened subaerial barrier islands. The processes that led to barrier island formation may still be operating in areas where profiles have an excess of sand. For example, Pizzuto (1986, p.314) developed a sand budget for southern Delaware Bay, USA, based on measurements and concluded his results contradicted, "the notion implied by the Bruun Rule that sediment is carried offshore as sea level rises. Rather, these results suggest that sandy barrier sediments may be supplied from offshore".

Stive and de Vriend (1995) showed that 90 km of the central Netherlands shoreline advanced an average of about +30 m from 1895 to 1976 despite relative sea level rise of about 2 mm/yr. Using profile data, they showed the sand that advanced the shoreline came from seaward of the active profile — that is, seaward of closure depth. They considered the active profile to be such that morphologic changes could be noticed in a year, whereas further seaward the profile was morphologically weakly varying. They said that sand was driven shoreward by cross-shoreface transport induced by wave asymmetry, as described by Dean (1987), along with near-bed flows from density and wind-driven upwelling. Stive et al. (1990) showed that the active profile out to a depth of −8 m moved upward an amount equal to sea level rise and the shoreline advanced seaward, which is in agreement with the Dean equilibrium concept. In contrast, they showed that the northern Netherlands coast had a shortage of offshore sand due to a deficit produced by longshore sand transport. Profiles rose with rising sea level, but the shoreline receded as predicted by the Bruun rule. Whether the Bruun rule or Dean equilibrium dominates along a coast depends on offshore sand availability and probably the local rate of relative sea level rise.

Houston and Dean (2014) showed from historical measurements given in Absalonsen and Dean (2010) that the 575-km Florida east coast shoreline advanced seaward an average of +23.0 ± 5.6 m (errors are standard deviations) from 1869 to 1971. This advance was before widespread beach nourishment that started in the early 1970s and despite sea level rise of about 2.5 mm/yr. Houston (2015) performed a similar analysis for the 275-km southwest coast, and the shoreline change was +5.1 ± 11.3 m from 1872 to 1972 despite large losses to inlet shoals and a relative sea level rise of about 2.5 mm/yr. Houston (2015) added all sand sources and sinks and shoreline effects of longshore transport gradients and assumed that the Bruun rule governed shoreline response to sea level rise and determined that the shoreline should have receded −41.4 ± 7.6 m from 1872 to 1972. Therefore, standard deviation confidence intervals of measured and calculated shoreline change did not overlap, indicating there was a large source of missing sand. Both Houston and Dean (2014) and Houston (2015) showed that these large-scale sand gains could not have been produced by carbonate sand production by organisms, but were instead primarily produced by onshore movement of silica sand. A quantity of sand equal to 2.7 ± 0.8 m^3/m-yr (volume arriving per meter of shoreline per year) arriving from beyond closure depth was required to explain the measured southwest shoreline change from 1872 to 1972.