A MASS CONSERVATION MODEL TO PREDICT THE BEHAVIOUR OF COASTAL SOFT-CLIFFS DRIVEN BY SEA LEVEL RISE OVER MULTI-CENTURY TIMESCALES.

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INTRODUCTION

Soft rock cliffs are common coastal features made of erodible material, such as clay and glacial deposits. The erosion of soft-cliffed coasts threatens communities around the world, destroying homes and habitats. This type of coast is relatively common in the U.K., where coastal erosion is such that an estimated 8,900 properties (Climate Change Committee, 2021) are at immediate risk from it. A third of these properties are on the Norfolk coast, which is rich in soft cliffs (Figure 1).

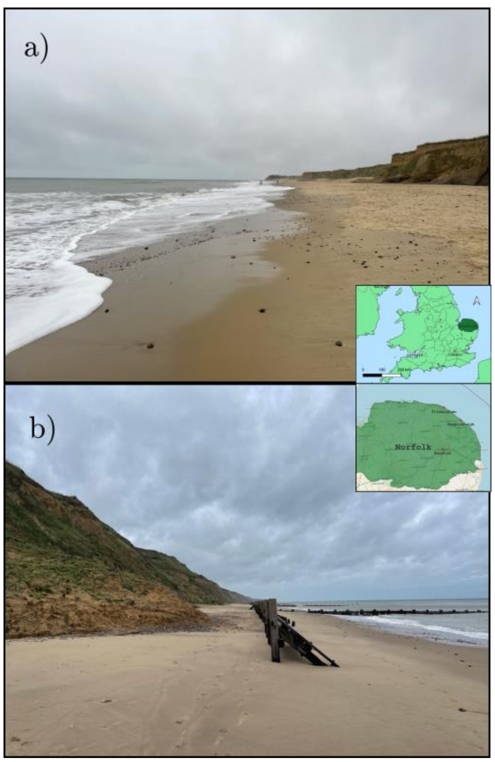

Figure 1 – Typical soft-cliffed coasts in North Norfolk. At Happisburgh (a), defenses (groynes) have been removed leading to rapid erosion, and at Trimingham (b) defenses (revetments and groynes) are mostly intact but have an uncertain future. The insert shows the position of the two locations.

Extreme retreat rates along this coast can be up to 20 m/year (Muñoz López et al., 2020). It is unknown exactly how climate change, which drives sea level rise (SLR) and may change local wave climates, will affect the rate of cliff erosion. Separating the contributions to coastal erosion of SLR and sea storms is a necessary step to inform coastal adaptation strategies (Ranasinghe et al., 2023).

In this work we aim to improve the understanding of the contribution of SLR to future rates of cliff retreat to inform long term coastal management and adaptation to climate change. We are interested in understanding changes in future retreat rate under different scenarios of SLR projections (Clark et al., 2016) for different soft-cliffed coasts. We are also seeking to identify potential changes in coastal typology (i.e. cliff disappearance). This objective requires that the evolution of the coast is simulated over multiple centuries.

Here we present a numerical model suited for estimating the evolution of these coastal systems over centuries in response to SLR alone. To achieve computational efficiency, we propose a simple conceptual model, based on a mass-conservation approach. In this model we have relaxed the conditions used by Wolinsky and Murray (2009) when solving the Exner equation for cliffed coastlines. In particular, the assumptions of constant SLR and simplified inland topography. In this work we remove these restrictions, and obtain a simple behavioural equation for soft-cliffed coasts for which an analytical solution exists. This allows study of the conditions for existence of an equilibrium rate and the dynamics of equilibrium approach.

METHODOLOGY

Mass conservation is used to derive a first-order differential equation for cliff retreat rate due exclusively to SLR. Over a small timestep, the volume eroded from a vertical faced cliff is equated to the volume necessary for the beach to shift vertically at the same rate as the relative SLR (Figure 2). The beach fronting the cliff is here assumed to have an equilibrium profile. The resulting equation is used to predict long-term cliff retreat rates. Under the restrictive condition of constant inland slope, the equation has an analytical solution even if the SLR is time dependent.

For variable inland slope the resulting equation is solved numerically.

RESULTS

By analysing the theoretically predicted behaviour of the system it is found that if the inland slope is sufficiently steep and approximately constant in time, an equilibrium cliff height is approached. At this equilibrium, cliff recession rate is equal to the ratio of the rate of SLR to the inland slope.

We then solve the generalised equation, which includes variable rates of SLR, and realistic backshore topographies, for several sites along the Norfolk coast using topographies extracted from digital elevation models (Environment Agency, 2023) and projections of SLR based on different emissions scenarios (Clark et al. 2016).

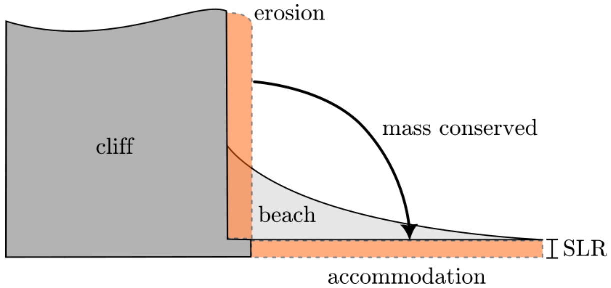

Figure 2 - Mass-conservation concept behind the cliff retreat model. Material is eroded from the cliff to support beach adaptation to SLR.

The model is run using a Monte Carlo approach, i.e. multiple simulations are carried out varying key input parameters within a suitable range, and a probability of typology change is provided as a function of time (Figure 3).

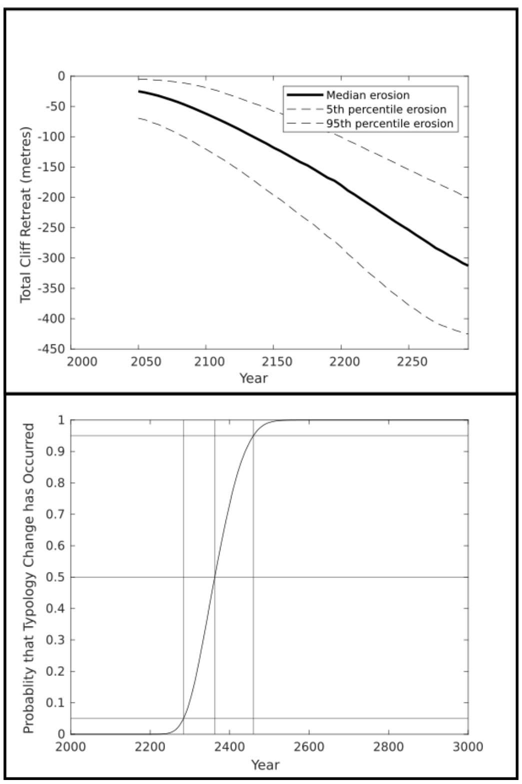

Figure 3 - Median erosion (a) and probability of coastal typology change (b) against time for a coastal transect at Happisburgh. Also included are the 5th and 95th percentile uncertainty bounds when key parameters are varied within suitable ranges. The model is forced with the 10,000 yearlong 2560 GtC (gigatonnes of Carbon) SLR scenario from Clark et al. (2016), considered a mid-range projection of long-term SLR.

Results show that the predicted erosion rates due to SLR vary by a factor of 2 along the Norfolk coast. Erosion rates predicted by the model are around 10-50% of the observed average rates, which is to be expected since we are looking solely at the contribution of SLR. The timescale of typology change varies between locations. On coasts with tall cliffs such as Trimingham, these transitions occur after thousands of years of SLR, whereas for shorter-cliffed areas such as Happisburgh, they may occur in the next few hundred years (Figure 3).

CONCLUSIONS

A simple predictive model for the evolution of soft-cliffed coasts due to SLR is developed. This can quickly incorporate projections of SLR under different future climate scenarios and provide a fast assessment of the impact on the future of such coasts. One key advantage of the presented model is that an analytical solution for the evolution of the system is derived. This can be used to understand how far a cliffed coast is from an equilibrium retreat rate, or if it is accelerating/decelerating with respect to the identified rate.
The ratio between the retreat rates predicted by the model and observed retreat rates may provide an indication of the contributions of SLR and other environmental drivers (such as waves) and factors such as the impact of human interventions.

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