# Fundamental limitations of shoreline models

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**Despite widespread use, many shoreline models rely on foundational assumptions that introduce significant uncertainties in coastal predictions and associated management decisions. As climate change intensifies risks to vulnerable coastal systems, it is imperative to strengthen efforts toward developing more robust and context-appropriate modelling approaches that reflect the evolving dynamics of coastal systems.**

Understanding shoreline evolution is crucial for effective coastal management decision-making, especially in an era of accelerating climate change and sea-level rise effects. Since the mid-20th century, two foundational shoreline models – the one-line theory of shoreline change[1] and the Bruun Rule[2] – have dominated predictions of long-term coastal change. However, while these models have provided useful first-order insights, their oversimplified assumptions often mask the complex physical processes that truly drive shoreline evolution, reducing their ability to capture the realities of dynamic coastal systems[3-8]. Given their continued use, questions remain as to whether the limitations of these early models have been meaningfully addressed, or if their inherent flaws continue to shape contemporary modelling outcomes.

The one-line model, introduced in the 1950s, assumes that shoreline change occurs primarily in response to gradients in longshore sediment transport, maintaining a time-averaged active coastal profile that shifts landward and seaward in response to uniform sediment loss and gain over the profile, respectively. This simplification both speeds up and stabilises how the shoreline morphology evolves, enabling computationally efficient and feasible applications over meso timescales (decades to centuries) – the timescales of interest for coastal management decision-making. However, it fails to capture the complexities of real-world coastal systems, particularly where cross-shore processes and three-dimensional wave-current interactions dominate. The Bruun Rule, on the other hand, introduced in the 1960s, remains one of the most widely applied models for predicting shoreline retreat in response to sea-level rise. It assumes that an equilibrium time-averaged beach profile is maintained, which moves landward and upward as relative sea levels rise, implying that there is an explicit linear relationship between sea-level change and shoreline change. However, the Bruun Rule does not account for longshore sediment transport, nearshore hydrodynamics, or human interventions, in turn leading to frequent misapplications in coastal modelling and management[5]. The underlying premise and simple computational structure of both models mean that they have very limited data requirements, which make them easy to apply across large spatial and temporal scales. Primarily for this reason, they are frequently adopted to inform coastal management decision-making, particularly in data-poor coastal regions, which incidentally: (a) tend to be the most vulnerable, and (b) require reliable shoreline predictions. Herein lies an issue regarding the widespread application of these models. The premise of their morphology update, which essentially dwindles down to shore-normal profile movement, means that they are limited to natural coastal systems, with straight shorelines, as such profile movement is unable to replicate shoreline behaviour in response to fixed coastal management structures and fail to consider complex morphologies, where depth contours are not parallel to the shoreline, typical of reef environments.

In recent decades, we have seen the emergence of hybrid models that attempt to integrate process-based simulations with the one-line theory assumptions[3,9,10]. The intent of these models is to bridge the gap between computational efficiency and the complexity underpinning the physics of coastal evolution. These models, which include the well-known MIKE21 model, GENESIS, and Delft3D, incorporate wave, flow, and sediment transport dynamics while still relying on the one-line assumption to update the shoreline morphology and position. Given the computational structure of these models, they provide more detailed insights into coastal sediment transport, particularly over meso timescales, but they remain constrained by two key limitations. *First*, they struggle with complex planform morphologies, particularly where depth contours are non-parallel to the shoreline[11,12]. In these cases, the one-line assumption of uniform sediment redistribution leads to unreliable results. *Second,* the assumption of a constant closure depth – inherited from the one-line theory embedded in these models – has been recently critiqued[4]. This depth defines the seaward extent of the active coastal profile. As a result, assuming it to be constant means that these models cannot account for the influence of sea-level rise, which is known to modify this depth over time. Recent research suggests that allowing the closure depth to vary over time and space can improve model predictions[4,12]. However, implementing such improvements requires long-term coastal datasets with high resolution – resources that are often unavailable, especially in Global South countries. Many of the world's most vulnerable coastal systems are found in these countries, particularly in the Caribbean and Pacific small islands, which are also typically characterised by complex morphologies.

Sea-level rise is arguably the most pressing contemporary challenge in coastal evolution modelling[13], yet existing approaches fail to adequately integrate its effects[4]. The one-line theory, for instance, does not account for vertical profile evolution, while the Bruun Rule assumes a simple upward translation of the coastal profile. Attempts to modify hybrid models by including a time-varying closure depth have shown promise but have also introduced new uncertainties, particularly regarding sediment availability and nearshore circulation effects[4]. Existing models also struggle to predict shoreline change in coastal systems where human interventions, such as hard defences and beach nourishment, disrupt natural sediment transport patterns. Hard defences often accelerate downdrift erosion, a phenomenon poorly captured by models that are rooted in equilibrium beach profile assumptions. Herein lies another key challenge – most 'natural' beaches are now being modified by some form of hard engineering. Failure to represent these effects over the timescales of concern for coastal management decision-making – meso timescales – effectively mean that we do not (yet) have reliable shoreline models to effectively inform such decisions globally.

Recent advances in hybrid shoreline modelling have attempted to account for complex morphologies by segmenting the coast into units with variable closure depths alongshore[12]. This approach, trialled and tested in fringing reef environments, has demonstrated improved predictive accuracy compared to traditional hybrid models[12]. However, it remains computationally demanding and reliant on site-specific calibration, limiting its broader applicability, particularly over the long-term timescales of interest for coastal management decision-making. While physics-based process models (e.g., Delft3D) offer detailed (and useful) insights into short-term coastal evolution, they are computationally prohibitive for meso timescale applications. This trade-off between model complexity and predictive scale remains a fundamental challenge in shoreline modelling.

These limitations are not just mere academic concerns; they actually have tangible impacts. Governments and international organisations invest billions in coastal adaptation measures that are often based on these theoretically and physically unrealistic models. In many cases, hard defences accelerate downdrift erosion rather than mitigating it, and beach nourishment projects are rapidly depleted because models fail to account for nearshore hydrodynamics and sediment pathways. If our predictive modelling approaches continue to be based on outdated and over-simplified assumptions, we risk worsening rather than mitigating the climate crisis at the coast.

Consequently, despite some advancements, contemporary shoreline models remain fundamentally constrained by the assumptions of the one-line theory and the Bruun Rule. While hybrid models with a time and space varying closure depth represent a step forward, they do not amount to a fundamental shift in how we conceptualise shoreline change and coastal evolution more broadly. They still inherit many of the same flawed assumptions that have long plagued coastal modelling, limiting their reliability and applicability for real-world coastal management decisions. To move beyond these constraints, future shoreline modelling efforts must prioritise: (a) high-resolution coastal monitoring, including bathymetric surveys, sediment transport measurements, and wave-climate monitoring, to refine model boundary conditions and setup; (b) dynamic closure depth modelling, reflecting changes in wave climate and sediment transport, to better capture shoreline morphodynamics; (c) improving simulations of sediment transport interactions with human interventions – coastal structures significantly alter sediment transport, necessitating model approaches that explicitly incorporate these effects rather than treating them as external boundary conditions; (d) probabilistic approaches – instead of deterministic shoreline change predictions, embracing probabilistic modelling approaches may better reflect the uncertainties inherent in long-term coastal evolution.

Taken together, while we have made strides in refining shoreline models, we have yet to fully transcend the foundational limitations of the one-line and Bruun Rule models. *A fundamental rethinking of shoreline modelling approaches is, hence, needed*. Such rethinking should embrace system complexity, integrate dynamic processes, and explicitly account for the uncertainties inherent in predicting shoreline change under future climate scenarios. Only then can we develop robust, adaptable models capable of informing sustainable coastal management in an era of unprecedented climatic change effects on coastal systems. The urgency of this rethinking cannot be overstated. As coastal megacities, small island states, and deltaic regions face unprecedented threats from climate change and sea-level rise, the continued reliance on overly simplified and assumption-laden shoreline models will only compound vulnerabilities. We must break away from the status quo. If we continue to base critical decisions on incomplete, deterministic models rooted in 1950/60s-era assumptions, we will be setting ourselves up for failure. The global coastal modelling community – now more than ever – has the tools, better data access, and computational power to move beyond these flawed approaches. What is needed now is the will to *prioritise accuracy over convenience, embrace complexity over reductionism, and confront uncertainty rather than rely on false confidence*. Only then can we develop the next-generation of shoreline models that will be capable of guiding effective and sustainable coastal management in an era of unprecedented changes to coastal systems that compromise their stability and sustainability.

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## Competing interests

The author declares no competing interests.