

Review

A critical review of closure depth theories and uncertainties: implications for shoreline modelling and coastal management

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ABSTRACT

The sustainability of coastal systems is being increasingly compromised as a result of climate-related coastal hazards and increasing human occupation of coastal zones. Shoreline models play an important role in predicting and understanding coastal systems behaviour, informing coastal resilience and adaptation strategies. A critical parameter in these models is the depth of closure (*DoC*), which defines the seaward extent of significant cross-shore sediment transport and shoreline morphodynamics. There are considerable uncertainties associated with estimating and identifying the *DoC*, which has implications for the accuracy of shoreline predictions and ensuing coastal management decisions. We, therefore, provide a critical literature review of existing theories and methods for defining and estimating the *DoC*, highlighting the complexities, uncertainties, and challenges. We also explore the role of the *DoC* in shoreline models, paying particular attention to their applicability across variations in timescale and coastal environments while considering the associated implications for coastal management decisions. Our findings highlight the need for standardised estimation methods and a better understanding of the *DoC* to improve the reliability and applicability of shoreline models across coastal morphologies and tidal environments. Our findings also emphasise the need for a paradigm shift in practice – from continuing to develop and apply flawed shoreline models to addressing the uncertainties underpinning the formulation and specification of key model parameters, of which the *DoC* is arguably the most critical. This shift is needed to enhance the predictive power and reliability of shoreline models, to better inform decision-making for coastal management and governance.

1. Introduction

Globally, the sustainability of coastal systems is threatened by rapid urbanisation and industrialisation and increasing levels of resource exploitation. These threats reduce the resilience and adaptive capacity of these systems to rising sea levels, flooding, and erosion hazards under climate change (Elliott et al., 2019; Lansu et al., 2024; Pardal et al., 2024). This threat, called coastal squeeze, takes a two-sided dynamic of beach erosion that traps coastlines between rising sea levels and fixed landward structures. This prevents the shoreline's natural landward migration, therefore, leading to declining beach widths and a gradual removal of intertidal zones (Doody, 2004; Luisa Martínez et al., 2014; Kahl et al., 2024). Coastal systems hold significant socioeconomic values for coastal residents and coastal zone users. In many countries, the coastal plain, for example, is the main agricultural area. Further value comes from the contribution of coastal systems to cultural preservation,

familial heritage, recreation, tourism, inspiration for artists, musicians, and writers, environmental awareness and stewardship, and social cohesion (community building) (Forbes et al., 2013; Ghermandi, 2015; Khakzad et al., 2015; Magnani and Pistocchi, 2017; Turnbull et al., 2020; Acott et al., 2022; Kjørholt et al., 2022; Mcleod et al., 2024). In particular, sandy coastal systems often form the primary socioeconomic resource for many small island states – the most vulnerable locations to rising relative sea levels (Nurse et al., 2014; Luijendijk et al., 2018; Seenath, 2022a; Sealey, 2024). Given the socioeconomic importance of coastal systems, significant efforts have been made to manage and protect these systems across local, regional, and global scales (Bongarts et al., 2021). These management initiatives have been and continue to be largely informed by shoreline evolution models, which simulate and predict shoreline change over various spatial and temporal scales in response to natural (e.g., hydrodynamics) and human (e.g., management) drivers of coastal geomorphology (Déguénon et al., 2023;

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Alvarez-Cuesta et al., 2024; Muroi et al., 2024). Understanding changes in shoreline position, generally defined by tidal datums – Mean High Water, Mean Low Water, Mean Sea Level – is often considered to be a good proxy of overall coastal systems behaviour and response (Boak and Turner, 2005; Seenath, 2022b).

Following the introduction of the one-line model of shoreline change (Pelnard-Considere, 1956) and the Bruun Rule (Bruun, 1962), there has been a linear progression in the evolution of shoreline models from empirical models, which are based on the principles of the one-line theory and the Bruun Rule, to numerical ‘physics-driven’ models (in one-dimension, two-dimension, and three-dimension), and hybrid models, which merge principles of empirical and numerical models (Seenath, 2022b). Each has benefits (e.g., process understanding of change) and challenges (e.g., restrictive assumptions and applicability across time and space). More recently, hybrid shoreline models have been gaining traction in related literature, primarily because they provide a good compromise between model complexity and computational efficiency (Section 4.4) for simulating shoreline evolution over the mesoscale (10–100 km; 10–100 years) (Ashton and Murray, 2006; Karunaratna et al., 2008; Kaergaard and Fredsoe, 2013; Seenath, 2022a; Muroi et al., 2024) – the primary spatiotemporal scale of interest for decision-making in coastal management (French et al., 2016; Van Maanen et al., 2016; Payo et al., 2020; Seenath and Dale, 2024).

Cowell and Kinsela (2018) offer a conceptual framework for understanding the various spatiotemporal scales over which coastal areas evolve by dividing the shoreface into three compartments. *First*, the upper shoreface, which is located seaward (landward) of the low tide line (lower shoreface) and extends to a limiting water depth, beyond which rates of sediment flux and morphological change are too gradual to support instantaneous shoreface response at annual timescales. *Second*, the active shoreface, which includes the area from the low tide line to the depth where wave action ceases to significantly affect sediment movement – depth of closure (Nicholls et al., 1998; Udo et al., 2020; Seenath, 2022b) – is influenced by waves and tides and evolves over timescales of years to decades. *Third*, the lower shoreface, which is affected by wave shoaling, evolves over timescales of decades or longer. Cowell and Kinsela’s (2018) conceptual framework converges well with the established spatiotemporal scales of shoreline evolution by Stive et al. (2002).

Appropriate parameterisation of the active shoreface in shoreline models, however, is challenging, with implications for suitable and effective coastal management decisions (Udo et al., 2020). This challenge specifically relates to the specification of the depth of closure (*DoC*) – the seaward extent of the active coastal profile – which governs the cross-shore extent of shoreline morphodynamics and ensuing shoreline predictions (De Figueiredo et al., 2020; Udo et al., 2020; Dastgheib et al., 2022; Seenath, 2022a, 2023; Muroi et al., 2024). Despite its fundamental role in shoreline models, existing research has not adequately addressed two critical aspects: (a) the full extent of the uncertainties surrounding *DoC* estimation, particularly across different coastal environments and timescales, and (b) the need for standardised guidelines to ensure more reliable and consistent *DoC* specification in shoreline models.¹ This oversight is significant because the *DoC* is not only a key governing input for shoreline evolution modelling but it also serves as an important proxy for sea-level change (see, e.g., Shand et al., 2013; Seenath, 2022a) – which is often theorised to be the primary driver of mesoscale coastal evolution (Masselink et al., 2020; Hunt et al., 2023). We, therefore, need to examine current understandings of the *DoC* – *what it is, where it is, and how best to estimate and specify it*. Additionally, we need to carefully consider its role in shoreline models in order to refine their parameterisation, to better inform coastal

management decisions. We recognise that there are other parameters and variables within shoreline models – including sediment parameters (grain size, porosity, etc.) and friction coefficients. However, there are substantive sensitivity studies on these inputs relative to the *DoC*, which is often treated as a ‘constant’ in the parameterisation of shoreline models (see Seenath, 2022b), even though it governs the extent of shoreline morphodynamics in these models by directly informing the shoreline morphology update and associated shoreline predictions.

We address the above gaps in this critical review paper, which aims to identify current understandings of the *DoC* – theories, assumptions, and estimation – and its role and parameterisation in shoreline models. Our review enables an understanding of the *DoC* in the context of contemporary shoreline modelling and coastal management decision-making. A key aspect of our review focuses on identifying current uncertainties with *DoC* estimations in shoreline modelling and defining pathways to address these uncertainties, in order to more accurately apply shoreline models for coastal management decision-making. Such insights will have theoretical implications for improving our knowledge of coastal systems’ evolution and practical implications for improving coastal management decisions through better-informed shoreline modelling approaches.

1.1. Operational definitions

Here, we first provide our operational definitions of key terms that underpin the core narrative of our review.

Closure depth (*DoC*): The maximum offshore depth beyond which no significant cross-shore sediment transport occurs under normal wave and tide conditions. It marks the seaward boundary of the active coastal profile in shoreline models.

Inner depth of closure (*IDoC*): The shallower limit of *DoC*, representing the seaward extent of regular sediment movement influenced by daily waves and tides.

Outer depth of closure (*ODOC*): The deeper limit of *DoC*, marking the offshore boundary beyond which only extreme storm events cause significant sediment transport.

Cross-shore sediment transport: The movement of sediments perpendicular to the shoreline.

Longshore sediment transport: The movement of sediments parallel to the shoreline.

Shoreline morphodynamics: The study of how and why shorelines change over time due to interactions between waves, tides, sediment transport, and coastal topography.

Shoreline models: Computational or empirical tools used to predict shoreline change over time in response to natural forces (waves, tides, sea level rise) and human interventions (coastal defences, dredging).

Numerical shoreline models: Models that use a physics-driven approach, underpinned by mathematical equations (e.g., Navier Stokes equations), to simulate physical coastal processes, including sediment transport, wave action, and tide-induced changes.

Empirical shoreline models: Models that use historical observations to predict shoreline evolution without explicitly simulating physical coastal processes (e.g., the Bruun Rule for sea-level rise effects).

Hybrid shoreline models: Models that couple empirical and numerical modelling approaches. These models typically use the outputs of numerical simulations of sediment transport to predict shoreline change based on empirical relationships (e.g., the one-line theory).

Equifinality (in the context of this review): Equifinality refers to the concept that different *DoC* estimation methods and shoreline modelling approaches may produce similar shoreline evolution predictions, even if they are based on different theoretical assumptions or parameterisations. This introduces uncertainty in model validation because a good fit between model outputs and observed shoreline changes does not necessarily imply that the underlying physical processes are correctly represented. This means that even if a particular *DoC* estimation approach leads to accurate shoreline predictions in certain coastal

¹ Apart from the traditional (idealistic) definitions and formulations, *DoC* specification in shoreline models is traditionally based on a stepwise calibration approach (i.e., treated as a ‘tuning’ parameter).

conditions, the results may still be driven by compensating errors rather than an accurate representation of shoreline morphodynamics. This uncertainty presents a challenge for ensuring that shoreline models are truly reliable for coastal management applications.

Wave transformation: The process by which waves change as they move from deeper to shallower water, influenced by seabed morphology (e.g., reefs, sandbars, depth variations) and other factors (e.g., wind).

2. On defining the closure depth: theories and assumptions

The *DoC* represents a *theoretical* morphodynamic boundary separating the active nearshore zone from the less active offshore zone in terms of sediment transport over a defined observation period (Udo et al., 2020; Hoagland et al., 2024), most often at annual timescales (Nicholls et al., 1996; Ortiz and Ashton, 2016). There are various definitions of the *DoC*, largely based on situational contexts. A common definition of the *DoC* is the most seaward depth beyond which there is no significant cross-shore sediment transport (Kraus et al., 1998; Valiente et al., 2019; Udo et al., 2020; Seenath and Dale, 2024). Generally, this is the zone where wave impact on bed stresses and sediment transport is considerably reduced compared to in the nearshore zone (Ortiz and Ashton, 2016). Additionally, the *DoC* is sometimes related to a geological transition zone marked by changes in sediment characteristics and depositional processes, indicating the boundary between more dynamic nearshore environments and stable offshore conditions (Wallace et al., 2010; Valiente et al., 2019). The above definitions depart from the original conceptualisations of the *DoC* by Hallermeier (1978) and Birkemeier (1985), who defined it as a conservative depth value for the seaward extent of significant sediment transport in the nearshore. In coastal systems with shore-perpendicular depth contours in response to an irregular spatial distribution of reef substrate or related rock substrate, the *DoC* is considered to be the most seaward depth landward of the first occurrence of hard substrate (Eversole and Fletcher, 2003). An underlying commonality in these definitions is that the *DoC* is primarily a function of the cross-shore extent of sediment transport in response to wave action. This adds to the complexity in establishing a standard definition of the *DoC* for a coastal system, as such processes are dependent on a complex interplay of local drivers, including geomorphology, sedimentology, and human interventions (Mason and Coates, 2001; Seenath and Dale, 2024).

In more recent times, shoreline modelling studies have considered the *DoC* to be the most seaward depth contour that follows (mirrors) the shape of the shoreline (Kaergaard and Fredsoe, 2013; Seenath, 2022b). This definition, relative to those summarised above, is largely based on a qualitative inspection of depth contour lines and coastal profiles to identify the point on the beach profile beyond which we can see no significant change in beach planform morphology or bed elevation (Aagaard, 2011; Van Der Werf et al., 2017; Valiente et al., 2019; Seenath, 2022a) (Fig. 1). This qualitative definition of the *DoC* converges well with the more empirical definitions previously mentioned. For instance, considering the most seaward depth contour, which mirrors the shape of the shoreline, to be the *DoC* is akin to considering the *DoC* as the offshore extent of significant cross-shore sediment transport. The shape of depth contours within the continental shelf is largely a result of sediment transport, wave action, and undertow currents, which together influence the evolution of coastal profiles. However, the evolution of coastal profiles is a far more complex process, further influenced by the underlying coastal geomorphology and sedimentology. Alongshore, cross-shore, and temporal variations in these and coastal processes more broadly may mean that the *DoC* varies across space and time (Nicholls et al., 1998; Marsh et al., 1999; Seenath, 2022a, 2023), which add to the complexity of identifying a standard *DoC* definition.

Moreover, defining the *DoC* becomes even more complex when we consider the inner depth of closure (*IDoC*) and the outer depth of closure (*ODoC*). The *IDoC* is traditionally considered to be the depth where regular wave action ceases to cause significant sediment transport under

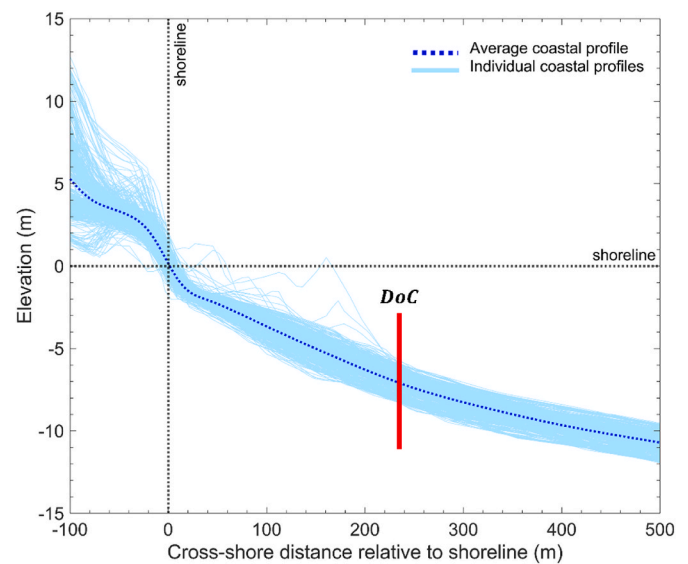


Fig. 1. Identification of the *DoC* along a coastal profile based on qualitative visual inspection. The red bar indicates the depth beyond which we see no significant change in bed elevation, marking the *DoC* where profile changes become gradual and coincide with the basal limit of the envelope of coastal profile variations. This approach is a static, manual process and does not inherently account for seasonal or annual variations in shoreline morphology. In existing shoreline modelling practices, the *DoC* is typically assumed to be spatially and temporally constant – see Sections 4.1 and 4.3 – with its estimation based on the initial bed profile at the start of a simulation, without dynamic adjustments over time (Seenath, 2022a, 2022b, 2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

normal conditions (Hallermeier, 1978; Birkemeier, 1985; Brutsche et al., 2016; Townsend et al., 2024). The *ODoC*, on the other hand, is a deeper depth boundary beyond which sediment transport is negligible (Brutsche et al., 2016; Guillén et al., 2024), including during typical storm conditions, except during periods of extreme sea levels or storm events (Robertson et al., 2007; Barrineau et al., 2021). Both depths, in the context of coastal engineering and management, refer to specific depths associated with significant changes in sediment movement. They are, therefore, critical for understanding the overall sediment regime of a coastal system in order to appropriately inform coastal management responses to issues of erosion, for example, which may compromise the sustainability of the system. Given the preceding contexts, the *IDoC* is, therefore, the seaward limit of significant sediment movement in response to daily wave and tidal conditions. It marks the offshore extent of the zone where beach profiles and sediment (re)distribution are in constant response to ongoing hydrodynamic conditions. The *ODoC* is located further offshore than the *IDoC* in a zone where sediment movement is minimal under normal wave and tidal conditions. Notable changes in cross-shore sediment distribution beyond the *ODoC* is a rare occurrence (Barrineau et al., 2021; Mcfall et al., 2021), mainly influenced by long-term geological processes or extreme events rather than regular wave and tide conditions (Kraus et al., 1998). The *ODoC*, in this regard, facilitates a conceptual understanding of the overall sediment budget and long-term sustainability of coastal systems. Hence, understanding and identifying both *IDoC* and *ODoC* are important for informing coastal management decisions (Nicholls et al., 1998; Brutsche et al., 2016; Razak and Khan, 2020; Townsend et al., 2024). However, the challenge in identifying a standard definition for these depths relates to the considerable variations in coastal processes (both hydrodynamics and morphodynamics) across space and time.

3. Where lies the closure depth? Estimation methods, challenges and uncertainties

3.1. Mathematical formulations

Despite the theoretical importance of the *DoC* as a morphodynamic boundary, considerable uncertainty exists in relation to its identification (Cowell et al., 2006; Shand et al., 2013; Aragonés et al., 2019; De Figueiredo et al., 2020; Jones et al., 2024), due to the vagueness of its definition in terms of temporal variability and specifics regarding what constitutes ‘significant’ sediment movement and wave action (Valiente et al., 2019). Consequently, there is no standard implemented and/or best practice method for *DoC* calculation, particularly in shoreline modelling studies. The most common *DoC* estimation methods still remain the mathematical formulations of Hallermeier (1978, 1980) and Birkemeier (1985):

$$d_i = 2.28H_e - 68.5 \left(\frac{H_e^2}{gT_e^2} \right) \text{ Hallermeier (1978)} \quad (1)$$

$$d_i = 2\bar{H}_s + 11\sigma_s \text{ Hallermeier (1978)} \quad (2)$$

$$d_i = \left(\bar{H}_s - 0.3\sigma_s \right) \bar{T}_s \left(\frac{g}{5000D} \right)^{0.5} \text{ Hallermeier (1980)} \quad (3)$$

$$d_i = 1.75H_e - 57.9 \left(\frac{H_e^2}{gT_e^2} \right) \text{ Birkemeier (1985)} \quad (4)$$

$$d_i = 1.57H_e \text{ Birkemeier (1985)} \quad (5)$$

where d_i = predicted depth of closure over ‘ t ’ years, referenced to mean low water; D = median grain size; g = acceleration due to gravity; H_e = effective wave height/wave conditions that are exceeded for 12 h per year; \bar{H}_s = annual mean significant wave height; T_e = associated wave period; \bar{T}_s = average period associated with the average significant wave height; U_b = maximum horizontal wave-induced fluid velocity at water depth (d); σ_s = associated standard deviation of wave height.

The foundations of a formal *DoC* estimation method started with Hallermeier (1978) lab (physical modelling in wave tanks) and field experiment data being used to calculate a critical value of a sediment entrainment parameter, which he related to a form of the Froude number (F_r) – a dimensionless number that characterises the flow regime of a fluid (Eq. (6)):

$$F_r = \frac{U_b^2}{ygd} = 0.03 \text{ Hallermeier (1978)} \quad (6)$$

where U_b = maximum horizontal water velocity near the bed, g = acceleration due to gravity, d = water depth, and y' = ratio of the density difference between sediment and fluid to fluid density.

Hallermeier used this foundation to relate the depth at which significant sediment movement ceases (*DoC*) to wave characteristics, thereby providing a theoretical basis for determining the *DoC* based on wave energy and sediment properties. Hallermeier’s *DoC* equation (Eq. 1) has historically been used for the preliminary design stages for coastal engineering defences (Capobianco et al., 2002; Brutsche et al., 2016), primarily because of its perceived reliability (Sabatier et al., 2004). However, this equation is mainly used for annual assessments of the *DoC* in sandy beaches where wave climates are relatively stable and consistent over time, and data are readily available. In response to data limitations for many coastal sites, Hallermeier proposed a simplified version of his original *DoC* equation – Eq. 2 – directly relating the *DoC* to the mean significant wave height and associated standard deviation. Hallermeier (1980) established an outer limit *DoC* equation – Eq. 3 – for estimating the maximum water depth for sand motion initiation by the yearly median wave condition – this depth is further seaward of the

maximum depth for erosive cutting of the nearshore by yearly extreme waves (inner limit of *DoC* – Eqs. 1 – 2).

Hallermeier *DoC* Eqs. 1 – 3 are appropriate for exposed microtidal coastal environments with high wave energy and low tidal ranges (Hallermeier, 1978, 1980). The underlying assumptions of these equations, in terms of wave-induced sediment movement, align well with the dynamics of environments with small water level variations, therefore leading to reliable estimations of the *DoC* (Brutsche et al., 2016). However, such equations have limited applicability in macrotidal coastal environments due to the combined influences of wave and tidal forcings not being adequately captured in these equations (Valiente et al., 2019). Although in Eq. 1, for example, tidal action can be accounted for by defining the *DoC* relative to a vertical datum, such as Mean Low Water, doing so would not explicitly account for the role of tidal currents (Valiente et al., 2019). Moreover, Hallermeier’s (1978) Eq. 1 has been shown to predict conservative *DoC* values over the short-term while overestimating it over the long-term, providing significant differences in *DoC* relative to field observations beyond four years (Nicholls et al., 1998). Additionally, during calm conditions, Hallermeier’s (1978) Eqs. 1 – 2 tend to underestimate observed *DoC* s (Sabatier et al., 2004).

In later years, Birkemeier (1985) empirically proved that Hallermeier’s Eq. 1 overpredicted *DoC* values by 25 %, and, in turn, proposed an adjustment to this equation – Eq. 4 – to correct for *DoC* overestimations. Birkemeier’s adjusted expression for the *DoC* retains the underlying forcing functions as Hallermeier’s Eq. 1, defining the *DoC* as being largely a function of significant wave heights. Birkemeier offers a simplified equation – Eq. 5 – relating the *DoC* to the effective wave height, which refer to wave conditions that are exceeded only 12 h out of a single year. Therefore, like Hallermeier’s *DoC* equations (Eqs. 1 – 2), Birkemeier’s *DoC* equations (Eqs. 4 – 5) are most applicable for microtidal coastal environments. These environments tend to be largely wave-dominated (Short, 2020), with little applicability to macrotidal coastal environments where large tidal ranges play a critical role in influencing coastal geomorphology and associated morphodynamic boundaries, such as the *DoC* (Valiente et al., 2019). There have also been further proposed adjustments to Hallermeier’s Eq. 1 in more recent times, including Capobianco et al. (1997)’s suggested expression, which defines the *DoC* primarily as a function of the non-breaking significant wave height exceeding 12 h per year (Valiente et al., 2019).

3.2. Direct estimation methods

Where extended datasets on coastal profile morphology (spanning several years) exists, direct *DoC* estimation methods based on profile comparison have shown to yield reliable *DoC* values (Kraus et al., 1998; Nicholls et al., 1999; Hartman and Kennedy, 2016; Aragonés et al., 2019). This approach involves examining coastal profile envelopes to identify the point on the profile beyond which there is no significant change in bed elevation (Fig. 1). While this approach might be reliable in capturing realistic *DoC* values, it is time consuming and expensive to facilitate, particularly given the extensive dataset requirements. For this reason, direct *DoC* estimates are only normally available for a handful of sites (Valiente et al., 2019). A variation of this direct estimation approach – which involves looking at depth contour lines in topo-bathymetric Digital Elevation Models (DEMs) and/or considering bathymetric and subsurface sedimentology maps – have started gaining traction in related literature (Falqués and Calvete, 2005; Kaergaard, 2011; Kaergaard and Fredsoe, 2013; Abou Samra et al., 2021; Al-Mutairi et al., 2021; Seenath, 2022b; Seenath and Dale, 2024). This approach is more akin to a visual qualitative inspection of data and involves identifying the most seaward depth contour that follows the shape of the shoreline to be representative of the *DoC*.

There are five fundamental issues with using depth contour lines to identify the *DoC*. First, the *DoC* is a dynamic parameter – perhaps more a variable than a parameter – as it fluctuates over time in response to

variations in wave, tidal, and sediment conditions, among other local morphology forcings (Nguyen et al., 2021; Seenath, 2022a; Townsend et al., 2024). A complicating factor in macrotidal settings, in particular, is the presence of tidally-driven sand waves in the nearshore, which may act independently of the littoral profile, complicating the selection of the *DoC*. As it represents the depth beyond which no significant cross-shore sediment transport occurs over a defined period, using depth contour lines (in a topo-bathymetry DEM or interpolated computational mesh/grid) will only allow for a static estimate of the *DoC*, failing to account for inherent process dynamics that influence the *DoC*. *Second*, the accuracy of a topo-bathy DEM is directly related to instrument collection error/accuracy and spatial resolution (Seenath, 2018; Meadows et al., 2024). Depth contour lines from coarse DEMs will inevitably mask the intricacies and subtle variations in the underlying bathymetry, therefore, only allowing for a conservative or generalised *DoC* estimation. *Third*, reliable *DoC* estimations require both a critical and analytical understanding of hydrodynamics (waves, tides, currents), sediment transport rates, and historical changes in bed elevations (Robertson et al., 2008; Townsend et al., 2024). As DEMs only capture the topo-bathymetry conditions at the point of data collection, relying on such data alone without consideration of larger timescale morphology, coastal processes, and sediment transport data will inevitably result in an inherently uncertain *DoC* estimate. *Fourth*, *DoC*s can significantly vary along a shoreline in response to variations in wave exposure, sediment supply, nearshore morphology, and human interventions (Eversole and Fletcher, 2003; Nguyen et al., 2021; Seenath, 2023; Townsend et al., 2024). DEMs typically provide a generalised overview of depth contour lines, often masking critical morphology details essential for reliable *DoC* estimations – this point also relates to the point on spatial resolution. *Fifth*, bathymetry surveys that underpin DEMs often contain significant data gaps – related to instrument error or failure – that are generally filled by interpolation (Seenath, 2015; Novaczek et al., 2019; Li et al., 2023). Consequently, depth contour lines generated may not be fully representative of the ‘true’ observed coastal morphology, with adverse implications for *DoC* estimations.

3.3. Sediment-driven approaches

Recognising the limitations of the above *DoC* estimation methods, other studies have established *DoC* estimation methods based on sediment data. One such example is Aragonés et al. (2018) study, which established a new method for *DoC* estimation based on cross-shore changes in median sediment grain size. Specifically, their work defined the *DoC* as the point where the trend in sediment size breaks with increasing depth. A limitation of this approach and related sediment data approaches is that such methods indicate the maximum cross-shore extent of sediment transport (Valiente et al., 2019). However, the *DoC* represents a significant morphodynamic boundary in coastal systems. While cross-shore sediment transport occurs throughout the entire coastal profile, its impact on beach planform morphology varies with depth. Landward of the *DoC*, for example, there are clear noticeable changes in beach planform morphology resulting from sediment transport driven by combined wind-wave-tide action. Seaward of this boundary, cross-shore sediment transport continues but at reduced rates that are generally insufficient to cause significant changes in beach planform morphologies over timescales of concern to coastal management. It is important to note that sediment movement does not cease at the *DoC*. Instead, the relationship between sediment transport and morphological change becomes less direct. As water depth increases, wave energy at the seabed decreases, reducing its ability to mobilise and transport sediment effectively. This gradual reduction in transport capacity leads to diminishing morphological changes with increasing depth. Beyond the *DoC*, bedforms and sediment characteristics (e.g., size, distribution) still respond to changes in wave-stirring and tidal-current forcing (Kraus et al., 1998). However, these responses are typically insufficient to alter the overall beach planform morphology,

which is the primary concern for coastal engineers and managers.

However, enhanced anthropogenic activities can significantly influence the change in *DoC* in coastal regions by altering sediment dynamics, wave energy, and seabed morphology. Coastal engineering structures, such as seawalls, groynes, and breakwaters, disrupt natural sediment transport, leading to localised erosion and accretion (Justine and Seenath, 2025). Wave and current interactions with coastal engineering solutions, such as wave refractions and diffraction of waves and currents, and associated effects on sediment transport play a key role in influencing coastal profile (and shoreline) morphology (Stive et al., 2002; Widyaningias and Kanayama, 2012; Seenath, 2022b). Changes in coastal morphology further influence wave action, which, in turn, affects the *DoC*. In this regard, anthropogenic activities have an indirect impact on the *DoC*. Activities such as dredging and sand mining directly remove sediment from the nearshore system, which can potentially deepen the *DoC*. These activities may reduce local sediment availability, creating new residual sediment transport pathways and morphological change in deeper water (Friend et al., 2006; Poulos and Ballay, 2010). Climate change-induced sea-level rise and increased storm intensity can further exacerbate these changes by enhancing wave energy, which can push the *DoC* seaward (Nicholls et al., 1998; De Figueiredo et al., 2020; Seenath, 2022a). In areas adjacent to river deltas, the response of *DoC* to changes in terrestrial sediment supply depends on fluvial sediment discharge and hydrodynamic conditions (Warrick, 2020). A reduction in sediment supply due to dam construction (Regard et al., 2023), deforestation, or land use changes can lead to sediment starvation, causing coastal erosion, which has the potential to deepen the *DoC* as wave action becomes more dominant in reshaping the seabed. Conversely, increased sediment supply, such as from dam removal (Warrick et al., 2019), high erosion rates upstream or artificial sediment nourishment, may result in a shallower *DoC* due to the accumulation of finer sediments that dissipate wave energy more efficiently. The interplay between sediment supply and hydrodynamic forcing, in turn, determines the extent to which *DoC* adjusts, as we repeatedly allude to, since high-energy environments may continue to maintain a relatively deep *DoC* despite increased sediment inputs. Understanding these complex interactions is essential for informing sustainable coastal management and mitigation strategies under ongoing anthropogenic and climatic changes.

The *DoC* concept is particularly relevant for practical coastal management, focusing on observable changes over months to years rather than minor alterations over longer time scales. Sediment data approaches for *DoC* estimations often reflect the maximum depth of measurable sediment transport. While this depth is related to the *DoC*, it may not directly correspond to the depth at which significant morphological changes occur (Phillips and Williams, 2007). The *DoC*, as used in coastal engineering and management, represents a practical boundary for observable morphological changes rather than an absolute limit of sediment movement. By recognising the continuous nature of sediment transport processes across the coastal profile while considering the varying impact on morphology with depth, we can begin to better understand the significance of the *DoC* in coastal systems and its relevance for informing shoreline management decisions.

3.4. Challenges beyond simple planform morphologies

All *DoC* estimation methods discussed above provide a coastal-system wide *DoC* value, implying a spatially (and temporally) constant *DoC*. The underlying assumption of a spatially constant *DoC* is generally valid for simple beach planform morphologies (characterised by shore-parallel depth contours and a relatively straight shoreline geometry) but invalid for complex beach planform morphologies (characterised by shore-perpendicular depth contours and irregular shoreline geometries) (Seenath, 2022b, 2023) – Fig. 2. Variations in wave energies alongshore may result in some areas having a deeper *DoC* than others. Coral reef environments are good examples of complex beach planform

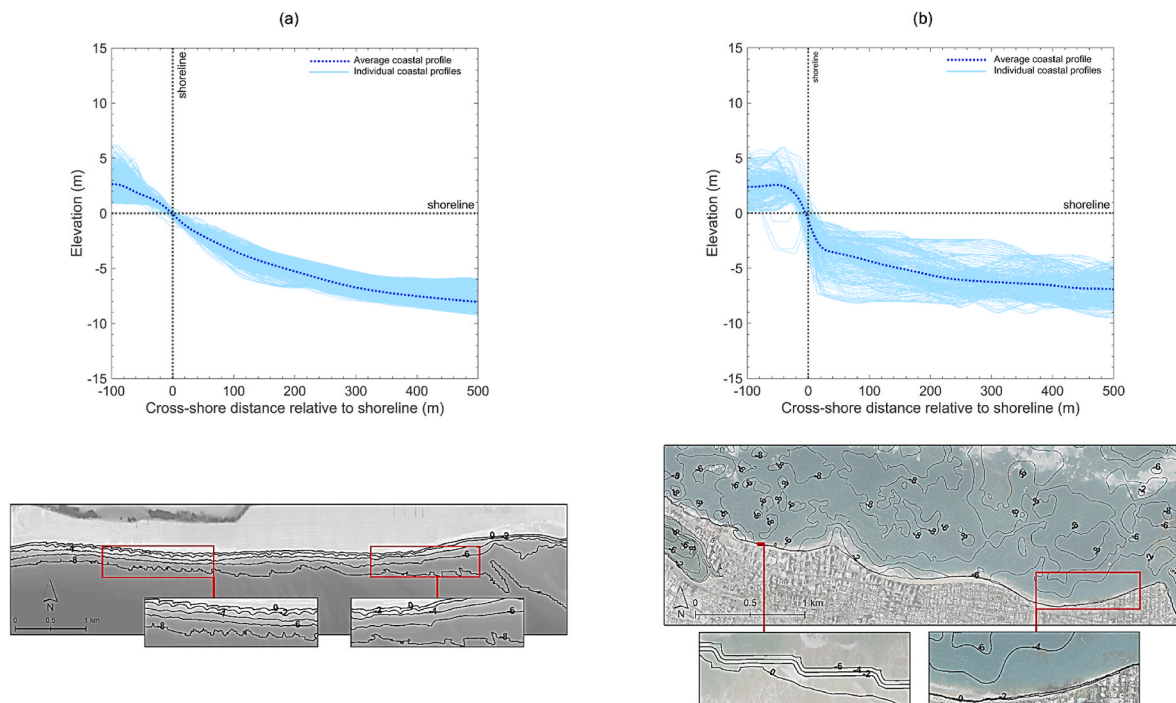


Fig. 2. Simple (a) and complex (b) beach planform morphologies. The former is characterised by shore-parallel depth contours and a linear sloping beach profile envelope (aligning with the underlying morphology assumptions of *DoC* estimation methods), whereas the latter is characterised by shore-perpendicular depth contours and a non-linear sloping beach profile envelope (not aligning with the underlying morphology assumptions of *DoC* estimation methods).

morphologies. In such morphologies, wave transformation and breaking over non shore-parallel depth contours tend to result in considerable variations in wave energies approaching the shoreline and influencing coastal profile evolution alongshore (Eversole and Fletcher, 2003; Sabatier et al., 2004; Yao et al., 2019). For instance, alongshore variations in coastal profile slope as a result of irregular reef substrate distribution may mean that coastal segments experiencing greater wave energy are likely to have a deeper *DoC* relative to those with gentler profiles and more energy dissipation (De Figueiredo et al., 2020). The limited applicability of existing *DoC* estimation methods in complex morphologies, such as reef environments, has given rise to the *DoC* in these systems being defined based on the spatial distribution of hard substrate – with the *DoC* at any point along a complex morphology coast generally considered to be the most seaward depth where reef substrate first appears (Eversole and Fletcher, 2003; Seenath, 2023). Although a practical assumption, such an approach for establishing *DoC* variations have the same inherent limitations as the *DoC* mathematical formulations (Section 3.2) and direct estimation methods (Section 3.3): (a) failure to account for the non-linearity in coastal dynamics, and; (b) requirement of multi-year coastal profile data, which may not be financially practical. Overall, this implies that existing *DoC* estimation approaches are primarily limited to simple beach planform morphologies, characteristic of natural straight sandy beaches (note: existing *DoC* estimation methods are specific to sandy beaches – Townsend et al., 2024), which are, to some extent, becoming rare. This reinforces the notion that existing *DoC* estimation methods were developed for simple planform morphologies and lack applicability in complex coastal planform morphologies, where wave transformation, depth variations, and substrate heterogeneity introduce significant uncertainties in *DoC* determination.

In macrotidal and reef-dominated environments, the spatial and temporal variability in sediment transport processes further complicates *DoC* estimation. Standard empirical formulations (Eqs. 1–6) do not account for the influence of large tidal fluctuations or complex reef topographies, which fundamentally affect cross-shore sediment exchange and shoreline evolution (Eversole and Fletcher, 2003; Seenath, 2023).

This points to a need for improved *DoC* estimation approaches tailored to these settings, which characterise some of the world's most vulnerable locations (Figs. 3–4).

For complex planform morphologies more broadly, the *DoC* may be better conceptualised and treated as a *dynamic boundary* influenced by wave transformation over reefs, sediment transport pathways, and seabed substrate interactions (see, for e.g., Seenath, 2023). One possible way to facilitate this may be to integrate high-resolution remote sensing (see, for e.g., Nguyen et al., 2021) and acoustic seabed mapping (see, for e.g., Udo et al., 2020) with numerical modelling of coastal sediment transport, to refine *DoC* calculations for such morphologies. This integrated framework may be the way forward for defining a reliable and adaptive *DoC* estimation approach that captures the spatial and temporal variability of the *DoC*, which can improve how we parameterise coastal systems more broadly in shoreline models. This is, therefore, grounds for further research – that is, establishing an adaptive *DoC* estimation approach that can improve shoreline model accuracy (and reliability) to better inform coastal management strategies in complex morphologies.

Table 1 consolidates the key characteristics of *DoC* estimation approaches reviewed thus far, with particular attention to their functional contexts, and performance across varied coastal settings.

3.5. Implications for shoreline modelling and coastal governance: place, space and scale

The concept of a natural sandy beach is, arguably, declining as beaches are increasingly managed to cope with: (a) increasing human pressures under rapid urbanisation, and (b) vulnerability under rising sea levels (Cooper, 2022; Chalazas et al., 2024; Lansu et al., 2024). More fundamentally, complex planform morphologies – coral reef systems – characterise the world's most vulnerable sandy coastal systems, all of which are located in small island states, particularly those in the Caribbean and Pacific (Mycoo and Donovan, 2017; Seenath, 2022b; Kennedy, 2024) (Fig. 3). While coastal systems on a global scale are becoming increasingly threatened, the threats to coastal systems in these

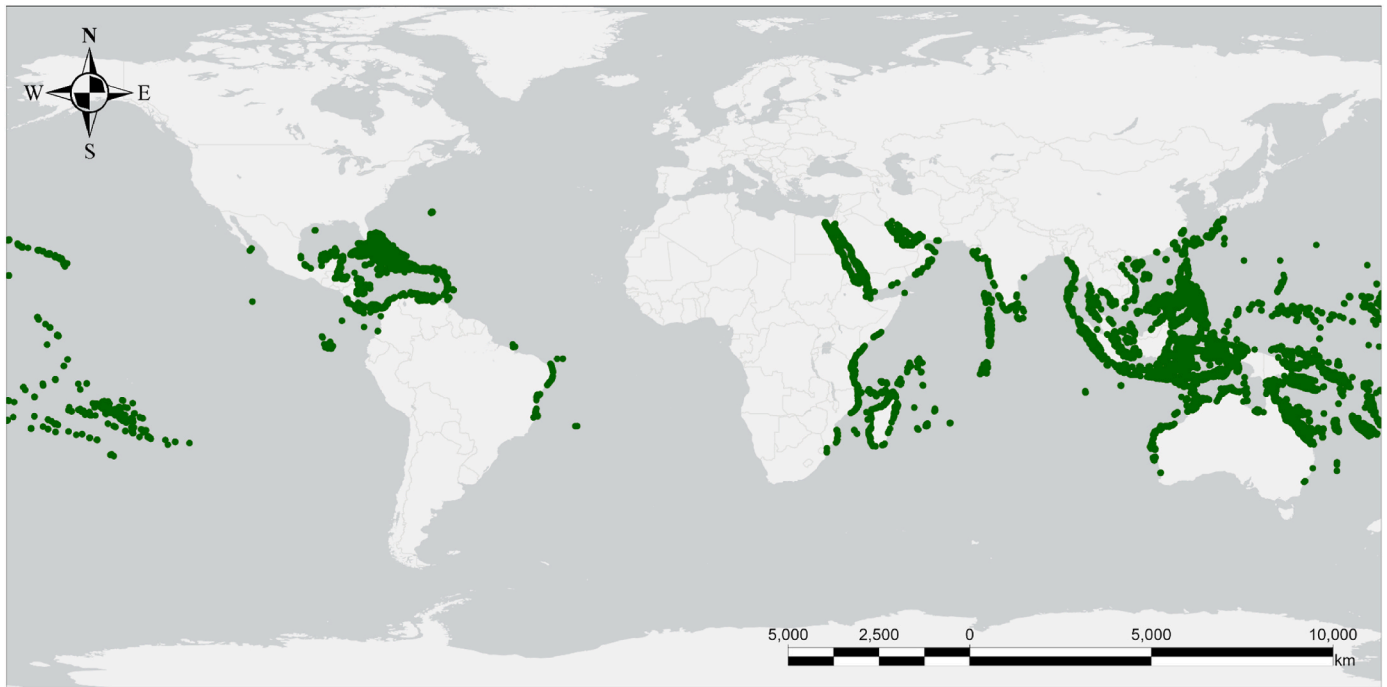


Fig. 3. Global coral reef (complex planform morphology) distributions highlighting regions where existing *DoC* estimation approaches are not theoretically applicable. In reef-dominated environments, wave energy transformation over complex bathymetric features alters sediment transport dynamics, which standard *DoC* estimation methods fail to capture. This underscores the limitations of these approaches in coastal planform morphologies, which characterise some of the world's most vulnerable coastal environments. *Credits:* UNEP-WCMC, WorldFishCentre, WRI, TNC (2021) (coral reef data); ESRI basemaps.

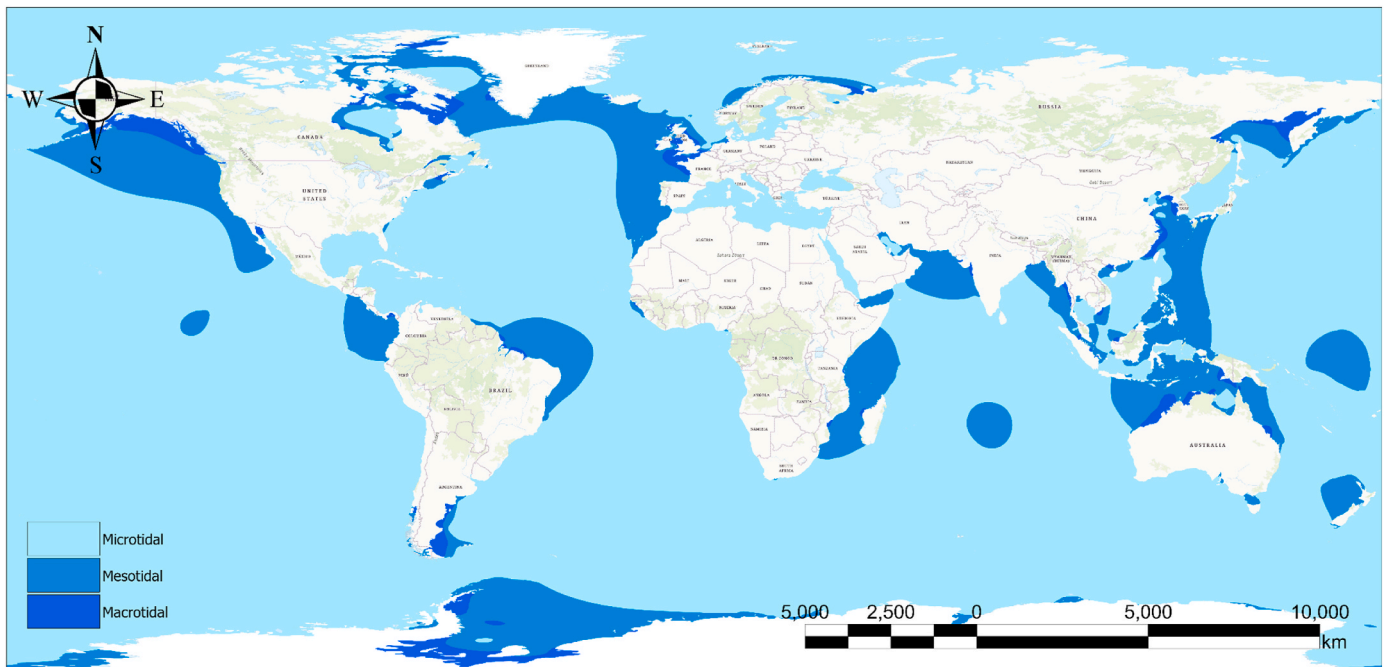


Fig. 4. Global variations in tidal ranges illustrating the dominance of macrotidal and mesotidal environments in certain regions. The reliance on existing *DoC* estimation methods – which are developed for microtidal conditions – will introduce uncertainties in these settings, where tidal currents have a more significant or equivalent role in sediment transport relative to wave action. *Credits:* Esri Ocean and Coastal Environments – Global Tidal Range Classification; ESRI basemaps.

small island states are disproportionately larger for reasons relating to smallness, resource limitations, socioeconomic coastal dependency, and limited scope for inland migration as the coastal zone erodes and faces threats of flooding and inundation from sea-level rise under climate change (Nicholls and Cazenave, 2010; Hubbard et al., 2014; Esteban et al., 2019; Martyr-Koller et al., 2021; Fellowes et al., 2022; Pörtner and

Belling, 2022).

Considering reef coastlines as an example of complex morphologies, there are >230,000 km of such coastlines globally (Burke and Spalding, 2022). The inability to estimate *DoC* s for complex morphologies, therefore, limits the usefulness and applicability of shoreline models (which often underpins coastal governance and management decisions –

Table 1

Comparative summary of DoC estimation methods, detailing their typical applications, reported strengths and weaknesses, and validation-based performance outcomes drawn from related literature.

Category	Method	Application	Strengths	Weaknesses
Mathematical formulations	Eq. 1	⇒Exposed microtidal sandy coasts with high wave energy (wave-dominated beaches)	⇒Provides a conservative short-term depth of closure, historically used in coastal design as a reliable seaward limit of the active profile. ⇒Aligns well with environments of small tidal range, yielding realistic DoC estimates on wave-dominated coasts (Brutsche et al., 2016; Valiente et al., 2019).	⇒Tends to overestimate long-term DoC (by ~25 % beyond observed, over multi-year timescales) and underestimate during calm wave climates (Capobianco et al., 2002; Valiente et al., 2019). ⇒Ignores tidal currents, so it breaks down on macrotidal coasts where tidal forcing is significant.
	Eq. 2	⇒Microtidal sandy shores with relatively stable annual wave climate (used for yearly DoC assessments on coasts with little interannual wave variability)	⇒Simplified variant of Eq. 1 that uses common wave climate metrics (mean and variability). Easier to apply when only long-term average wave data are available (Udo et al., 2020).	⇒Shares Eq. 1's limitations - focusing on average conditions can miss extreme events, potentially under-predicting DoC if storm waves are significant. Like other wave-only formulas, it is not suited to environments with large tidal ranges or unusual wave climate variability. Neglects tidal currents and infrequent extremes (Capobianco et al., 2002).
	Eq. 3	⇒Exposed sandy shorefaces (microtidal) to estimate the outer limit of sand motion (the 'wave base') further offshore of the inner DoC. Often considered for defining the depth beyond everyday profile changes, under median wave conditions.	⇒Incorporates sediment size into the depth calculation, accounting for grain-size-dependent transport thresholds. Provides a theoretical offshore bound where average wave action ceases to mobilise sand, useful for understanding the maximum active depth for sand transport (Nicholls et al., 1998).	⇒Seldom directly validated in the field - significant profile changes rarely reach this depth except in extreme events. Different criteria can yield (in some cases the computed inner DoC exceeds the outer DoC), revealing conceptual inconsistencies. Overall, it serves as a theoretical guide but with uncertainty in practical application (Capobianco et al., 2002).
	Eq. 4	⇒Developed from field data on a microtidal Atlantic beach (Duck, NC); applicable to wave-dominated microtidal coasts similar to those of Hallermeier's study. Typically used for annual closure depth on open sandy beaches with small tidal range.	⇒Empirically calibrated to observations - corrected Hallermeier's Eq. 1 by ~25 % to better match measured DoC s. ⇒Produces improved agreement with observed profile change limits at Duck, NC and has been used as a refined estimate for annual DoC on similar coasts (Brutsche et al., 2016).	⇒Remains a wave-only approach; still neglects tidal currents and site-specific sediment influences (assuming wave climate dominates). Its empirical tuning to one site means accuracy can degrade in very different settings (e.g., different wave climates or geology). Essentially limited to microtidal straight beaches, like the original dataset, for best performance (Capobianco et al., 2002).
	Eq. 5	⇒Intended for the same environments as Eq. 4 (straight, microtidal sandy shorelines), but offers a simplified predictor for annual closure depth. Suitable for quick estimates on wave-dominated coasts where detailed wave period data are unavailable.	⇒Extremely simple to apply, requiring only an easily determined extreme wave height statistic. Useful in data-poor cases for preliminary studies - it condenses the DoC estimate to a single representative wave parameter (Udo et al., 2020).	⇒High uncertainty due to oversimplification. By ignoring wave period (steepness) and sediment factors, it may misestimate DoC if local wave conditions or sediment differ from the assumed norm. Validation studies note inherent uncertainties with this one-parameter approach, so it may require site-specific calibration (Valiente et al., 2019).
Direct estimation methods	Profile envelope method	⇒Beaches with long-term monitoring (multi-year profile surveys). Common on research coasts (e.g., Duck, NC or other well-studied sites) where successive bathymetric profiles allow tracking of cumulative change.	⇒Site-specific and empirical: directly identifies DoC from observed morphology - the point beyond which no significant depth change occurs. Yields realistic values grounded in actual sediment movement; past studies confirm its reliability when sufficient data exist (Kraus and Harikai, 1983; Nicholls et al., 1998).	⇒Data and labour intensive: needs many years of surveys, making it time-consuming and expensive. Only feasible at well-instrumented sites, so coverage is limited. Results can depend on survey frequency and the chosen threshold for 'no significant change,' introducing some subjectivity in defining closure depth (Capobianco et al., 2002).
	Regional LiDAR analysis	⇒Regional scale open coasts where airborne bathymetric LiDAR (or sonar) surveys provide broad coverage. Best for extensive sandy coastlines with relatively clear water (to allow LiDAR penetration) - e.g., applied over hundreds of kilometres of U.S. coastline.	⇒Enables efficient large-area assessment of DoC. For example, analysis has been done over approx. 600 km of sandy shoreline using LiDAR data (Hartman and Kennedy, 2016), capturing spatial variability and reflects cumulative storm effects.	⇒Relies on specialised data - needs extensive LiDAR coverage and favourable conditions (clear water, suitable survey timing). ⇒Determining DoC from digital elevation change requires a vertical change threshold, which can affect the result. If the threshold is too high or low, it may under- or over-estimate the true closure depth, so expert judgement is required (Valiente et al., 2019).
Sediment - driven	Sediment Grain Size Trend	⇒Sandy beach profiles with distinct cross-shore sorting of sediment (e.g., uniform sand beaches where grain size decreases offshore). Applied on microtidal Mediterranean coasts to find DoC via sediment characteristics.	⇒Does not require wave climate data - uses secondary evidence of the active profile extent. The depth at which median grain size trend breaks align with the maximum transport tone, with validation against profile-derived DoC showing ~7–10 % agreement (Aragónés et al., 2018).	⇒Indicates the maximum extent of sediment transport, which can lie seaward of the depth that influences beach morphology. Thus, the grain-size break method can overestimate the effective DoC (showing a deeper limit where some transport occurs, even if the shoreline position is unaffected) (Aragónés et al., 2018). ⇒Additionally, it requires extensive sediment sampling and may not capture temporal shifts in sediment distribution.

see Section 4) in some of the world's most critically important and vulnerable environments. As we discuss in Section 4, the *DoC* may be the most critical parameter in these models. The key issue here is not that *DoC* estimation uncertainties have directly led to flawed coastal management decisions, but rather that the lack of appropriate *DoC* estimation methods for these environments limits the reliability of shoreline models, in turn restricting their potential use in coastal planning. This is particularly relevant for small island states, which generally house the world's most vulnerable coastal systems and do not have the funds to spend on large costly research and monitoring projects.

Moreover, considering (a) the global distribution in tide ranges – micro, meso and macro – (Fig. 4) and (b) that existing mathematical *DoC* estimation methods are limited to microtidal regions, we see coastal regions in each continent that are mesotidal and macrotidal, where such methods will not be applicable. These regions include some very vulnerable islands in Micronesia and Nauru. This, therefore, further reduces the global reliability of shoreline models for informing coastal management and governance decisions in regions that are most in need of such models. It also reduces the applicability of these models in some regions where they already play a key role in influencing such decisions, including the UK and the US west coast, with implications for the efficacy of ongoing and future decision-making for coastal management and governance.

Furthermore, using standard mathematical formulations based on wave parameters (Section 3.1) and direct estimation methods based on depth contour lines (Section 3.2) for determining *DoC* s do not account for the heterogeneity in shoreline morphodynamics, with adverse implications for shoreline model predictions and associated coastal management decisions (Udo et al., 2018, 2020). The *DoC* is the result of several drivers that interact with each other, including waves, intertidal morphology, and sedimentology (Townsend et al., 2024), which are not captured in existing *DoC* estimation methods (Eqs. 1–5; Sections 3.1–3.2). In some regions, different drivers may have considerably different influences on the *DoC*, which further reduces the applicability of *DoC* estimation methods for parameterising shoreline models on a global scale. For example, areas with coarser sediments may have shallower *DoC* s than those with finer sediments (Townsend et al., 2024). Regions experiencing significant sea-level rise (e.g., low-lying Pacific islands) may have deeper *DoC* s, as higher water levels will allow waves to travel further inland and transport sediments offshore (Seenath, 2022a). Those with increasing storm intensity (e.g., Caribbean Islands) may have deeper *DoC* s, as more intense storms are associated with higher waves and significant offshore sediment movement (Cooper and Pilkey, 2004; Robertson et al., 2008). Relying on metrics strictly based on wave parameters with little consideration of topography, sediment textures, micro timescale drivers (e.g., storms), etc., will inevitably introduce uncertainties in *DoC* estimations, which may compromise the credibility of shoreline predictions and associated coastal management decisions.

4. On the importance of the closure depth for shoreline modelling: a conceptual understanding

The *DoC* is perhaps the most important parameter in shoreline modelling, as it represents the seaward limit of significant cross-shore sediment transport and coastal profile evolution. Improved understanding and prediction of the *DoC* are both critical for the design of coastal engineering and management schemes. These are largely informed by shoreline model predictions, which provide a good proxy of overall coastal change and response to natural and human forcings (Kraus et al., 1998; Boak and Turner, 2005; Brutsche et al., 2016; De Figueiredo et al., 2020; Razak and Khan, 2020; Townsend et al., 2024).

Reliable detection and estimation of the *DoC* is important for coastal engineers and managers for two main reasons. *First*, it helps design and position coastal defence structures effectively over timescales of years to decades, to interact with sediment transport processes and mitigate risks

associated with climate-related hazards (e.g., sea-level rise, flooding, and erosion) (Hallermeier, 1978; Birkemeier, 1985; Brutsche et al., 2016; Valiente et al., 2017; Aragonés et al., 2019). The *DoC* finds applications for subaqueous beach nourishment placement, where suitable materials must be placed landward of the *DoC* to ensure its inclusion in an annual active littoral zone (Marsh et al., 1999; Karasu et al., 2016; Willson et al., 2017). For the design of coastal structures, Hallermeier (1980) states that breakwaters parallel to the shore should be placed seaward of the *DoC* to provide better wave protection with minimum effects or obstruction to littoral processes. *Second*, and, perhaps, more importantly, it underpins shoreline predictions over various timescales in response to natural and human forcings (Pelnaud-Considere, 1956; Bruun, 1962; Kaergaard and Fredsoe, 2013; Aragonés et al., 2019; De Figueiredo et al., 2020; Seenath, 2022b), facilitating coastal hazard risk assessments and coastal management planning across local, regional and global scales.

DoC specifications in shoreline models have recently been shown to significantly influence shoreline predictions, with the inclusion of temporal and spatial variations in *DoC* resulting in shoreline predictions considerably different from those associated with a static, spatio-temporally constant *DoC* specification (see Seenath, 2022a; Seenath, 2023). Static *DoC* specifications is the common form of *DoC* parameterisation in shoreline modelling studies (e.g., Kristensen et al., 2013; Seenath, 2022b; Muroi et al., 2024). We have also seen the inclusion of spatial variations in *DoC* being able to better predict shorelines in complex morphologies (see Seenath, 2023). However, apart from the theoretical uncertainties underpinning current *DoC* estimation methods, there are uncertainties regarding *DoC* specifications over various timescales in shoreline models (Nguyen et al., 2021). Although, temporal and spatial *DoC* variations have been facilitated in recent shoreline modelling studies, these studies were based on a manual prescription of temporal and spatial *DoC* variations, meaning that (at this time) dynamic *DoC* response to forcings within shoreline models is not yet possible. Given the constraints of *DoC* estimation approaches, coupled with the inherent constraints of shoreline models (due to their various simplifying assumptions), we need to understand the timescales of concern for coastal management, how best to prescribe the *DoC* based on these timescales, and the specific role of the *DoC* in shoreline models. The preceding sections, therefore, synthesise current shoreline modelling approaches, paying particular attention to their temporal applications benchmarked against their relevance for coastal management and governance decisions. Within this discourse, we consider the role of the *DoC* over the various timescales facilitated by existing types of shoreline models.

4.1. Historical empirical shoreline models

Traditionally, two classes of shoreline models were used to inform coastal management and governance decisions – empirical models (discussed here) and numerical models (Section 4.2). In the last decade, we have seen a progression towards the use of hybrid models, which combine elements of both (Section 4.3).

Empirical models rest on observed, historical data to formulate statistical relationships between shoreline position and some forcing mechanism (French et al., 2016; Gijnsman et al., 2018; Seenath, 2022b). Standard examples here are the one-line theory of shoreline change (Pelnaud-Considere, 1956) and the Bruun Rule (Bruun, 1962) (Fig. 5). Empirical models, such as these, are based on the equilibrium beach profile theory (Larson et al., 1987; Pontee, 2017), assuming that the active coastal profile – area between beach berm and *DoC* – maintain a constant time-averaged (years to decades) form across space and simply moves in a shore-normal direction along with the shoreline position in response to a change in sediment budget. In the one-line theory, shoreline and profile movement are in response to longshore sediment transport gradients, whereas these movements in the Bruun Rule are in response to the total amount of relative sea-level rise over the period of

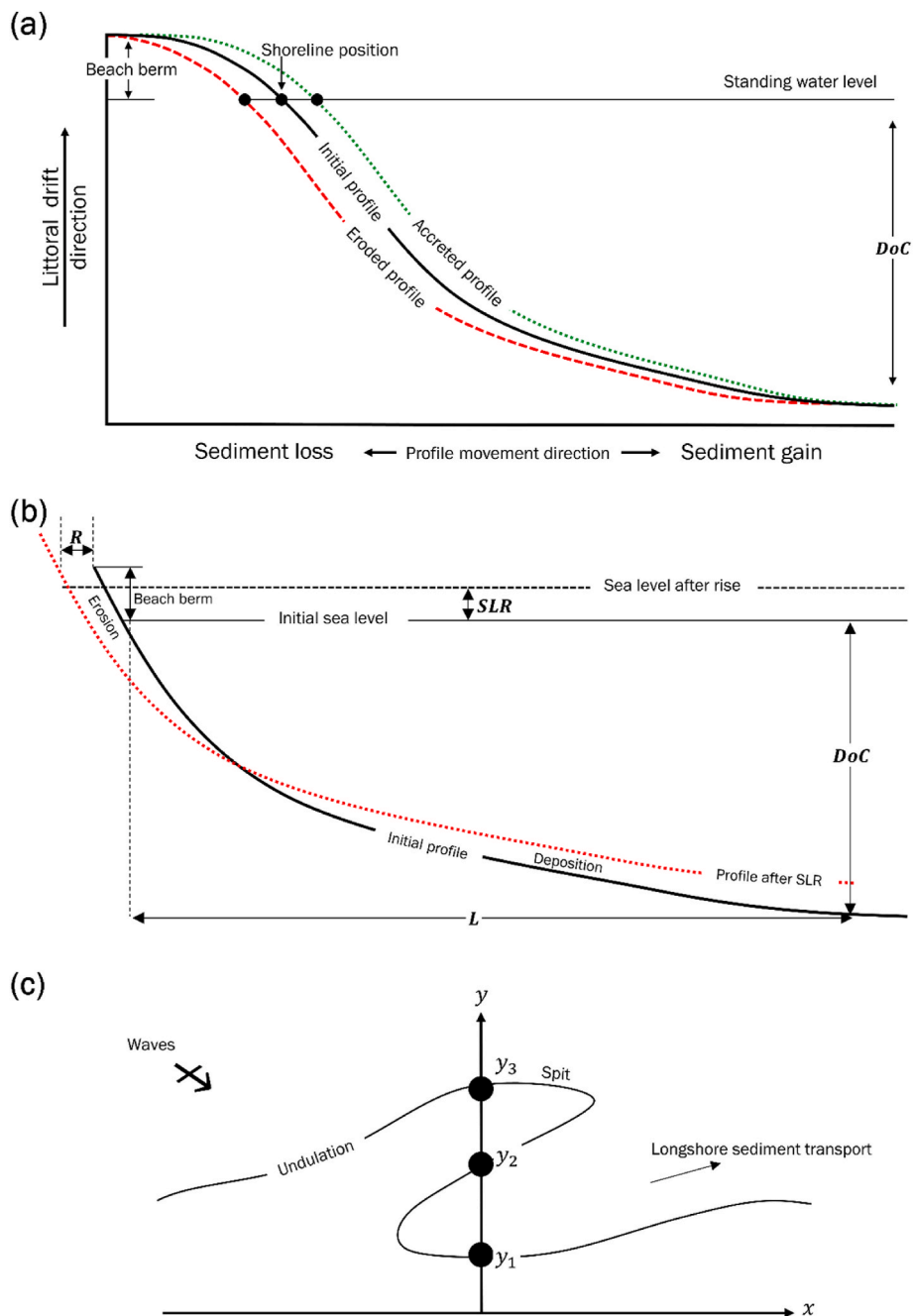


Fig. 5. Overview of empirical shoreline models and their challenges in complex morphologies. **(a)** One-line theory model: In this model, sediment gain (loss) over the active coastal profile – beach berm to DoC – based on littoral drift gradients causes the profile and shoreline to move seaward (landward). **(b)** Bruun Rule: In this model, sea-level rise (SLR) pushes the active coastal profile – beach berm to DoC – upward and landward, causing the upper beach to retreat (R) with the eroded material deposited offshore. **(c)** Complex shoreline configuration: As the profile in the one-line and Bruun Rule models moves in a shore-normal direction, this challenges the application in complex morphologies with bends and curvature in the shoreline geometry. In such cases, the shoreline may have three y coordinate crossings in areas with bends for a given x coordinate, creating instabilities in shoreline continuity solutions.

study (Seenath, 2022b). Both approaches, therefore, simulate ‘observed’ behaviour but overlook the physical processes that alter the coastal profile. While other forcings – tides, waves, and wind among others – are implicitly accounted for in their forcing functions (sediment gradients in the case of the one-line theory and sea-level rise in the case of the Bruun Rule), the neglect of the smaller scale natural dynamics at play within coastal systems means that their predictions are inherently uncertain and unlikely to be physically realistic. Although predictions from these models are useful, they may mask the true magnitude of shoreline change in response to the complex interplay of natural and human forcings operating within coastal systems. For instance, the Bruun Rule

has been shown to underpredict observed shoreline change by several orders of magnitude (see Seenath and Dale, 2024).

Furthermore, the one-line theory model and the Bruun Rule each largely exclude a critical component of sediment transport – cross-shore sediment movement in the case of the one-line theory model and longshore sediment movement in the Bruun Rule (Fig. 5). Although the longshore component of sediment transport is often the primary forcing mechanism of shoreline change (and hence the reason for the one-line theory being more reliable and receiving less criticism than the Bruun Rule) (Cowell et al., 1995; Seenath and Dale, 2024), cross-shore sediment movement is fundamental for coastal profile evolution (Robinet

et al., 2018; Ding et al., 2021). From a coastal management perspective, we need to understand both shoreline and profile responses to natural and human forcings, not one or the other. Additionally, the assumption of entire coastal profile movement in a shore-normal direction means that empirical models, such as the Bruun Rule and the one-line theory, are limited to simple planform morphologies, which are typical of naturally straight shorelines with no human interventions (Seenath, 2022b; Seenath and Dale, 2024). Although coastal engineering schemes can be accounted for (to an extent) in these models, their inclusion is accompanied by significant limitations, particularly as these schemes significantly affect sediment transport by trapping and redirecting sediment movement – such influences on sediment transport do not match the idealistic assumptions of shore-normal movement of coastal profiles and shoreline positions in empirical models. While empirical models may be modified to better describe the complex interactions between coastal engineering, sediment transport, and shoreline evolution, such modifications will still introduce uncertainties as the empirical relationships built into these models represent natural coastal dynamics and not those subjected to human modifications. In turn, empirical shoreline models are more limited in their use, particularly as most sandy beaches are now managed by some form of engineering (Seenath, 2022b).

More fundamentally, in the context of this review paper, the *DoC* is undoubtedly the most important parameter in empirical models, as it marks the end of the coastal profile. The assumption of entire profile movement, therefore, means that the *DoC* is considered to be constant in space and time in empirical models. This means that empirical models cannot account for the natural fluctuations in coastal conditions – tides, waves, wind, and morphology among others. There is ample evidence of the *DoC* responding to variations in wave climate and sea-level conditions (see, e.g., Nicholls et al., 1998; Nicholls et al., 1999; Valiente et al., 2019; Nguyen et al., 2021; Seenath, 2022a). For this reason, the *DoC* is treated as a good proxy of overall sea-level change (Seenath, 2022a). Yet, the Bruun Rule, which defines shoreline change as a function of sea-level change, does not account for this temporal fluctuation in sea-level, since it assumes that the *DoC* is both spatially and temporally constant. There is also evidence of the *DoC* responding to nearshore wave-current conditions, which influence the gradients in longshore sediment transport (Marsh et al., 1999). Despite this, the one-line theory – which defines shoreline change as a function of longshore sediment transport gradients – fails to account for the temporal variability in nearshore circulation, since it also assumes a spatially and temporally constant *DoC*. These assumptions raise an important question on the theoretical validity of both models for simulating shoreline change. While both models may provide shoreline change predictions that match up to those observed, there is the question of equifinality and whether we are getting reliable results for the wrong reasons, where reliable here refers to realistic shoreline change predictions and wrong meaning a theoretically and physically unrealistic conceptual model of the coastal system. It goes without saying that such uncertainty can compromise the credibility of shoreline predictions, with implications for the efficacy of associated coastal management and governance decisions.

The one benefit of empirical models, however, is that – by holding coastal profiles constant in terms of their form and using statistical relationships to predict shoreline response – they can facilitate macroscale simulations of shoreline change (centennial to millennia across thousands of kilometres) at low computational cost with minimal data requirements (primarily a DEM) (Seenath, 2022b). For this reason, they are often used to inform coastal management decisions in data-poor coastal regions, which, incidentally, are the most vulnerable (Appeaning Addo et al., 2008), but also in data-rich regions (e.g., in Europe) (Seenath and Dale, 2024).

Overall, empirical shoreline models rely on historical data and statistical relationships to predict shoreline changes. They are computationally efficient, require minimal data, and can model shoreline evolution over large spatial (thousands of kilometres) and temporal

(centennial to millennia) scales. However, they oversimplify coastal processes by assuming that sediment transport occurs in the shore-parallel direction, ignoring the effects of shore normal processes. They also neglect smaller-scale natural dynamics, such as tides and wave interactions, ultimately leading to significant uncertainties in their predictions. While useful for broad-scale coastal management, their oversimplification limits their reliability.

4.2. Contemporary numerical models

To address the limitations and uncertainties of empirical models, numerical models became more prominent in shoreline modelling studies, geared towards better informing coastal management and governance decisions, particularly in the late 20th and early 21st century. These models are physics-driven, solving the complex physics underpinning shoreline and broader coastal morphodynamics through partial differential equations, such as the shallow water equations. Numerical models range in dimensions from one-dimension (unidirectional evolution processes – e.g., cross-shore beach profile evolution) to two-dimension (horizontal simulations in x, y – cross-shore and longshore), and three-dimension (simulations in x, y and z – depth) (Reeve et al., 2016, 2019; Seenath, 2022b; Tassi et al., 2023). Examples include Delft3D (<https://oss.deltares.nl/web/delft3d>), OpenTelemac (<https://www.opentelemac.org/>), XBeach (<https://oss.deltares.nl/web/xbeach/>), and GENESIS (<https://csdms.colorado.edu/wiki/Model:GENESIS>). In theory, the setup of these models should enable a comprehensive understanding of coastal systems' behaviour (Fig. 6). However, there are two key limitations. *First*, numerical models are data-driven and computationally costly, which means that they are not applicable in data-poor (vulnerable) regions, where they are perhaps most needed. *Second*, coastal systems dynamics, although extensively studied, are not yet fully understood and, thus, there are significant uncertainties regarding the parameterisation and discretisation of key coastal processes within numerical models. For example, undertow currents – which run beneath the surface of waves with vertical variations in strength by depth – are the primary driving mechanism behind coastal profile evolution (Franz et al., 2017; Albernaz et al., 2019). However, these currents are difficult to simulate accurately. As a result, in numerical models, particularly two dimensional models (which are most commonly applied for shoreline evolution studies), the coastal profile degenerates to an unrealistic shape, causing significant instabilities in simulations longer than daily to yearly timescales, as the cross-shore component of sediment transport is not adequately solved due to the poor representation of and an inability to account for undertow currents (Kristensen et al., 2013; Franz et al., 2017; Albernaz et al., 2019; Seenath, 2022b). For this reason, numerical models are limited to micro timescales (days to years), which are not suitable for sustainable coastal management decision-making. Such decisions typically need meso timescale (decadal to centennial) predictions (French et al., 2016; Van Maanen et al., 2016; Payo et al., 2020; Seenath and Dale, 2024).

Although limited to micro timescales, numerical models have two key advantages over empirical models, evident from the literature cited above. *First*, because of their physics-driven approach, they are able to handle all types of coastal geomorphology and, hence, have more general applicability than empirical models, which are limited to simple morphologies. *Second*, because of their physics-driven approach, they provide a good platform, in theory, for simulating and understanding coastal response to natural and human forcings over micro timescales. It is important to consider that morphological processes operating over these timescales – waves, tidal currents, storm surges, supra-, inter-, and sub-tidal morphology, sedimentology, vegetation, and human influences among others – can influence coastal behaviour over meso and longer timescales (Stive et al., 2002; Cooper and Pilkey, 2004; Cooper et al., 2018; Seenath and Dale, 2024). Hence, numerical 'physics-driven' models enable a good foundational understanding of coastal systems'

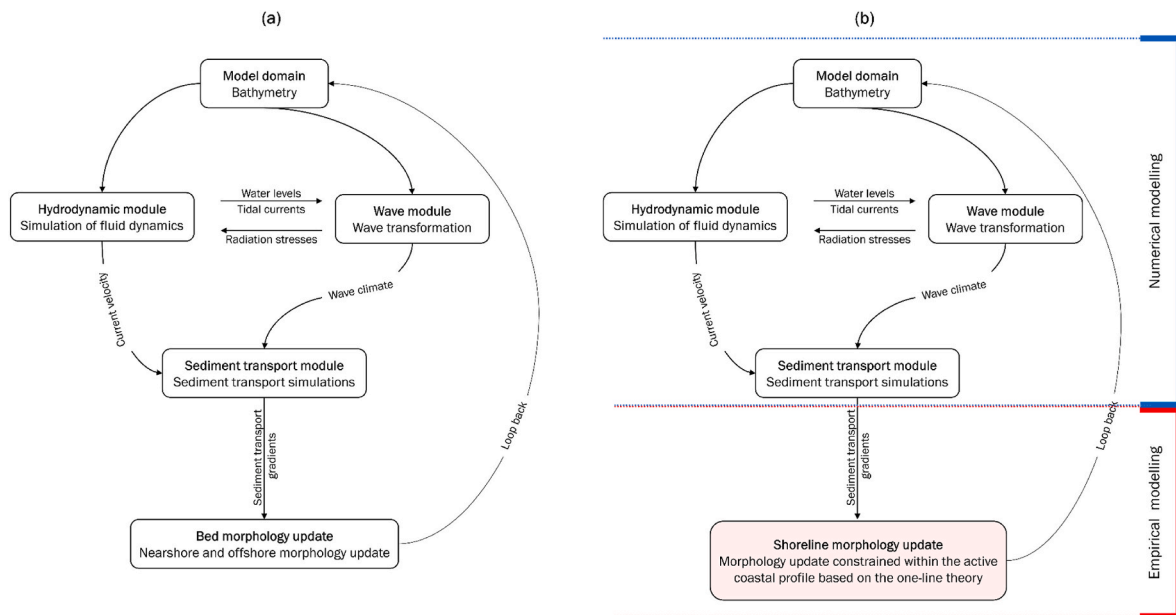


Fig. 6. Computational differences between numerical (a) and hybrid (b) shoreline models. The key difference between both models relates to the morphology update. In the former, the bed morphology is updated across the entire computational domain. In the latter, the morphology update is constrained within the limits of the active coastal profile – beach berm to DoC – based on the one-line theory of shoreline change.

behaviour, which have implications for better designing coastal engineering and management schemes. For this reason, numerical models, providing short-term simulations, were extensively used to inform coastal management decisions until recently (within the last decade), when the focus of coastal management started moving towards meso timescales, which enable a better understanding of coastal system dynamics.

Overall, numerical shoreline models address the limitations of empirical models by using physics-based equations to simulate detailed coastal processes, including wave action, sediment transport, and nearshore hydrodynamics. These models provide a more comprehensive understanding of shoreline behaviour by resolving interactions between natural and human-driven forces. However, they require extensive computational resources and high-quality data, making them less feasible for long-term or large-scale applications, particularly in data-poor regions. Additionally, due to unresolved complexities in nearshore processes (e.g., undertow currents), numerical models generally fail to provide theoretically and physically realistic predictions of long-term shoreline evolution, making them more suitable for short-term (micro timescale) predictions rather than for sustainable coastal management decision-making.

In the context of this review paper, the DoC is not an explicitly specified parameter in numerical models (Appenning Addo et al., 2008). However, the DoC is generally used to define the boundary between the active nearshore zone and the less active offshore zone in the

computational domain of these models, with the active nearshore zone often having a finer grid (spatial) resolution than the offshore zone (see Fig. 7). In this regard, the DoC, although not explicitly specified, underpins the discretisation of the coastal system within numerical models. Therefore, indirectly, the DoC also defines the active coastal zone in numerical models, influencing the nearshore hydrodynamics operating within these models and resulting coastal profile and shoreline predictions, with implications for coastal management decisions.

4.3. Moving towards hybrid models

Over the last two decades, hybrid models, such as MIKE21 shoreline morphology model (<https://www.dhigroup.com/technologies/mikeporedbydhi/mike-21-shoreline-morphology>), have been increasingly gaining prevalence for shoreline modelling, to inform coastal management (Ashton and Murray, 2006; Slott et al., 2010; Kaergaard and Fredsoe, 2013; Karunaratna and Reeve, 2013; Kristensen et al., 2013; Hurst et al., 2015; Seenath, 2022a, 2023; Muroi et al., 2024). These models couple numerical models for sediment transport simulations with empirical models for the shoreline morphology update. More specifically, hybrid models retain the physics-driven approach of numerical models for process simulations of sediment transport and use the calculated sediment transport rates and gradients to update the shoreline morphology based on the empirical one-line theory model of shoreline change (Fig. 6). The Bruun Rule, because of its many

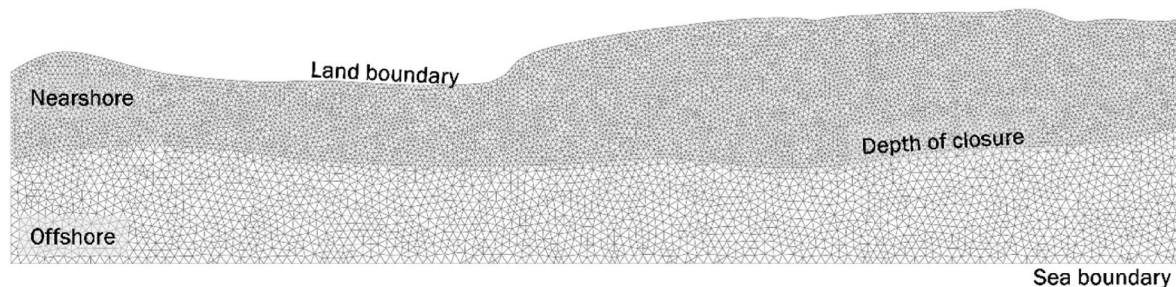


Fig. 7. Computational mesh for numerical model simulations of sediment transport at a barrier island in New York. Here, the two zones – offshore and nearshore are separated by the DoC, with the DoC explicitly determining where ‘detail (resolution)’ in bathymetry is needed in the model for waves and hydrodynamics.

limitations (Cooper and Pilkey, 2004; Seenath and Dale, 2024), is rarely embedded within such models (Seenath, 2022b). The numerical engine underlying these models allows for detailed simulations of sediment transport processes, accounting for the complex interplay of natural and human drivers of sediment transport (Larson et al., 2016). In hybrid models, the calculated sediment gradients are uniformly distributed within the active coastal profile – beach berm to DoC – with the profile (and shoreline position) moving seaward (landward) in response to sediment gain (loss) over the profile. There are three benefits of this approach, summarised from papers cited here. *First*, the use of the one-line theory stabilises the shoreline morphology update, preventing erroneous breakdown of coastal profiles (which limit numerical models to micro-timescales) while enabling meso timescale sediment transport simulations. *Second*, the use of a physics-driven approach for sediment transport simulations allows hybrid models to account for diverse coastal morphologies and natural and human forcings on longshore and cross-shore sediment transport. *Third*, the coupling of a physics-driven approach with an empirical modelling approach allows larger morphological speed-up, enabling computational efficiency over meso timescales.

Despite these benefits, there are several fundamental limitations of hybrid models related primarily to the DoC. Using the one-line theory to stabilise the shoreline morphology update essentially means that the inherent uncertainties of this theory are transferable to hybrid models. For instance, as per the one-line theory, the DoC is spatially and temporally constant. Treating the DoC as spatiotemporally constant, means that the ‘full’ effects of key drivers of coastal change – e.g., sea-level rise and bed morphology – are not accounted for in the shoreline morphology update (Seenath, 2022a, 2022b, 2023). Therefore, although the impact of natural and human drivers is embedded within the calculated sediment transport rates, their full effects on coastal morphology are not incorporated when the shoreline morphology is updated. With the DoC constant in time and space, hybrid models effectively assume no changes to the active limits of the profile, which is fundamentally wrong (theoretically and physically) as such limits change under variations in forcing functions (Kraus et al., 1998; Nicholls et al., 1998; De Figueiredo et al., 2020). The DoC’s role in hybrid models is that of a shoreline morphodynamic boundary – sediment movement is confined within the profile up to the prescribed DoC. With sea-level rise, there may be deeper DoC s (Cooper and Pilkey, 2004; Robertson et al., 2008; Seenath, 2022a). Holding the DoC constant while forcing rising sea-levels into the model will increase the energy for sediment transport, with potentially a larger volume of sediments being distributed within a narrower active coastal profile than would otherwise happen in reality.

Additionally, we know that the DoC varies in complex planform morphologies (Eversole and Fletcher, 2003; Seenath, 2023). While hybrid models are able to handle such morphologies in their sediment transport simulations (Fig. 6), there is a critical question of whether the effects of such morphologies are adequately represented during the shoreline morphology update. For instance, we know that the DoC varies alongshore in complex planform morphologies, and we also know that the DoC marks the offshore limit of sediment movement in hybrid models. Holding the DoC constant in space means that the zone of active coastal profile and shoreline morphodynamics within these models will be larger or shorter in cross-shore width than observed for some coastal segments. Where active coastal profile zones have a larger cross-shore dimension in hybrid models than observed, sediment movements will be forced in areas that would otherwise be morphologically inactive (Kaergaard, 2011), introducing further errors in the resulting shoreline predictions.

The implications of the above limitations extend beyond shoreline modelling to coastal governance strategies. Coastal systems in small island states and macrotidal environments, in particular, will face heightened challenges in coastal management decision-making due to the spatial and temporal variability of DoC, which is virtually ignored in existing shoreline models. In macrotidal regions, where sediment

transport is strongly influenced by tidal forces relative to wave action, DoC estimation becomes even more complex. A study examining an embayed, macrotidal, and exposed coast shows that traditional DoC estimation methods might not be directly applicable in such settings, instead requiring a multi-criteria approach to accurately assess sediment dynamics (Valiente et al., 2017). Similarly, coastal systems in small island states with irregular hard substrate face unique shoreline modelling challenges related to DoC variability (see Seenath, 2023). The Intergovernmental Panel on Climate Change (IPCC) notes that sea-level rise and associated coastal changes present significant risks to low-lying islands, which can compromise the stability of their geomorphology (Oppenheimer et al., 2019). This will further undermine the applicability of standard DoC estimation methods, which cannot account for spatial and temporal variations in drivers of coastal evolution (De Figueiredo et al., 2020; Seenath, 2022a, 2023). These complexities highlight the need for region-specific adaptations in DoC estimation to enhance the reliability of shoreline models for informing effective coastal management strategies in these regions, which are some of the world’s most vulnerable locations.

Furthermore, the use of the one-line theory for stabilising the shoreline morphology update essentially eliminates the role of the cross-shore sediment gradient in coastal profile evolution, as the one-line theory is based on the premise that shoreline change is a function of longshore sediment transport (Pelnaud-Considere, 1956). While longshore sediment transport provides the primary forcing for shoreline change (Cowell et al., 1995; Seenath and Dale, 2024), the evolution of coastal profiles are primarily governed by cross-shore transport (Franz et al., 2017; Albernaz et al., 2019). From a coastal management perspective, we need a careful consideration of both components of sediment transport for modelling and predicting shoreline change. The conventional ‘hold-the-line’ coastal management approach (facilitated by hard engineered defences) designed to maintain existing shoreline positions is giving way to more environmentally friendly and potentially more sustainable nature-based approaches (Justine and Seenath, 2025). This emerging paradigm shift in coastal management approaches further reinforces the need for reliable shoreline modelling abilities to better understand coastal response to these alternative approaches over the timescales of concern for sustainable coastal management and governance decision-making.

While we acknowledge the advancements made in shoreline modelling capabilities with the introduction of hybrid models (e.g., the ability to now facilitate meso timescale sediment transport simulations), five fundamental questions arise on their applicability and suitability for shoreline modelling, particularly where the resulting predictions are to inform coastal management and governance decisions.

1. Is the one-line theory a theoretically and physically realistic concept for modelling and understanding meso-timescale shoreline change?
2. Do hybrid shoreline models offer a significantly better alternative to empirical shoreline models? After all, the key governing equations that drive the evolution of coastal profile and shoreline positions in hybrid models are the same equations that drive empirical models.
3. Do hybrid shoreline models adequately capture the effects of sea-level rise, which is often assumed to be the primary driver of mesoscale coastal evolution?
4. Are wave transformations over non-linear bed morphology and their effects on shoreline dynamics effectively accounted for in hybrid shoreline models?
5. Given their reliance on the one-line theory for shoreline morphology, are hybrid shoreline models truly applicable beyond simple planform morphologies?

These questions (and perhaps more unidentified questions) raise concerns about the ‘real’ progress made in overcoming the limitations and challenges of empirical and numerical shoreline models. What is particularly concerning, however, is that these questions/uncertainties

are strongly related to the uncertainties regarding the estimation, identification, and specification of the *DoC*.

Overall, hybrid shoreline models attempt to bridge the gap between empirical and numerical shoreline models by combining physics-driven sediment transport simulations with an empirical shoreline morphology update based on the one-line theory. By adopting the one-line theory for the shoreline morphology update, hybrid shoreline models can facilitate meso timescale predictions (decades to centuries) at low computational cost. Despite these benefits, their reliance on the one-line theory for morphological stability inherit the limitations of empirical shoreline models associated with the assumption of a spatially and temporally constant coastal profile and *DoC*. This over generalisation means that hybrid models cannot realistically account for the effects of sea-level rise and complex planform morphologies when updating the shoreline morphology, which raises questions about their theoretical validity for shoreline modelling in cases where such modelling is to inform decision-making for sustainable coastal management.

4.4. Relevance for coastal management and governance

We have repeatedly drawn reference to the importance of shoreline models for coastal management without context. We assume that this is standard knowledge among the coastal science community, but for broader audiences, we summarise here seven reasons why shoreline models are pivotal to the effective design and governance of coastal systems based on literature cited in preceding sections. The *first* (and perhaps the most obvious), relates to prediction of shoreline changes in response to natural and human forcings (local and external). Such predictions allow us to understand how shorelines will change due to various hydrodynamic forcings, such as waves and currents, where they might lose or gain sediment, enabling critical planning and mitigation decisions in response to various coastal threats, hazards and risks. *Second*, complementing existing historical data, these models allow us to ‘see’ into the future, indicating the probable impacts of climate change on coastal systems – *how they might respond to increasing storm frequency and intensity, changes in sediment supply etc.* In the absence of such a ‘future lens’ (of course, grounded by credible hindcasting results), adaptive planning efforts for building coastal resilience to climate change will be done rather ‘blindly’. *Third*, apart from shoreline protection planning, shoreline models allow us to understand the role of natural ecosystems in coastal resilience and how these systems might interact with coastal processes under future climate conditions. Such knowledge has spillover benefits for coastal conservation and restoration initiatives. *Fourth*, shoreline models provide a good indication of sediment regimes, enabling planners to better develop beach nourishment projects. Shoreline models can enhance the accuracy of sediment budget evaluations and predict the spatial impact of human interventions on coastal systems, thus, helping to inform sustainable coastal management strategies. *Fifth*, these models allow for exploratory studies to compare the effectiveness of coastal defence designs (e.g., hard structures, nourishment, or nature-based solutions) on shoreline stability, providing a good platform for engineers to design and optimise coastal protection structures. Such studies inevitably help boost resiliency planning in the face of an uncertain future climate. *Sixth*, predictions from shoreline models coupled with infrastructural data allow us to gauge potential flood and inundation areas and socioeconomic risks in response to climate-related coastal hazards, which is critical for developing emergency preparedness and response initiatives. *Finally*, the visualisation of shoreline model outputs plays a key role in enhancing community awareness of the probable impacts of climate-related coastal hazards, with direct benefits for building environmental stewardship among local coastal stakeholders – such stewardship also contributes to the success of overall coastal management as it helps to shape adaptive management schemes at the local community level.

Shoreline models are, therefore, indispensable tools for coastal management decision-making. The concern here relates to the impact of

the uncertainties surrounding the *DoC* on these important and critical decision-making processes. Beyond informing local and regional coastal planning, the estimation of *DoC* and its role in shoreline modelling also have implications for international maritime governance. Various legal frameworks, such as the United Nations Convention on the Law of the Sea, rely on bathymetric and morphological data to define maritime boundaries (Nguyen and Vu, 2025), while coastal management policies, including the UK’s shoreline management plans (<https://www.gov.uk/guidance/shoreline-management-plans>), often emphasise the need for robust coastal modelling approaches. As shoreline models contribute part of the ‘evidence base’ for coastal management decisions, ensuring that *DoC* estimation methods are reliable and adaptable is not only a scientific concern but also a regulatory necessity.

5. ‘Recent’ advances in closure depth estimations

Recent studies have highlighted the importance of variable shoreface *DoC* limits on coastal response to sea-level rise, showing that these limits significantly affect sediment exchange and cross-shore distances of shoreline retreat (De Figueiredo et al., 2020). Climate change affects *DoC* estimation *indirectly* by driving sea-level rise – this, in turn, calls for a dynamic, rather than static, approach to *DoC* specification in shoreline models. To this end, advances in hybrid modelling have attempted to include seasonal changes in the *DoC* in order to predict the evolution of shorelines more accurately under monsoon wave-dominant conditions (Nguyen et al., 2021). Additional advances in these types of models have included the introduction of temporal (spatial) variations in *DoC* under wave climate variations, to better account for sea-level rise (complex planform morphologies) effects in shoreline evolution (Seenath, 2022a, 2023). Within the last decade, we have also seen newer methods of calculating the *DoC* based on trends in sediment size, to increase accuracy by accommodating the influence of different characteristics and morphologies in various coastal areas (Aragonés et al., 2018). Other works have focused more closely on better quantifying the net cross-shore sediment transport, to improve *DoC* estimations (see, e.g., Aragonés et al., 2019). Furthermore, there has been recent work done on extending current *DoC* mathematical formulations for defining the *DoC* in embayed macro tidal coasts (see Valiente et al., 2019).

Despite some credible advances in *DoC* estimation approaches for improving shoreline modelling, all of the ‘recent’ *DoC* estimation approaches summarised above are largely based on extensions of the existing (uncertain) *DoC* estimation methods – primarily the mathematical formulations summarised in Section 3.1. For instance, consider Seenath (2022a, 2023) papers; while these studies have improved overall hybrid modelling approaches by facilitating temporal and spatial variations in the *DoC*, the approach used to estimate these variations is the simplified Birkemeier equation (Eq. 5), which, as previously discussed, has inherent uncertainties related to simplified assumptions on what defines the *DoC*. Even more so, Seenath (2022a, 2023) approach do not allow the *DoC* to dynamically ‘evolve’ over time and space under wave-climate and sea-level variations. Rather, his approaches are based on a manually prescribed process rather than a fully dynamic automated process. To date, shoreline modelling studies – those based on new, modified or existing approaches – are still largely dependent on the age-old mathematical *DoC* formulations (Udo et al., 2020). The reliance on these traditional mathematical formulations is problematic when applied across diverse coastal systems, where geomorphological and hydrodynamic variations challenge the assumption of a universal *DoC* definition. In reef environments, for example, the *DoC* is defined as the most seaward depth landward of the first occurrence of hard substrate rather than sediment mobility thresholds, as seen in microtidal sandy coastal systems (Seenath, 2023). Similarly, in macrotidal environments, where tidal currents significantly influence sediment transport, *DoC* estimates based on wave-driven sediment thresholds may misrepresent the active coastal profile (Valiente et al., 2017). These regional differences in coastal settings reinforce the need for more adaptable *DoC*

estimation methods that can accommodate site-specific coastal characteristics, rather than relying on a one-size-fits-all approach. This raises an important question – *should we continue to prioritise the refinement of contemporary shoreline modelling approaches (e.g., hybrid 2D/one-line approaches), or should we direct our efforts to address the uncertainties inherent in long-standing formulations (e.g., DoC) that underpin the parameterisation of these models?* This question rests on the premise that continued refinements of equations and parameters in shoreline modelling based on uncertain empirical formulations would not necessarily reduce the uncertainty or increase the credibility of resulting shoreline predictions. Instead, we may just be conforming to equifinality, ending up with models that produce the ‘right’ results for the wrong reasons, where right refers to the best match between observed and modelled phenomena and wrong refers to a physically (and theoretically) unrealistic conceptual model of the coastal system, both of which could lead to sub-optimal coastal management decisions.

6. Future research directions: what next?

With increasing coastal vulnerability in response to accelerated sea-level rise and storm intensity under climate change, we need greater predictive power to understand coastal systems’ response to these challenges, to better inform coastal resilience and adaptation decisions. This requires us to carefully consider whether existing shoreline modelling approaches, which are based on long-standing uncertain parameterisation of key parameters and variables, are ‘fit-for-purpose’ for studying coastal evolution in response to 21st century and future environmental challenges. From our review, it is clear that we have not made significant progress since the release of empirical shoreline models, despite some credible advances towards hybrid shoreline models, as contemporary hybrid models still have the underlying uncertainty associated with empirical models built into their design. Starting with the *DoC*, which plays a fundamental role in governing shoreline morphodynamics within shoreline models, we need to establish more robust and reliable *DoC* estimation methods that consider the complex interplay of processes and local factors – tides, wind, waves, intertidal morphology, and sediment currents among others – which influence this important depth boundary. This will likely require extensive coastal monitoring across variations in coastal geomorphology and tidal environments at the local scale coupled with process-based modelling to understand the evolution of the *DoC*. Such an understanding will help play a critical role in shaping the future of shoreline models, to better inform decision-making for coastal management and governance.

A more effective way forward, we argue, would be the development of an **adaptive framework for *DoC* estimation** that moves beyond static (spatio-temporally constant) assumptions and incorporates dynamic modelling approaches. Rather than relying on predefined *DoC* thresholds based on historic empirical *DoC* estimations (Section 3.1), future research should work towards exploring methods that continuously refine *DoC* estimates based on evolving environmental conditions. This would likely involve integrating multi-source data, including real-time updates from satellite-derived bathymetry, LiDAR, UAV-based photogrammetry, and in-situ measurements, that account for spatio-temporal changes in sediment transport and coastal geomorphology. A recent study on the assessment of measured and computed *DoC* around Japan has demonstrated the effectiveness of combining various data sources to enhance *DoC* estimation accuracy (Udo et al., 2020). More so, making use of process-based numerical models alongside empirical datasets may allow for regionally tailored *DoC* parameterisation that reflects site-specific geomorphological and hydrodynamic characteristics. For instance, recent advancements in hybrid shoreline models have enabled time-varying *DoC* s in response to annual variations in wave climate (Seenath, 2022a), highlighting the potential of such integrated approaches. A critical aspect of the adaptive framework for *DoC* estimation should also include the integration of sediment-driven

approaches (see, e.g., Aragonés et al., 2019) (Section 3.3) with complementary methodologies to enhance predictive accuracy. For instance, combining sediment grain size analysis with wave-current modelling can potentially yield a more dynamic representation of sediment transport pathways, addressing the spatial and temporal variability inherent in coastal systems. Advances in machine learning and artificial intelligence could also play a key role in the adaptive framework, as predictive models trained on historical wave climates, sediment transport patterns, and shoreline evolution trends may help identify changes in *DoC* under different environmental forcing conditions. The quantification of cross-shore sediment transport, for example, has been enhanced through machine learning techniques (Goldstein et al., 2019) – such an approach can potentially be leveraged to provide more accurate *DoC* calculations, considering the direct link between cross-shore transport and the *DoC*.

Machine learning techniques have increasingly been applied in coastal morphodynamic modelling, offering promising alternatives to traditional empirical and numerical approaches. Recent studies show how machine learning can enhance bathymetric depth estimation and nearshore hydrodynamic predictions, which are closely related to *DoC* estimation. For example, Lowell and Hermann (2024) applied categorical boosting (CatBoost) to improve bathymetric depth change estimates using multi-temporal Sentinel-2 satellite imagery. By integrating multi-source and multi-temporal data, their model reduced the root mean squared error (RMSE) in these estimates by 30 % compared to traditional model-differencing approaches. This shows the potential for machine learning to refine depth estimations in coastal environments where seabed morphology evolves under dynamic wave and sediment transport conditions. As seabed morphology influence the *DoC* through impacts of wave action, similar approaches could be adapted for *DoC* estimation. Likewise, Wei and Davison (2022) applied convolutional neural networks (CNNs) to predict nearshore wave and hydrodynamic conditions, integrating numerical model outputs with observed data. Their study shows how CNN-based models can effectively capture spatial-temporal wave transformation, wave-driven circulation, and sediment transport patterns, offering significant improvements over conventional physics-based models. Given that *DoC* estimation depends on understanding sediment transport dynamics and wave-seabed interactions, machine learning techniques, such as CNNs, hold promise for being able to predict *DoC* variability based on historical wave and sediment transport conditions. While machine learning has yet to be widely applied to *DoC* estimation, these studies illustrate its broader potential in coastal process modelling. By training machine learning models on extensive datasets of historical profiles, wave climates, and sediment transport rates, we can potentially develop more adaptive and site-specific methodologies for *DoC* estimation. Future research should, therefore, examine the feasibility of integrating machine learning into adaptive *DoC* estimation frameworks, particularly for environments where traditional methods fail to capture complex seabed dynamics and hydrodynamic variability. Similarly, probabilistic modelling approaches, such as those adopted for projecting shoreline changes (see, e.g., Thiéblemont et al., 2021) may be useful to integrate in an adaptive *DoC* estimation framework. Such approaches can help address the inherent uncertainty in *DoC* estimation by accounting for multiple possible *DoC* values based on variations in hydrodynamic forcing, sediment characteristics, and coastal morphology. However, while probabilistic modelling approaches hold promise, their application to *DoC* estimation remains unexplored, requiring further research to evaluate their feasibility across different coastal environments.

While machine learning, remote sensing, UAV-based photogrammetry, and data-driven modelling hold promise for improving *DoC* estimation, their practical implementation in diverse coastal settings remains an open research challenge. The extent to which these methods can dynamically capture *DoC* variability, particularly in response to changing wave climates, sediment transport, and sea-level rise, requires further study. Additionally, integrating high-resolution observational

datasets with process-based models presents challenges related to data availability, computational demands, and site-specific calibration, especially for data-poor small island states – the most vulnerable regions where shoreline models (and, in turn, reliable *DoC* estimates) are arguably most needed for informing coastal management and governance. Future research should, therefore, also focus on addressing these uncertainties, testing the feasibility of emerging approaches across a range of coastal geomorphologies, and developing methodologies that bridge theoretical advancements with practical shoreline modelling applications.

Additionally, an adaptive *DoC* estimation framework must recognise the multi-scale nature of *DoC* variability – short-term fluctuations due to storm events versus long-term shifts driven by sea-level rise – ensuring that estimation methods remain responsive across different timescales. Studies show that wave-based parameterisations developed for microtidal beaches may not be directly applicable to macrotidal environments, reinforcing the need for adaptable *DoC* estimation methods (Valiente et al., 2019). It is also essential that adaptive *DoC* estimation frameworks align with the governance and management needs of specific coastal regions, particularly in data-poor environments, such as small island states, where standardised models may lack applicability. One potential avenue for doing so is by integrating geomorphic frameworks, which offer structured approaches for categorising coastal settings based on physical and sedimentological characteristics. By including these frameworks into adaptive *DoC* estimation frameworks, we may be able to better account for variations in coastal morphology and sediment dynamics that influence *DoC* thresholds across different environments. Such an approach has been useful in the context of sea-level rise impact assessments (Eliot, 2013). In adapting *DoC* estimation frameworks to specific governance and management contexts, geomorphic frameworks could serve as a basis for refining region-specific parameterisation strategies, particularly where data availability is limited. Overall, through an adaptive framework for *DoC* estimation, future research can work towards refining *DoC* estimations that not only improve shoreline model accuracy but also enhance their relevance for informing coastal management.

Apart from an adaptive *DoC* estimation framework, other innovative ways of improving *DoC* estimation may be to apply geostatistical models that predict *DoC* based on spatially mapped grain size distributions, in turn linking sediment characteristics with sediment transport thresholds under varying wave and current conditions. Or perhaps, more simply, *DoC* estimation can be based on some form of statistical standardisation, similar to how storm surge levels are referenced to a probability of occurrence over defined time periods. Understanding the role and how to effectively capture the effect of the parameters and variables underpinning shoreline evolution, such as the *DoC*, we argue, should be prioritised rather than continuing to modify and extend flawed shoreline modelling approaches for studying coastal systems behaviour. This is particularly important since such models typically contribute to the ‘evidence base’ for coastal management and governance decisions.

7. Conclusions

We provide a critical theoretical review of the *DoC* (theoretical underpinnings and estimation methods), its use within shoreline models, and its implications for coastal management and governance decisions. We do not only synthesise existing *DoC* estimation methods but critically assess their theoretical validity, practical limitations, and implications for shoreline modelling and coastal governance. By evaluating the assumptions underlying these methods, we identify key gaps that should be addressed to enhance the reliability of *DoC* parameterisation in future applications of shoreline models. From this review, we draw four conclusions.

1. Existing *DoC* estimation approaches are fundamentally uncertain due to broad overgeneralisation of the coastal system. Their overgeneralisation

fails to consider the complex interplay of processes and local factors that influence the *DoC*. Existing *DoC* estimation methods are most applicable to microtidal sandy coastal systems with simple planform morphologies, limiting their effectiveness in complex planform morphologies – e.g., reef environments – which characterise some of the world’s most vulnerable coastal systems (i.e., those in small island states). This, in turn, reduces the reliability of shoreline models that treat the *DoC* as a critical morphodynamic boundary in these vulnerable locations where precise predictions are most needed for effective coastal governance.

2. Credible advances have been made in the evolution of shoreline modelling approaches from empirical to numerical and hybrid approaches for informing coastal management and governance decision-making. However, hybrid models, which are now being increasingly applied to inform such decisions, retain the uncertainty of empirical models in their morphology modelling component (i.e., when updating the shoreline morphology in response to sediment transport gradients). Given these challenges, future efforts should prioritise the development of **adaptive *DoC* estimation frameworks** that integrate real-time observational data, process-based modelling, and machine learning-based predictive approaches. Without such advancements, existing shoreline models may continue to propagate uncertainties that compromise effective coastal management and adaptation planning.
3. Although hybrid models supposedly allow applications across variations in coastal geomorphology, their assumption of a spatio-temporally constant *DoC* essentially limits their applications to natural straight sandy beaches. This raises a critical question – do hybrid shoreline models actually facilitate a better understanding of coastal system dynamics than empirical shoreline models?
4. Greater efforts are needed to address the fundamental uncertainties in long-standing empirical formulations that underpin the parameterisation of key parameters and variables – e.g., the *DoC* – in shoreline models. This should be a matter of priority rather than focusing on continuing to extend theoretically and physically flawed shoreline modelling approaches for simulating and understanding coastal systems behaviour, the implications of which can compromise the efficacy of coastal management and governance decisions.

To address some of the challenges pointed out in our conclusions, we call for a paradigm shift from refining flawed shoreline modelling approaches to addressing foundational uncertainties in *DoC* estimation through an *adaptive, data-driven framework*. Such a framework may involve integrating multi-source datasets (e.g., satellite-derived bathymetry, LiDAR, UAV photogrammetry, and in-situ measurements) with process-based models, machine learning, and probabilistic methods to continuously refine *DoC* estimates in response to evolving coastal conditions. This approach is essential for capturing both short-term fluctuations (e.g., storm events) and long-term morphodynamic changes (e.g., sea-level rise) while addressing regional variability in sediment transport and hydrodynamics. Advancing the field will require localised studies to account for geomorphological and tidal differences, alongside collaborations between coastal scientists, engineers, and policymakers to ensure improved *DoC* estimation translates into practical (and reliable) decisions for coastal management. Overcoming practical challenges, particularly in data-poor regions, will be key to developing tailored approaches that align with governance needs. Ultimately, by integrating theoretical advancements with applied shoreline modelling, an adaptive framework will likely enhance the predictive accuracy of these models, with longer term benefits for better informing coastal management and governance decisions.

CRedit authorship contribution statement

Connor J. Durkin: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **Avidesh**

Seenath: Writing – review & editing, Visualization, Formal analysis, Conceptualization. **Michiel A.F. Knaapen:** Writing – review & editing, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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