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Short communication

A new approach for handling complex morphologies in hybrid shoreline evolution models

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ABSTRACT

Hybrid shoreline evolution models are being increasingly used to inform the management of sandy coastal systems. These models generally apply a two-dimensional physics-driven approach to calculate littoral drift and the one-line theory to update the shoreline morphology. As per the one-line theory, the calculated littoral drift is uniformly distributed over the active coastal profile. A key challenge facing the application of hybrid models is that they fail to consider complex morphologies when updating the shoreline morphology. Complex morphologies are defined herein by non-parallel depth contours to the shoreline, a characteristic feature of many vulnerable sandy coastal systems. This study illustrates the deficiency of the current hybrid 2D/one-line approach when applied to hindcast shoreline change from 2014 to 2016 along a sandy coast with fringing reefs in Puerto Rico. Results show that the hybrid approach is unable to predict observed shoreline change (*Brier Skill Score* = 0) as a result of the one-line theory assumption of a spatially constant closure depth, which defines the offshore extent of significant cross-shore sediment transport. To address this, a new hybrid approach is developed for application in complex morphologies that accounts for alongshore variations in the closure depth. In the new hybrid approach, the coast is divided into segments according to the alongshore distribution of fringing reef substrate with each segment having a different closure depth specified based on their underlying bed morphology. Results show that this new hybrid approach enables a more realistic simulation (*Brier Skill Score* = 0.4) of observed shoreline change. This finding explicitly demonstrates that the closure depth is an important variable in shoreline evolution models. It also implicitly indicates that we are likely to better simulate shoreline evolution in complex morphologies over timescales of concern in coastal management by allowing the closure depth to vary alongshore in hybrid models.

1. Introduction

Hybrid 2D/one-line models, hereafter hybrid models, are being increasingly applied to simulate 10 to 100-year shoreline evolution to inform the management of sandy shorelines (Ashton and Murray, 2006; Kaergaard and Fredsoe, 2013; Van Maanen et al., 2016; Roelvink et al., 2020), which characterise 31% of the world's ice-free coastal zone (Luijendijk et al., 2018). These models apply a two-dimensional physics-driven approach to simulate littoral drift in response to the combined interactions of external forcings (e.g., tides, waves, morphology), which they then uniformly distribute over the active coastal profile (i.e., beach berm to closure depth) to update the shoreline morphology in line with the one-line theory. In hybrid models, sediment aggradation (degradation) over the active coastal profile shifts the profile seaward (landward). The closure depth marks the offshore extent of significant cross-shore sediment transport, identifiable as the point on the beach profile beyond which we can see no significant change in bed elevation (Kraus et al., 1998; Nicholls et al., 1999).

Hybrid models have been developed to address the limitations of two-dimensional coastal area and behaviour-oriented models, both of which are traditionally used to simulate shoreline change for informing coastal management (De Vriend et al., 1993; Hanson et al., 2003; Pontee, 2017; Seenath, 2022b). The shoreline morphology update in two-dimensional coastal area models typically becomes unstable in simulations longer than 10^1 years because the coastal profile gradually evolves to an erroneous shape as a result of these models not being able to account for undertow currents, which drive the evolution of coastal profiles (Franz et al., 2017). Behaviour-oriented models, on the other hand, assume the active coastal profile responds to changes in wave climate (one-line theory) or sea-level (Bruun Rule) by adjusting its form to an equilibrium shape (González et al., 1999; French et al., 2016; Pontee, 2017). This assumption stabilises the shoreline morphology

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update, allowing 10 to 100-year simulations, but prevents behaviour-oriented models from considering the various external forcings that interact with each other and influence shoreline morphology (Cooper and Pilkey, 2004; Roelvink et al., 2016; Pontee, 2017). The usefulness of hybrid models is that the one-line theory constrains the shoreline morphology update, allowing 10 to 100-year two-dimensional simulations of littoral drift, which is often the primary driver of shoreline change. However, a key issue facing the widespread application of these models is that they cannot account for depth contours that are non-parallel to the shoreline (i.e., complex morphologies), which characterise many vulnerable sandy coastal systems globally, in the shoreline morphology update (Seenath, 2022b). This issue is directly linked to the assumptions of the one-line theory, which form the basis of the shoreline morphology update in hybrid models.

The one-line theory is based on the premise that depth contours are parallel to the shoreline, therefore: (a) the shore-normal movement of one contour line is considered to be a proxy of overall coastal change; (b) the vertical limits of the active coastal profile (i.e., beach berm and closure depth) are considered to be constant in time and space (Pelnard-Considere, 1956; Hoang, 2022). In complex morphologies, wave propagation and transformation over non-parallel depth contours tend to generate considerable spatial variations in wave heights reaching the shoreline, causing some coastal segments to have a shallower closure depth than others (Eversole and Fletcher, 2003; Sabatier et al., 2004; Keshtpoor et al., 2015; Yao et al., 2019). Hybrid models may consequently fail to simulate physically realistic trends and patterns of shoreline change alongshore in these morphologies as the assumption of a spatially constant closure depth will erroneously expand or reduce the cross-shore width of the active coastal profile, as illustrated by Seenath (2022a, b). An overly deep closure depth, for example, will incorrectly push the active coastal profile further seaward, forcing the distribution of littoral drift in areas that would normally be morphologically inactive (Kristensen, 2013). As a result, overly deep closure depths in hybrid models may inaccurately reduce the volume of sediment available for distribution onshore, which can cause an overprediction (underprediction) of shoreline erosion (accretion) (De Figueiredo et al., 2020). Seenath (2022b) hypothesised that varying the closure depth alongshore in hybrid models may enable us to better incorporate the effects of non-parallel depth contours to the shoreline on the cross-shore distribution of littoral drift, and hence obtain more reliable predictions of shoreline change in complex morphologies.

Building on Seenath (2022b) recommendation, this exploratory study develops, tests, and proposes a new hybrid shoreline modelling approach for application in complex morphologies. It, therefore, addresses a very specific technical limitation of hybrid shoreline modelling, setting the foundation for the continued development and refinement of the hybrid 2D/one-line concept. In particular, this study:

(a) develops a new hybrid 2D/one-line shoreline modelling approach that accounts for alongshore variations in the closure depth.
(b) evaluates how well the new hybrid approach simulates shoreline change in a complex morphology relative to the current hybrid approach, which assumes a spatially constant closure depth alongshore. Here, the focus is on providing *proof of concept* of the new modelling approach developed by trialling its application in one coastal system, characterised by a complex morphology. Such an approach is consistent with related hybrid shoreline model development studies (e.g., Ashton et al., 2001; Kaergaard and Fredsoe, 2013; Karunarathna and Reeve, 2013; Seenath, 2022a).

Following sections introduce the test site (Section 2), methods (Section 3), and results (Section 4), and discuss the wider implications of the findings (Section 5).

2. Test site

Building on Seenath (2022b), this study continues the focus on a 4 km microtidal (mean tide range = 0.34 m) sandy coastal system in Puerto Rico (Fig. 1), which is characterised by a complex morphology in response to fringing reefs. There are two reasons for the continued focus on this site. *Primarily*, the coastal geomorphology of the site presents a significant challenge for hybrid models. The non-parallel depth contours to the shoreline and irregular spatial distribution of reef substrate at the site (Fig. 1) mean that the closure depth here varies alongshore (Eversole and Fletcher, 2003), violating the one-line theory assumptions that drive the shoreline morphology update in hybrid models. Therefore, if the new hybrid approach presented in this paper improves the accuracy of shoreline change predictions at this location, we can be confident that it would be appropriate for application in other complex morphologies. *Secondly*, there is extensive high-resolution coastal data available for the site (NDBC, 2017; NOAA, 2017; NCEI, 2019; NOAA, 2019), which is an essential requirement for model development, testing, and any subsequent application.

3. Data and methods

3.1. Data and study period

The simulations of shoreline change, which underpin this study, are driven by high-resolution open-access topo-bathymetry and coastal processes data available for the test site. The temporal coverage of all data obtained spans from 01.10.2014 to 31.03.2016. This micro timescale period is sufficient for addressing the aims of this study because if a shoreline model fails to replicate or predict realistic trends and patterns of shoreline change over such small timescales, the errors introduced will propagate and generate uncertain predictions over longer timescales (Seenath, 2022b). Also, alongshore patterns of shoreline change over timescales of concern in coastal management (i.e., 10 to 100 years) are influenced by various local forcings (e.g., waves, intertidal morphology, and sedimentology) that operate over micro timescales (Cattaneoand Steel, 2003; Cooper and Pilkey, 2004; Zeinali et al., 2021). In addition, shoreline change at the test site generally shows a seasonal pattern of accretion and erosion in response to storm waves associated with the Atlantic Hurricane Season, which runs from June to November annually (Morelock and Barreto-Orta, 2003). Evaluating the capability of a shoreline model to provide realistic micro timescale predictions is, therefore, important for identifying and addressing its limitations before applying it over longer timescales and larger spatial domains (Seenath, 2022a).

A 2014 and 2016 Digital Elevation Model (DEM) of the test site are obtained from the National Oceanic and Atmospheric Administration (NOAA), each with a spatial resolution of 3 m, vertically referenced to Mean High Water (MHW) in metres, and horizontally referenced to WGS84 in metres (NCEI, 2019; NOAA, 2019). The 2014 DEM provides the initial observed conditions (i.e., topo-bathymetry, active coastal profile, closure depth, and beach berm) for simulating shoreline change, and the MHW line in this DEM is considered to be the initial shoreline. The MHW line in the 2016 DEM provides the ground truth data (i.e., final observed shoreline) for quantifying the accuracy of shoreline change predictions.

A 2014 to 2016 time series of tide (NOAA, 2017), wind (NOAA, 2017), and wave climate (NDBC, 2017) data for the test site are also obtained. These provide the primary boundary conditions and forcings for simulating shoreline change. The tide data are in 6-min intervals and vertically referenced to MHW in metres. The wind data (wind speed (m/s) and direction (deg.)) are also in 6-min intervals. The wave climate data (wave height (m), period (s), and direction (deg.)) are in 60-min intervals.

A 2013 orthophoto (spatial resolution = 0.1 m) of the test site is used to obtain locational data on all hard defence structures present at the

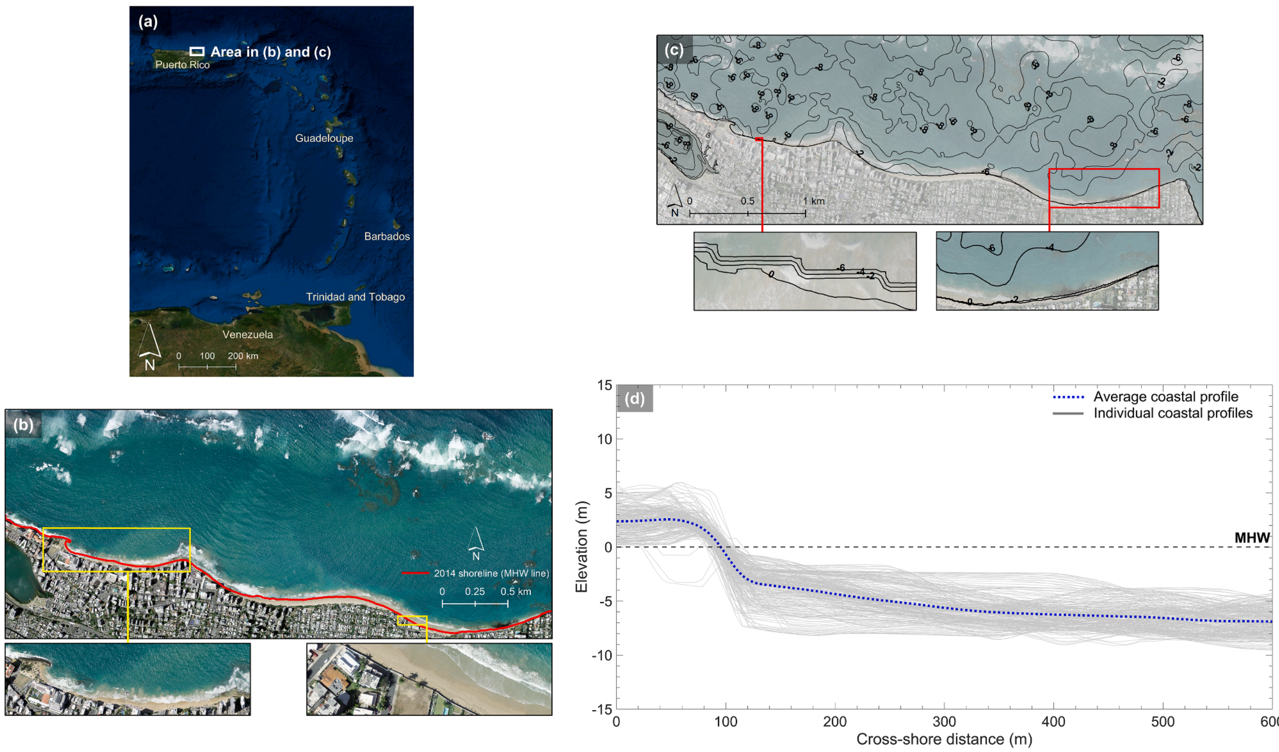

Fig. 1. Test site in Puerto Rico (adapted from Seenath (2022b)). (a) Location. (b) 2013 orthophoto of the site. (c) Contour map showing a complex morphology (non-parallel depth contours to the shoreline) in the nearshore. (d) 2014 coastal profile envelope and average coastal profile. *Credits*: DigitalGlobe (satellite image in a) and USGS (orthophoto in b).

site. Elevation data on these structures are obtained from the 2014 DEM. These datasets are subsequently used to digitise, discretise, and represent the hard structures at the test site in the computational domain used for simulating shoreline change.

3.2. Model selection

This study departs from Seenath (2022b) hybrid shoreline modelling study, which was carried out using MIKE21. For this reason, MIKE21 forms the basis of this study. Importantly, however, MIKE21 can account for: (a) complex morphologies in two-dimensional littoral drift simulations; (b) shoreline curvature, which is a characteristic feature of the test site, when updating the shoreline morphology (Kaergaard and Fredsoe, 2013). Other hybrid models possess either one of these abilities, not both (Seenath, 2022b). As a result, MIKE21 provides the most appropriate basis for developing the hybrid approach further to handle complex

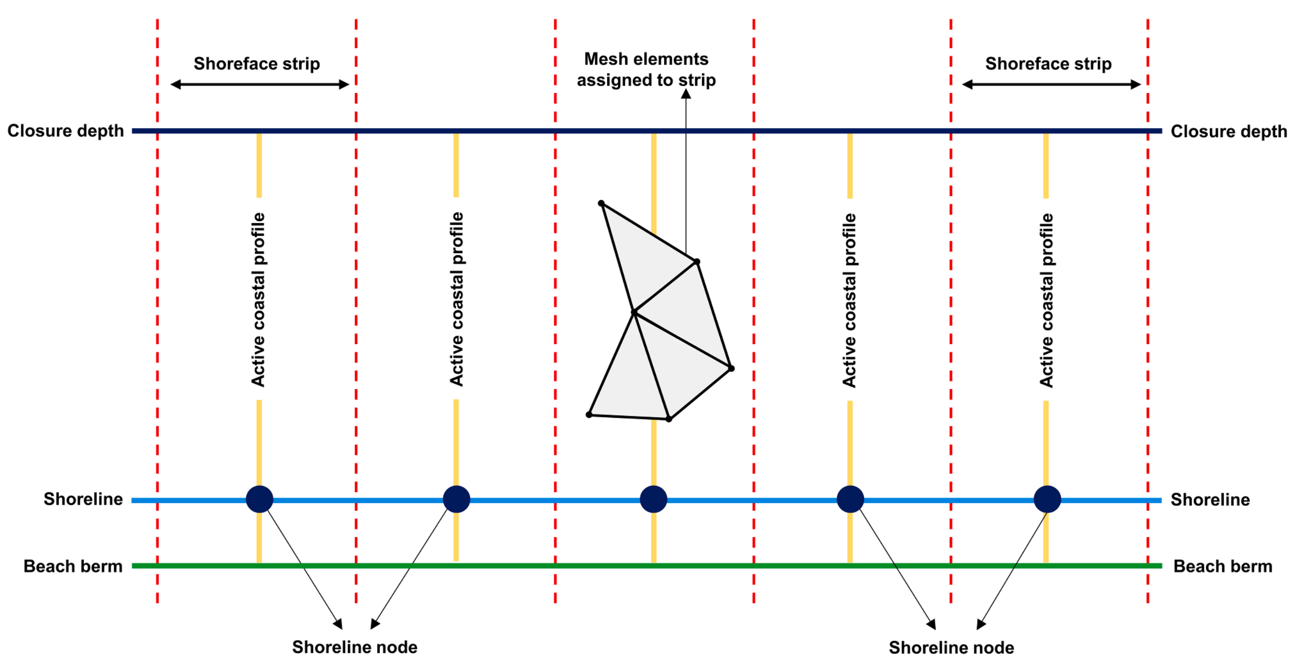

Fig. 2. Schematic diagram of the structure of MIKE21 SM computational domain.

morphologies when updating the shoreline morphology.

3.3. Model description

MIKE21 combines a two-dimensional wave, flow, and sediment transport model with a one-line shoreline model by coupling four modules: Spectral Wave (MIKE21 SW), Hydrodynamic (MIKE21 HD), Sand Transport (MIKE21 ST), and Shoreline Morphology (MIKE21 SM). Each of these modules are well-documented by DHI (2017). However, a brief description of MIKE21 SM is given below as this study primarily focuses on developing this module to enable alongshore variations in the closure depth.

MIKE21 SM is a one-line shoreline model that uses the littoral drift gradients derived from the coupling of MIKE21 SW, HD, and ST to simulate shoreline change based on the one-line theory. It divides the shoreface into shore-perpendicular strips (Fig. 2). In each strip, MIKE21 SM integrates the change in sediment volume (*vol*) with a predefined active coastal profile to calculate the change in shoreline position at each time step in a simulation (Δt) using a modified version of the one-line theory equation:

$$\frac{\Delta N}{\Delta t} = \frac{vol}{dA_z} \tag{1}$$

where ΔN is the horizontal distance over which the shoreline moves perpendicular to its orientation, and dA_z is the vertical area of the active coastal profile in each shoreface strip over which *vol* is uniformly distributed. The active coastal profile moves shore-normal in response to sediment redistribution. The change in *vol* at Δt is determined from the littoral drift gradients.

More specifically, MIKE21 SM assigns elements in the computational mesh used for littoral drift simulations (see Section 3.4 for details of the computational mesh) to a shoreface strip, as illustrated in Fig. 2. The change in sediment volume in each mesh element located between the beach berm and closure depth in a shoreface strip is totalled to work out the sediment volume available for cross-shore distribution in that strip. If mesh elements overlap strips, MIKE21 SM uses piecewise constant interpolation to map sediment transport gradients onto strips. The total sediment volume calculated for a shoreface strip then becomes uniformly distributed over the active coastal profile in that strip. If the active coastal profile in a shoreface strip gains sediment, the profile in that strip accretes and moves seaward together with the shoreline node (position) in the strip. The reverse happens if the active coastal profile in a shoreface strip loses sediment (i.e., the profile erodes and moves landward). Fig. 2 provides a schematic diagram of MIKE21 SM computational domain.

3.4. Computational mesh

The simulations of shoreline change, which underpin this study, are carried out using the MIKE21 finite volume mesh generated and calibrated by Seenath (2022b) for the test site selected (Fig. 3). The mesh dimensions are 4 km alongshore and 3 km cross-shore. It extends from ~5 m above MHW to ~50 m below MHW, covering the full spatial extent of the fringing reef network. The offshore boundary is considerably deep, enabling the propagation and transformation of waves over the reefs and wave approach to the shoreline. The highest tide level on record at the test site is less than 1 m above MHW (NOAA, 2017), which means that the land boundary is also adequately high in elevation to prevent the entire computational domain from flooding and causing spurious predictions of littoral drift and shoreline change. The mesh is split into two zones, nearshore and offshore, both separated by the offshore boundary of the fringing reef network. The maximum element area is 2025 m^2 (45 m resolution) in the nearshore, and 4900 m^2 (70 m resolution) in the offshore. These resolutions correspond to the spatial

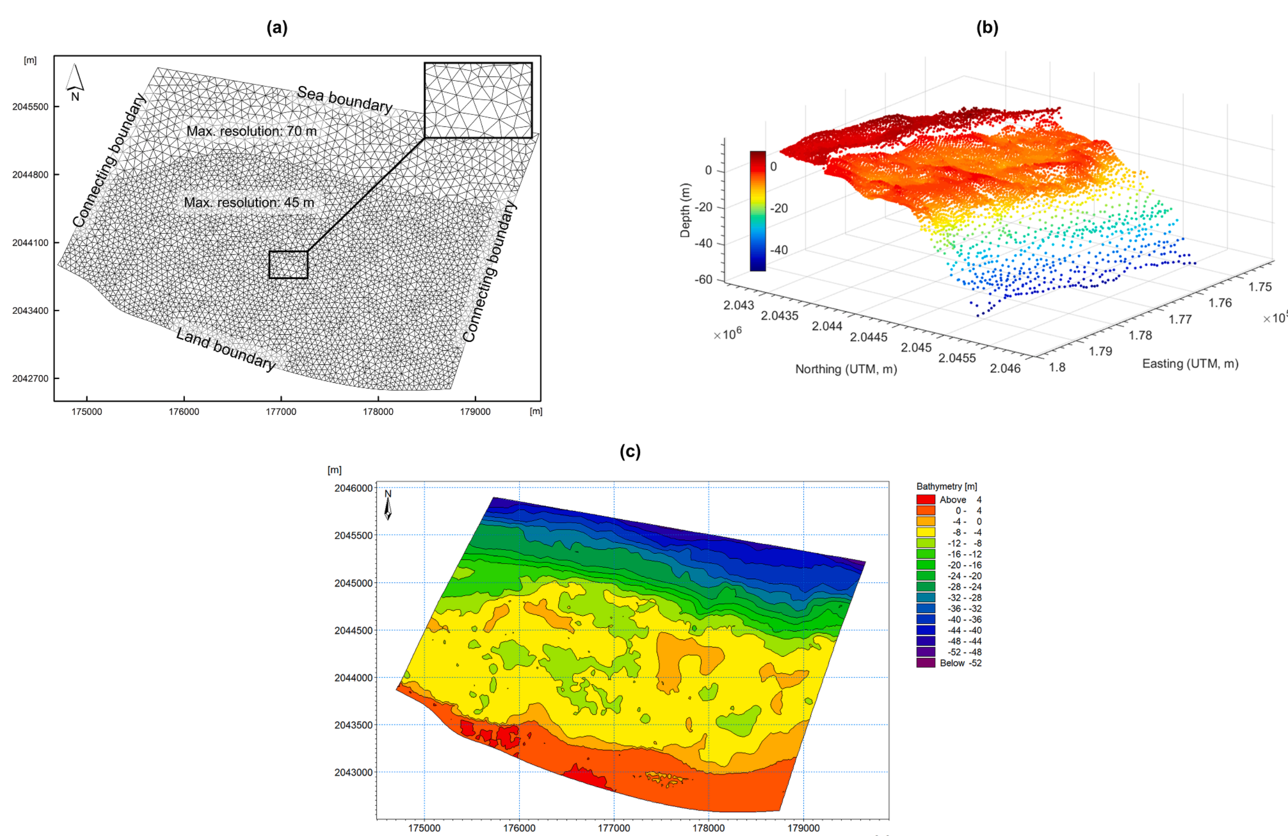

Fig. 3. Computational mesh for the 2D coupled wave, flow and sediment transport simulations. (a) Finite volume mesh generated and calibrated by Seenath (2022b). (b) Mesh nodes interpolated with the 2014 DEM. (c) 2D plan view of the interpolated mesh.

scales over which primary drivers of shoreline evolution (e.g., waves and tides) operate (Stive et al., 2002). Altogether, the mesh has 7071 triangular elements and a land, sea, and two connecting boundaries (Fig. 3). The 2014 DEM obtained is interpolated onto the mesh using the natural neighbour approach to generate the initial mesh topo-bathymetry for simulating shoreline change (Fig. 3).

3.5. *Model parameterisation and calibration*

Following an extensive stepwise calibration against nearshore discretisation, sediment properties, bed friction, and the weir coefficient of hard defences, Seenath (2022b) established an optimal parameterised MIKE21 model for the test site selected (Table 1). Therefore, the same calibrated MIKE21 model is used in this study as the basis for developing the new hybrid approach. Please see Seenath (2022b) for details of the calibration process, and Table 2 for a summary of the results.

3.6. *Enabling closure depth variations alongshore*

Using the calibrated MIKE21 model established for the test site, an iterative process that enables the closure depth to vary alongshore in the hybrid 2D/one-line shoreline modelling approach is developed, as illustrated in Fig. 4a. The iterative process developed involves successively applying a two-dimensional physics driven approach to simulate littoral drift over the entire computational mesh whilst applying the one-line theory to constrain and update the shoreline morphology in defined (smaller) coastal segments with a similar bed morphology. This iterative process only modifies the way in which the shoreline morphology is updated in the hybrid approach. Specifically, it:

(a) divides the coast into segments based on similarities in bed morphology (seven segments in this case). Here, coastal segmentation is based on the spatial distribution of shared shore-parallel depth contours to conform with the one-line theory, which drive the shoreline morphology update. Individual coastal segments defined are, hence, continuous coastal stretches with either (i) shared shore-parallel depth contours devoid of reefs, (ii) shared shore-parallel depth contours landward of reef substrate, or (iii) shared shore-parallel depth contours in areas with breaks in reef networks. Considering this, coastal segmentation here is based on a visual (qualitative) inspection of bed morphology and not an objective quantitative measure. Nonetheless, this approach enabled a generalised discretisation of the closure depth variability alongshore and is non-consequential as this is an exploratory study, designed to test whether including closure depth variations alongshore can improve the application of hybrid models in a complex morphology. The qualitative approach adopted for coastal segmentation provides an interim solution for handling alongshore variations in closure depth until we are able to allow the closure depth to vary freely over space in hybrid models. Closure depth specification in each defined segment, however, is based on established closure depth definitions. In particular, Eversole and Fletcher (2003) found that the closure depth in reef environments corresponds to the deepest point landward of the first occurrence of reef substrate. Thus, the closure depth in segments with reefs or breaks in reef networks is specified as the deepest shore-parallel depth contour landward of reef substrate in the 2014 DEM, as illustrated in Fig. 5. On the other hand, the closure depth in simple morphologies (e.g., linear sloping beaches) is considered to be the depth along the beach profile beyond which we can see no significant change in bed elevation (Kraus et al., 1998). This depth typically coincides with the most seaward depth contour that follows the shape of the shoreline (Kaergaard and Fredsoe, 2013; Seenath, 2022b). Therefore, in segments with no reef substrate, the closure depth is specified as the deepest shore-parallel depth contour that mirrors the shape of the shoreline in the 2014 DEM, as illustrated in Fig. 5. The depth contours in the 2014 DEM are used as the basis for the closure depth specification process here because this DEM provided the initial conditions for simulating shoreline change.

(b) applies the one-line theory (through MIKE21 SM) to update the shoreline morphology in each segment whilst applying a two-dimensional coupled wave, flow, and sediment transport model (MIKE21 SW, HD, and ST) to simulate littoral drift gradients over the entire computational mesh (Fig. 3). These gradients provide the main driving flux for the shoreline morphology update. Focusing the littoral drift simulations over the entire mesh whilst constraining the shoreline morphology update (MIKE21 SM) to smaller individual coastal segments ensure that the sediment volume available for cross-shore distribution in each segment are reflective of the wave-current conditions operating across the model domain. An important point to note here is that littoral drift simulations are not carried out in MIKE21 SM. These are done in MIKE21 ST over the entire computational mesh generated in Section 3.4. Here, it is also important to note that MIKE21 SM computational domain (Fig. 2) is different from MIKE21 ST

Table 1
Optimal MIKE21 specifications established for the test site (Seenath, 2022b).

Input	Specifications
General	
Time step interval (output frequency)	86,400 s (daily)
MIKE21 HD	
Boundary condition: sea boundary in mesh	Tide data
Boundary condition: connecting boundaries in	Flather (open) boundary
mesh	Varying in domain
Coriolis forcing	0.8
Courant-Friedrich-Lévy (CFL) number	Barotropic
Density	29 $m^{1/3}/s$
Manning's n reciprocal*	30 s
Maximum time step	0.01 s
Minimum time step	0 $m^3/s/m$
Overtopping discharge	0.28
Smagorinsky coefficient (eddy viscosity)	Internally transfers from MIKE21
Wave radiation stresses	SW
Weir coefficient*	0.55 $m^{1/2}/s$
Wind forcing	Wind speed and direction data
Wind friction (varies based on wind speed)	0.001255 to 0.002425
MIKE21 ST	
Boundary condition: sea boundary in mesh	Zero-sediment flux gradient
Boundary condition: connecting boundaries in	Zero-sediment flux gradient
mesh	0.05
Critical Shields parameter	1.1
Grading coefficient*	0.25 mm
Grain diameter*	Internally transfers from MIKE21
Flow/wave forcing	SW
Maximum bed level change	10 m/day
Porosity*	0.3
Relative sand density	2.65
Time step factor	1
MIKE21 SW	
Boundary condition: sea boundary in mesh	Wave climate data
Boundary condition: connecting boundaries in	Lateral (open) boundary
mesh	Internally transfers from MIKE21
Current conditions (speed and direction)	HD
Maximum number of iterations	500
Nikuradse roughness	0.04 m
Reflection coefficient (structures)	0.5 (cross-shore structures)
	1 (longshore structures)
Spectral discretisation	360 ° rose
Water level conditions	Internally transfers from MIKE21
	HD
MIKE21 SM	
Berm height	1.5 m
Closure depth	5.5 m
Maximum number of iterations	500
Sediment transport gradients	Internally transfers from MIKE21
	ST

* *Calibrated parameter.*

Table 2
MIKE21 calibration results (01.10.2014 to 31.03.2016) for the test site (Seenath, 2022b). Bold values = model default values. *BSS* = Brier Skill Score.

Input	Units	Established range	Calibration variations	*BSS*	Optimal value
Nearshore discretisation	m	N/A	25	−0.05	45
			30	−0.06	
			35	−0.05	
			40	−0.05	
			45	−0.02	
			50	−0.08	
			55	−0.09	
			60	−0.14	
			65	−0.12	
Manning's *n* (Sandy beaches)	$m^{1/3}/s$	reciprocals: 28 – 50	29	0	29
			32	−0.02	
			33	−0.02	
			40	−0.06	
			50	−0.12	
Sand grain diameter	mm	0.0625 – 0.125 (very fine)	0.1	−9.85	0.25
		0.0125 – 0.25 (fine)	**0.2**	0.01	
		0.25 – 0.5 (medium)	0.25	0.03	
		0.5 – 1 (coarse)	0.5	0.03	
		1 – 2 (very coarse)	1	0.01	
Sand porosity	N/A	0.3 – 0.7	0.3	0.01	0.3
			0.4	0	
			0.5	−0.01	
			0.7	−0.19	
Sediment grading coefficient	N/A	< 1.27 (very well sorted)	**1.1**	0.03	1.1
		1.27 – 1.4 (well sorted)	1.3	−0.02	
		1.41 – 1.99 (moderately sorted)	1.5	−0.17	
		2 – 3.99 (poorly sorted)	2	−55.01	
		4 – 15.99 (very poorly sorted)			
		≥ 16 (extremely poorly sorted)			
Weir coefficient	$m^{1/2}/s$	0.11 – 0.27 (lateral structure)	0.11	0.02	0.55
		0.3 – 1.71 (broad crested structure)	0.55	0.03	
		1.77 – 2.26 (ogee crested structure)	0.77	0.03	
		1.71 – 1.82 (sharp crested structure)	0.99	0.03	
			1.21	0.03	
			1.44	0.03	
			1.82	0.03	
			1.838	0.03	
			2.21	0.02	

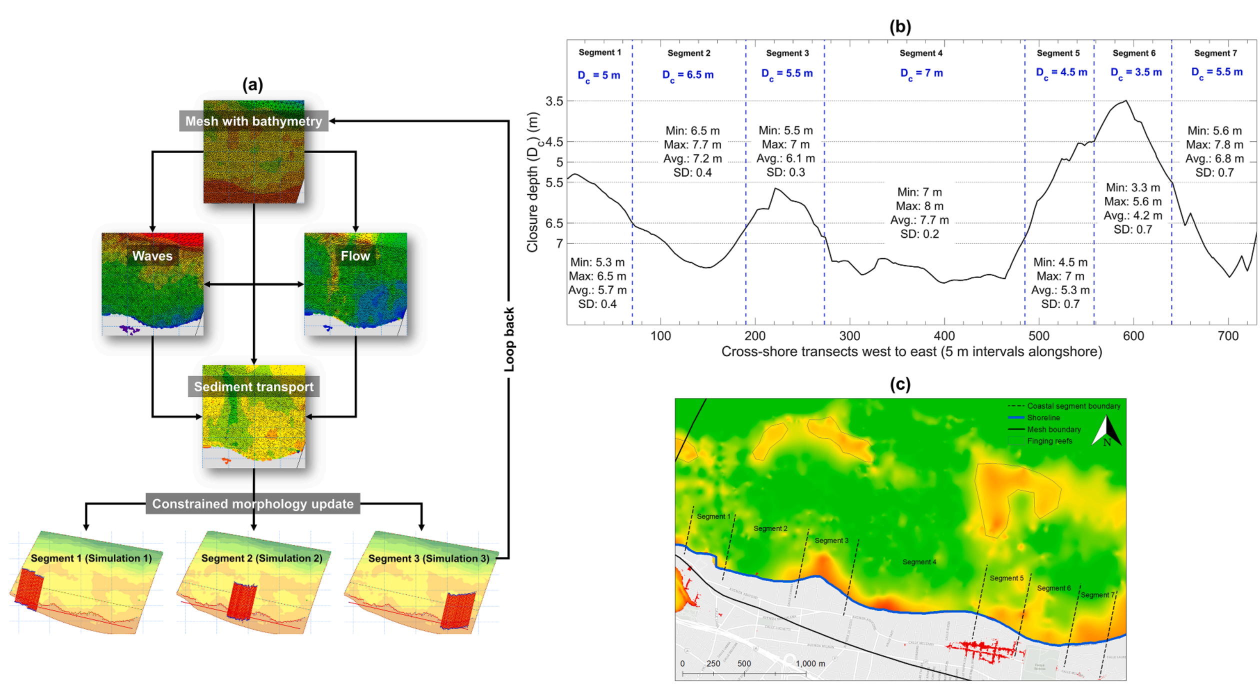

Fig. 4. New hybrid approach proposed for handling alongshore variations in closure depth. (a) Schematic illustration of the new hybrid approach. (b) Coastal segments and associated closure depths (D_c) defined for applying (a) in the test site. (c) 2D plan view of the coastal segments used for applying (a) in the test site. The black line in (b) indicates observed closure depths, which are based on the topo-bathymetry in the 2014 DEM. Blue values in (b) are the closure depth specifications applied in the new hybrid approach. Statistics in (b) summarise the observed closure depth variability at the test site. SD = standard deviation.

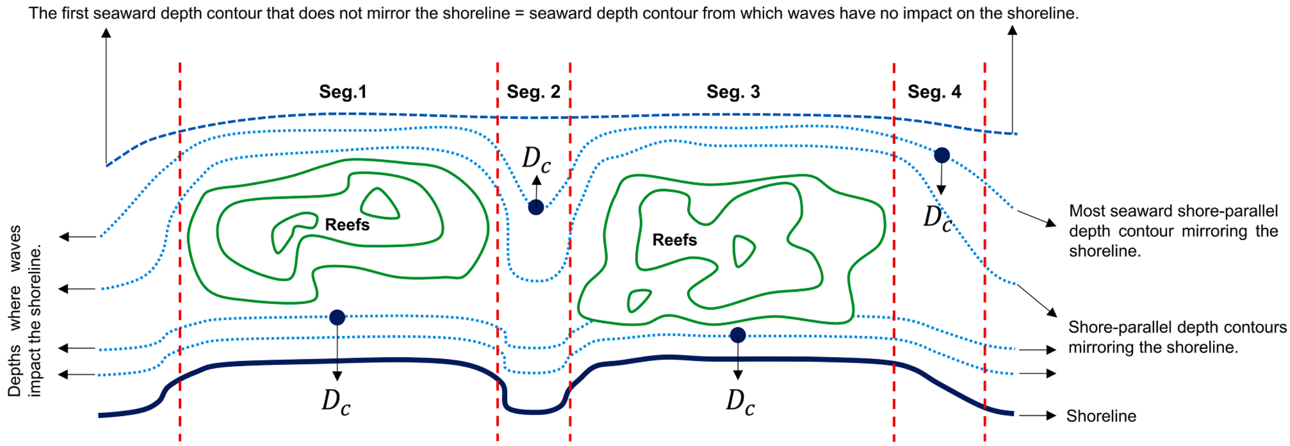

Fig. 5. Schematic diagram of the coastal segmentation and closure depth specification process used to develop the new hybrid approach. D_c = closure depth.

computational domain (Fig. 3). MIKE21 ST estimates the volume of littoral drift at each time step in the simulation for each element in its computational mesh. In MIKE21 SM, the total sediment volume used to update the shoreline morphology in a defined coastal segment is calculated by adding up the change in sediment volume in each mesh element that lies between the beach berm and closure depth in the shoreface strips in that segment. Recall that: (i) MIKE21 SM divides the shoreface within its computational domain into shore-perpendicular strips, as illustrated in Fig. 2; (ii) the change in sediment volume in each mesh element is determined from the littoral drift gradients in MIKE21 ST; (iii) MIKE21 SM uses piecewise constant interpolation to map littoral drift gradients onto shoreface strips if there is an overlap in mesh elements between strips. Essentially, MIKE21 ST generates a map of littoral drift gradients for the entire study area. MIKE21 SM then uses this map to extract and add up the sediment volume data for the active coastal profile (i.e., area from the beach berm to closure depth) in each shoreface strip in a coastal segment to update the shoreline morphology in that segment.

(c) pieces together the calculations of shoreline change from each coastal segment to map shoreline change alongshore.

The computational structure of the above process forces the hybrid approach within MIKE21 to update the shoreline position iteratively over irregular spatial intervals (also referred herein as coastal segments), with each spatial interval (coastal segment) having a different closure depth specified based on their associated (underlying) bed morphology. The iterative process developed, therefore, enables the offshore limit and cross-shore extent (width) of the active coastal profile to vary alongshore as we would expect to see in complex morphologies. The closure depth defines the seaward limit and, together with the beach berm, the cross-shore width of the active coastal profile. Here, it is important to remember that this is an exploratory study designed to gauge whether alongshore variations in the closure depth can improve the application of hybrid models in a complex morphology. As this is an exploratory study, further experiments with different levels of coastal segmentation (i.e., increasing and decreasing the number of coastal segments) are not considered. Such extensive experimentation of model development and testing is beyond the scope of this short communication paper.

3.7. Model simulations

Two hindcast simulations of shoreline change are carried out in the test site from 01.10.2014 to 31.03.2016, one applying the current hybrid approach and the other applying the new hybrid approach, as outlined below. The results from these simulations are used to test whether enabling an alongshore variable closure depth in hybrid models can improve their application in complex morphologies.

In the first simulation, the current hybrid approach, which assumes a spatially constant closure depth based on the one-line theory, is applied. This simulation is carried out using the interpolated mesh from Section 3.4 (Fig. 3) and specifications in Table 1. A noteworthy specification here is that a spatially constant closure depth of 5.5 m (relative to MHW) is forced in the model to conform with the one-line theory assumptions that underpin the current hybrid approach. While it is acknowledged that 5.5 m grossly overgeneralises the closure depth in the test site (Fig. 4b), the 5.5 m depth contour in the interpolated mesh is the deepest shore-parallel depth contour that is landward of the fringing reefs. As the current hybrid approach assumes shore-parallel depth contours when updating the shoreline morphology, specifying a closure depth deeper than 5.5 m would cause considerable errors in the corresponding shoreline continuity solutions (see Seenath (2022b)). The results of this simulation will, therefore, demonstrate how well we can apply the current hybrid approach in a complex morphology.

In the second simulation, the new hybrid approach developed, which simulates shoreline change iteratively over irregular spatial intervals to account for alongshore variations in the closure depth (Fig. 4a), is applied. This simulation involves seven iterative hindcasts of shoreline change (Fig. 4b; 4c). In each iterative hindcast, MIKE21 SM (i.e., the one-line model, which updates the shoreline morphology) is applied to a different coastal segment and the closure depth is modified based on the underlying bed morphology (Fig. 4). All other inputs are the same as those specified in the first simulation.

3.8. Model validation

702 cross-shore transects, spaced every 5 m alongshore, are used to quantify observations and predictions of shoreline change. The results obtained are subsequently used to calculate the Brier Skill Score (Brier, 1950) in order to estimate the accuracy of shoreline change predictions:

$$BSS = 1 - \frac{\sum (Sh_{obs} - Sh_{pred})^2}{\sum (Sh_{obs} - Sh_{init})^2} \quad (2)$$

where Sh_{init} is the shoreline position observed at the start of the simulation (i.e., the MHW line in the 2014 DEM), Sh_{pred} is the shoreline position predicted at the end of the simulation, and Sh_{obs} is the shoreline position observed at the end of the simulation (i.e., the MHW line in the 2016 DEM). The BSS ranges from -∞ to 1, with 1 indicating a perfect agreement between Sh_{obs} and Sh_{pred}, 0 indicating Sh_{pred} is closer to Sh_{init}, and a score < 0 indicating Sh_{pred} is further away from Sh_{obs}. Sutherland et al. (2004) BSS classification, which classifies a score of 1 to 0.5 as excellent, 0.5 to 0.2 as good, 0.2 to 0.1 as reasonable, 0.1 to 0 as poor, and ≤ 0 as bad, is used to interpret all *BSS* estimations.

4. Results

The results confirm that the current hybrid approach, which assumes a spatially constant closure depth, is not appropriate for application in complex morphologies (Fig. 6). This is evident from the poor fit ($BSS = 0$) between predictions of shoreline change from the first simulation (spatially constant closure depth) and associated observations (Fig. 6a and c). A $BSS = 0$ implies that the model is replicating initial conditions, which we can see from the first simulation predicting negligible shoreline change alongshore (range = −4 to 5.7 m; mean net change = 0.11 m; standard deviation = 1.17) relative to associated observations (range = −11.26 to 16.23 m; mean net change = 3.22 m; standard deviation = 5.7). There is also no discernible agreement between the alongshore variations (trends and directions) in shoreline change predictions from the first simulation and corresponding observations (Fig. 6a), which is further reflected by a Spearman's rank correlation coefficient (r_s) = 0. The poor results from the first simulation are a clear indication that the current hybrid approach, applied through MIKE21, cannot resolve the underlying physics of shoreline change at the test site despite being extensively calibrated (Table 2).

There is a better fit ($BSS = 0.4$) between predictions and associated observations of shoreline change following the application of the new hybrid approach (second simulation) (Fig. 6b and c), which accounts for alongshore variations in the closure depth. A $BSS = 0.4$ indicates that predictions of shoreline change generally move in the same direction as associated observations. This is evident from the new hybrid approach predicting net accretion and higher accretion magnitudes alongshore (39% erosion; 61% accretion; range = −8.76 to 13.27 m; mean net change = 0.91 m; standard deviation = 3.63) in line with associated observations (31% erosion; 69% accretion; range = −11.26 to 16.23 m; mean net change = 3.22 m; standard deviation = 5.7). These similarities are also captured by a Spearman's rank correlation test, which shows a moderate positive relationship ($r_s = 0.6$; $p < 0.0001$) between shoreline change predictions from the second simulation and associated observations. However, there is a stronger positive relationship between these predictions and observations ($r_s = 0.8$; $p < 0.0001$) towards the west of the test site from transects one to 350 compared to the east from transects 351 to 700 ($r_s = 0.5$; $p < 0.0001$). The weaker correlation in the east follows a clear underprediction of shoreline change in the eastern part of coastal segment four and across coastal segments five and six (Fig. 6b), which correspond to these segments having the largest observed closure depth variability and most generalised (shallow) closure depth specifications (Fig. 4b).

Overall, accounting for alongshore variations in the closure depth has considerably improved shoreline change predictions in the test site, which is defined by a complex morphology (Fig. 6). A two-sample Kolmogorov-Smirnov test further shows that the shoreline predictions derived from applying a spatially constant closure depth (first simulation) and an alongshore variable closure depth (second simulation) are significantly different ($p < 0.0001$) at all conventional levels of significance (0.01, 0.05, and 0.1).

5. Discussion

The results indicate that the current hybrid approach, which is limited to studying shoreline change in simple morphologies (i.e., linear sloping coastal systems with shore-parallel depth contours), can be extended to complex morphologies, where coastal profiles are non-linear. The one-line theory, which drives the shoreline continuity solutions in hybrid models, assumes the active coastal profile adjusts its form to a constant shape in response to wave action and associated cross-shore distribution of littoral drift. As per the one-line theory, the active coastal profile (together with the shoreline) retreats when the wave energy flux exceeds the equilibrium energy flux. However, the evolution of coastal profiles (and shorelines) is a much more complex three-dimensional process, mainly driven by vertical variations in undertow currents (Franz et al., 2017). Hybrid models do not account for these currents in their present form as they assume a constant time-averaged (equilibrium) active coastal profile with fixed vertical limits in line with the one-line theory. Although this assumption appears to be valid for simulating shoreline change in simple morphologies

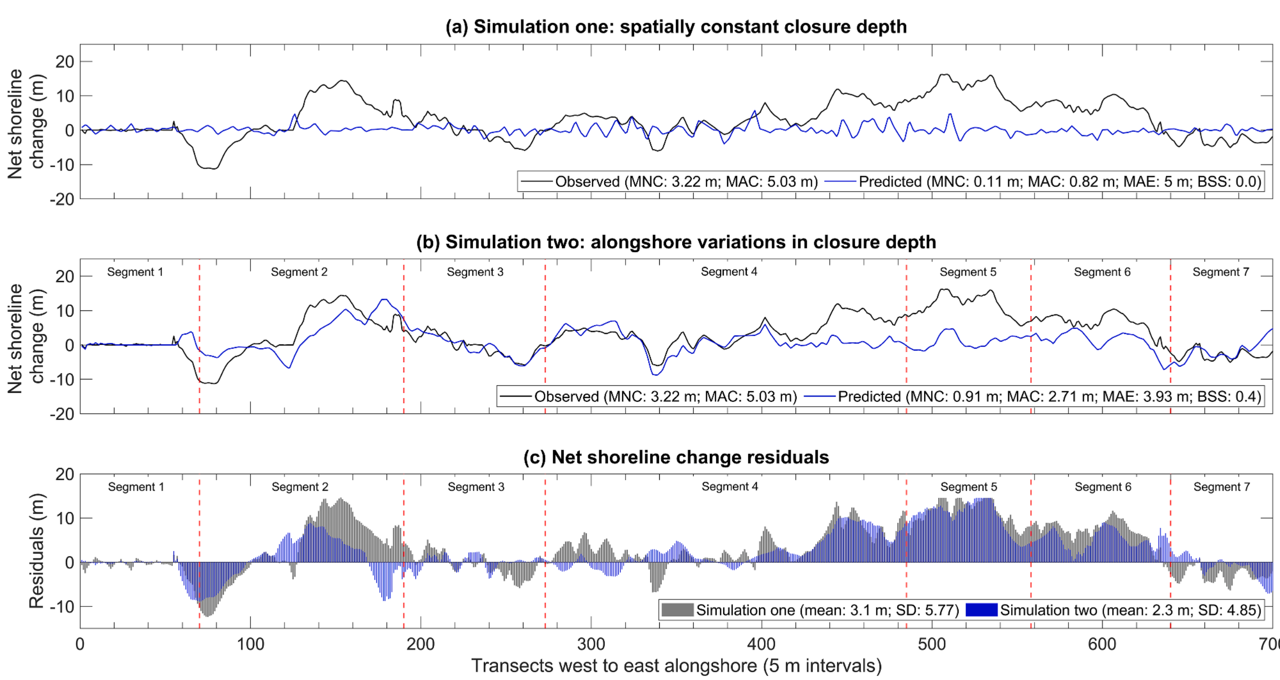

Fig. 6. Shoreline change observations and predictions (01.10.2014 – 31.03.2016) derived from applying the current hybrid approach (a) and the new hybrid approach (b). (c) shows the shoreline change residuals (*observed shoreline change – – predicted shoreline change*) from the current and new hybrid approach. MNC = mean net change, MAC = mean absolute change, MAE = mean absolute error, and BSS = Brier Skill Score.

(Ashton and Murray, 2006; Kaergaard and Fredsoe, 2013; Hurst et al., 2015), it is not appropriate for application in complex morphologies where the active coastal profile varies in form alongshore (see Fig. 6a). In these morphologies, wave propagation and transformation over non-parallel depth contours generates considerable spatial variability in the nearshore wave climate, which cause variations in the strength of undertow currents alongshore and associated depth limit of significant cross-sediment transport (Mariño-Tapia et al., 2007; Zhang et al., 2012; Franz et al., 2017). An end-result of this is considerable variability in the seaward depth limit (and consequently the cross-shore width) of the active coastal profile alongshore, which affect wave run-up and energy dissipation (both of which affects the bed morphology), influencing the alongshore patterns of shoreline change that we see in complex morphologies (Eversole and Fletcher, 2003; Risandi et al., 2020). The promising results from the new hybrid approach developed indicate that we can effectively mirror these three-dimensional alongshore variations in the active coastal profile within hybrid models by allowing the closure depth (and therefore the cross-shore width) of the equilibrium coastal profile to vary in response to variations in bed morphology alongshore. Doing so enables us to:

(a) account for the three-dimensionality of coastal profile evolution in response to alongshore variations in wave climate whilst maintaining the one-line theory principles. These principles stabilise the shoreline morphology update over timescales of concern in coastal management.
(b) better account for the cross-shore distribution of littoral drift, which ultimately improves the prediction of shoreline change alongshore (see Fig. 6).

Although shoreline change predictions improved following the application of the new hybrid approach (Fig. 6), there is still a clear underprediction of shoreline change in coastal segments with closure depth underestimations, notably the eastern part of coastal segment four and across segments five and six. The closure depth and beach berm together define the active coastal profile (cross-shore extent of sediment dynamics) in hybrid models. Underestimating either or both of these reduces the volume of sediment available for cross-shore distribution and the cross-shore extent over which littoral drift is distributed (Coelho et al., 2013; Udo et al., 2020), which affect the accuracy of shoreline change predictions in hybrid models (Kristensen, 2013). To explain this, Fig. 7 shows a hypothetical active coastal profile divided into four regions, each responding differently to wave-current conditions in a hybrid model: region one is eroding, two and three are stationary (neither accreting nor eroding), and four is accreting. If we underestimate the closure depth and, consequently, fail to consider the volume of sediment change in any of these regions, we will run the risk of obtaining unreliable predictions of shoreline change. For example, specifying the closure depth at the offshore boundary of region two in Fig. 7 would reduce the cross-shore width of the active coastal profile by excluding regions three and four. The model would then define the active coastal profile as extending from regions one to two only. The end-result would be an overprediction of shoreline erosion as half of the defined active coastal profile is eroding (region one) while the other half is stable (region two). This would lead to sediment erosion over the defined active coastal profile, erroneously forcing it to move landward (Kristensen, 2013). This landward movement would be erroneous since the sediment stability and accretion trends in regions three and four would have otherwise offset the sediment loss from region one. Considering the computational framework of hybrid models as deconstructed here, it is clear that:

(a) the first simulation failed to predict observed shoreline change *primarily* because it assumed a spatially constant closure depth, which masked the alongshore variability of the active coastal profile (Figs. 4b, 6a).
(b) the second simulation provided more realistic predictions *primarily* because it accounted for the general variability of the active coastal profile alongshore (Figs. 4b, 6b).

Focusing the shoreline morphology update on smaller coastal segments in order to incorporate more variations in the closure depth alongshore may have prevented the underprediction of shoreline change from the new hybrid approach. However, constraining the shoreline morphology update to smaller coastal segments based on the new hybrid approach, in its present form, would have significantly increased the computational cost of simulating shoreline change. The two-dimensional physics-driven approach that is used to calculate littoral drift in hybrid models determines the overall computational cost of shoreline change simulations in these models. As a result, each of the seven iterative hindcasts in the second simulation (new hybrid approach) had the same computational cost as the first simulation (current hybrid approach): ~ 18 h utilising four cores on a 2.8 GHz 16 core processor CPU. The second simulation was consequently seven times more computationally demanding (~ 126 h) than the first simulation (~ 18 h). In its present form, the new hybrid approach is, therefore, not likely to be computationally sustainable and feasible over timescales of concern in coastal management (i.e., 10 to 100 years). For the new hybrid approach to be computationally sustainable, we may need to develop the hybrid approach further to automate the response of

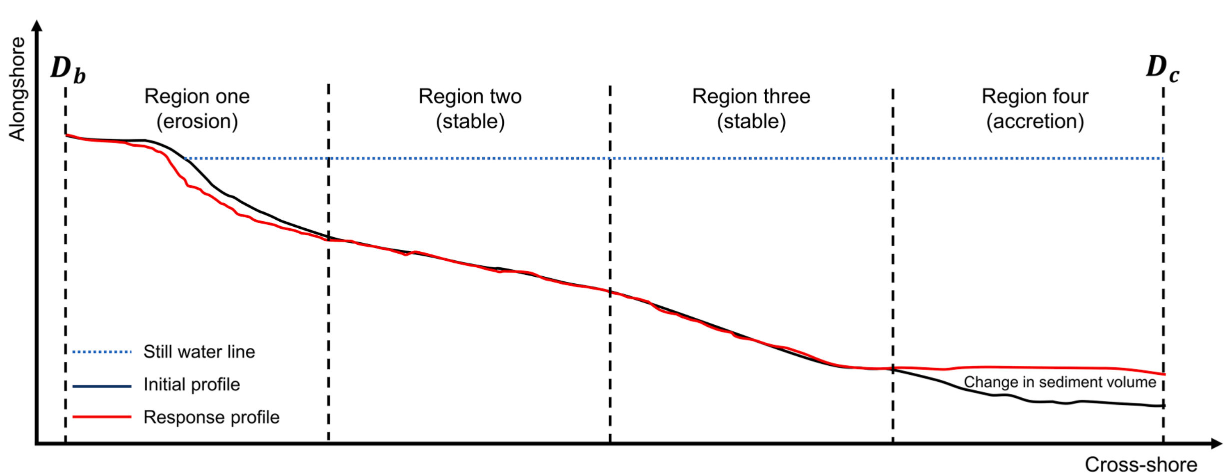

Fig. 7. Hypothetical active coastal profile (beach berm - D_b - to closure depth - D_c) divided into four evenly spaced regions. The initial and response profile represent the active coastal profile at the start and end of a littoral drift simulation, respectively.

the closure depth in the model to variations in the nearshore wave climate and bed morphology alongshore.

The coastal modelling community is still effectively in an experimental state, developing and testing new modelling approaches that can help us better study coastal systems behaviour over various time and space scales (Hoang, 2022; Seenath, 2022a). For example, Ashton et al. (2001) is one of the first studies to have successfully applied the hybrid approach over centennial timescales. Since the work of Ashton et al. (2001), the hybrid approach has been gradually developed to account for high-angle wave instabilities, drift-dominated shorelines, shoreline stabilisation schemes, and complex shoreline geometries (Ashton and Murray, 2006; Slott et al., 2010; Kaergaard and Fredsoe, 2013; Karunarathna and Reeve, 2013; Hurst et al., 2015). Most recently, the hybrid approach has been developed to account for sea-level rise (Seenath, 2022a). The results from the new hybrid approach presented in this paper can help inform the continued development of hybrid models as these are being increasingly sought after to support coastal management decisions across local to regional scales (Van Maanen et al., 2016; Payo et al., 2020). The new hybrid approach presented in this paper should also, in theory, be easily extended to any shoreline evolution model that applies the one-line theory for the shoreline morphology update, including CEM (Ashton and Murray, 2006), CoastalME (Payo et al., 2017), COVE (Hurst et al., 2015), GENESIS (Hanson, 1989), and UnaLinea (Sutherland et al., 2015). After all, enabling the new hybrid approach presented here is simply a matter of specifying alongshore variations in the closure depth and there are several qualitative indicators (e.g., point along the beach profile beyond which we see no significant change in bed elevation, most seaward depth contour following the shape of the shoreline, most seaward depth contour landward of hard substrate) and equations (see Valiente et al., 2019) available to identify the closure depth along a coast. Nevertheless, there is a clear need to determine whether an alongshore variable closure depth can improve the application of hybrid models in complex morphologies over timescales of concern in coastal management, particularly since these morphologies characterise some of the world's most vulnerable sandy coastal systems.

6. Conclusions

Using a fringing reef system in Puerto Rico as a test site, this study: (a) developed a new hybrid shoreline modelling approach that accounts for alongshore variations in the closure depth in order to handle complex morphologies; (b) tested how well this new hybrid approach performed in a complex morphology relative to the current hybrid approach, which assumes a spatially constant closure depth alongshore. The main results show that:

(a) the current hybrid approach is not suitable for application in complex morphologies, evident by a $BSS = 0$ and a $r_s = 0$ between associated shoreline change predictions and observations at the test site.
(b) the hybrid approach can be reliably extended to complex morphologies if developed to consider alongshore variations in the closure depth. This is evident from the new hybrid approach having a $BSS = 0.4$ by predicting alongshore trends and patterns of shoreline change that generally converged with those observed at the test site ($r_s = 0.6$; $p < 0.0001$).

These findings indicate that the closure depth is an important variable for modelling shoreline change in complex morphologies, aligning with the arguments of López et al. (2020). Importantly, by modifying existing hybrid models, as done here, we can capitalise on modelling advances already made whilst addressing the limitations of their application in complex morphologies. The next step is to determine the optimum resolution for representing closure depth variations alongshore and reconciling this optimum representation with the resolution of data available for sandy coastal systems globally that have a complex morphology.

CRediT authorship contribution statement

Avidesh Seenath: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization.

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.

Data availability

Data will be made available on request.

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