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Reduced-complexity modelling of the Culatra barrier island evolution

Modelización de complejidad reducida de evolución de la isla barrera de Culatra

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Abstract: Projections of long-term barrier island evolution are critical for preserving associated ecosystem services, yet they remain challenging to implement because of the computational costs and uncertainties associated with process-based modelling. Reduced-complexity models offer a practical way to simulate multidecadal morphological change by simplifying key physical processes while retaining predictive capacity. Here we test the ability of BRIE, a 2D barrier island model that incorporates longshore and cross-shore sediment fluxes and tidal inlet morphodynamics, to reproduce the elongation of Culatra island between 1958 and 2014, initiated by shifts in the tidal inlet prism balance in the Ria Formosa barrier system (S. Portugal). By imposing a gradual reduction of tidal prism in the Armona inlet and calculating the inlet aspect as the ratio of a stable inlet depth to the simulated inlet width, the model captured the evolution of barrier island elongation and inlet width reduction with very good accuracy (RMSE~200 m and Brier Skill Score~0.9). These results provide the first validation of BRIE against a real-world barrier island example, supporting its applicability over broader temporal and spatial scales.

Keywords: morphodynamics; barrier island; tidal inlet; equilibrium model; Ria Formosa.

Resumen: *Proyectar la evolución de islas barrera a largo plazo es fundamental para preservar sus servicios ecosistémicos, sin embargo, la modelización basada en procesos conlleva altos costes computacionales e incertidumbres. Los modelos de complejidad reducida ofrecen una vía práctica para simular cambios multi-decadales, simplificando procesos físicos y manteniendo la capacidad predictiva. En este trabajo evaluamos la capacidad de BRIE, un modelo 2D que incorpora flujos de sedimento litorales y transversales y la morfodinámica de canales de marea, para replicar el alargamiento de la isla de Culatra entre 1958 y 2014, iniciado por cambios en el equilibrio del prisma de marea en el sistema de Ría Formosa (sur de Portugal). Aplicando una reducción gradual del prisma de marea en la entrada de Armona y calculando su aspecto como la proporción de una profundidad estable de la entrada y la anchura simulada de la misma, el modelo capturó el alargamiento de la isla barrera y la reducción de la anchura de la entrada con muy buena precisión (RMSE~200 m y Brier Skill Score~0.9). Estos resultados proporcionan la primera validación de BRIE con un ejemplo real de islas barrera, respaldando su aplicabilidad en escalas temporales y espaciales más amplias.*

***Palabras clave**: morfodinámica; isla barrera; canal de marea; modelo de equilibrio; Ria Formosa.*

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1. Introduction

Barrier islands and the important ecosystem services they offer (e.g., coastal habitats, storm protection) are threatened by sea-level rise and deficient sand supply and could undergo rapid deterioration in the future (Vinent et al., 2021). Still, there is a critical gap in our ability to predict how these coastal landforms will respond to future conditions (Nienhuis & Lorenzo-Trueba, 2019b). Given that full-scale morphodynamic simulations over decadal to centennial timescales have significant challenges and limitations (e.g., high computational costs and uncertainties, error accumulation), an effective approach is to adopt simpler and faster numerical models —known as reduced-complexity models (RCMs)— that use simplified descriptions of fundamental system physics to

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estimate system response to forcing (Ranasinghe, 2020).

There are two main approaches in RCMs of long-term coastal morphologic change: coastline and equilibrium profile models. The former account for coastline changes due to wave-induced sediment transport. Examples are ShorelineS (Roelvink et al., 2020), that resolves processes of littoral drift, overwash, landward migration and inlet dynamics, and CoSMoS-COAST, a dynamic shoreline model with satellite-derived data assimilation (Vitousek et al., 2017). The latter resolve longshore fluxes along the coast and assess the morphological adjustment of the shoreface and cross-shore fluxes due to perturbations around the equilibrium. These include slope-driven transport (in response to the active shoreface adjustment) and overwash sediment fluxes (Lorenzo-Trueba & Ashton, 2014), tidal inlet dynamics (formation, migration, closure and tidal deposition) (Nienhuis & Ashton, 2016), and interactions between barrier, the backbarrier marsh and the lagoon (Lorenzo-Trueba & Mariotti, 2017). Several of these were integrated into BRIE (BarrieR Inlet Environment; Nienhuis & Lorenzo-Trueba (2019b)), to date the most holistic 2D barrier island RCM that incorporates overwash processes and shoreface adjustment, alongshore sediment transport, inlet dynamics and flood-delta deposition. To obtain, however, meaningful projections of barrier island adaptation to future climate, RCMs need to be tested against real-world cases, various forcing conditions and across a range of spatio-temporal scales (Nienhuis & Lorenzo-Trueba, 2019a). This work undertakes the challenge of testing the ability of BRIE to reproduce barrier island morphological changes from the Ria Formosa system over multi-decadal scales.

2. Study area

This study focuses on the eastern flank of the Ria Formosa barrier system (S. Portugal), where significant morphological changes took place in recent decades, and specifically on the stretch covering Culatra and Armona islands and the (Armona) tidal inlet separating them (Figure 1). Following its stabilization (1920s), the updrift Faro-Olhão inlet started capturing increasing portions of the tidal prism from the Armona inlet, triggering morphologic shifts (Pacheco et al., 2010). Sand began accumulating in the form of recurving spits at the islands on either side of the inlet, and primarily along the eastern edge of Culatra, resulting to island elongation and narrowing of the tidal inlet. Mapped shorelines (Figure 1) show that between 1952 and 2014 Culatra island elongated by around 3 km, while the Armona inlet narrowed from 4 to roughly 0.5 km (Kombiadou et al., 2019).

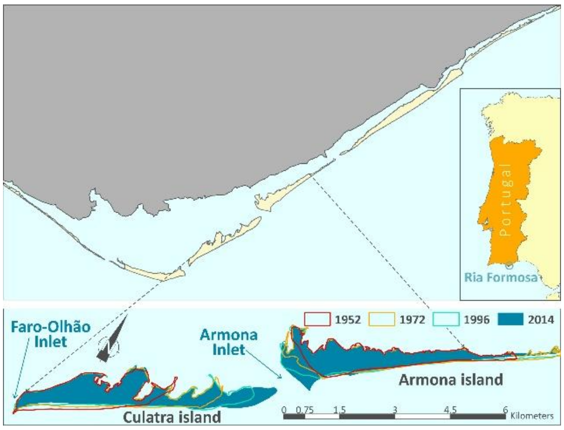

Figure 1. The Ria Formosa barrier islands (top) and the evolution of Culatra and Armona during the study period (1952-2014; bottom).

3. Methodology

BRIE assumes a uniform shoreface slope and calculates wave conditions at each step through a cumulative distribution function. Sediment fluxes and morphological changes (shoreface adjustment and position of shorelines) are then calculated from the wave characteristics at each time step. In this study we considered mean waves and tide amplitudes, however time-varying forcing conditions can be introduced. Wave climate data (average significant wave height and peak period and fractions of easterly and oblique waves) was obtained from offshore wave timeseries (Faro buoy recordings (1993 to 2025) and hindcasting results of the SIMAR (1958 to 1992) system; SIMAR (2026)). Barrier morphologies (alongshore width distribution), used for model initialisation and evaluation, were derived from oceanic and backbarrier shorelines from Kombiadou et al. (2019). Bathymetric data were obtained by historical maps.

The model domain was limited to the Armona inlet and the 2 barriers on either side (Figure 1), extending landwards to 3.5 km (backbarrier lagoon width), which is the mean distance between Culatra island and the mainland. Setting the basement slope parameter (uniform cross-shore gradient) of BRIE to 0.0015, the lagoon

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depths range from around 5 m at the backbarrier to 0 m at the mainland. Sediment median grain sizes were obtained from Costas et al. (2018).

To impose tidal inlet prism reduction within this simplified application that considers a single inlet, we increased the fraction of the lagoon area occupied by marsh (f_{marsh}), thereby decreasing the lagoon area contributing to tidal exchange with the ocean through the inlet with time. Values do not reflect actual marsh growth in the lagoon.

4. Results

The model sensitivity to the inlet aspect ratio (γ_{aspect}; depth to width) parameter values was evaluated, assuming f_{marsh} varying between 0 and 0.6 with simulation time (Figure 2). Parameter γ_{aspect} is an independent constant in the original BRIE formulation and, along with simulated width, is used to calculate inlet depth. It follows that inlet depth decreases with inlet narrowing under this approximation, however the results in Figure 2 show that simulated inlet narrowing is slower than the observations. These results indicate that γ_{aspect} is a critical tuning parameter that must vary (increase) with simulation time to capture the observed reduction in inlet width.

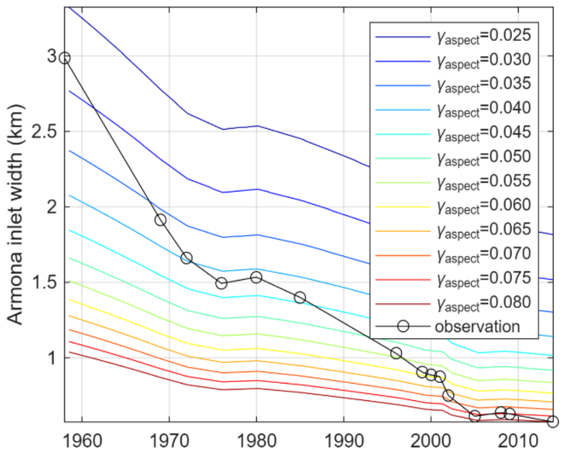

Figure 2. Evolution of observed and simulated inlet width for different values of γ_{aspect}.

To enforce this variability, the BRIE formulation was modified, calculating γ_{aspect} as the ratio of a stable inlet depth to the simulated width. The best results were obtained for an inlet depth of 2.5 m a tidal prism reduction (marsh cover increase) of 0 to 70% and are shown in Figure 3 for the Armona inlet width and the Culatra island elongation. The Root Mean Square Error (RMSE) is 182 m for the (Armona) inlet width and 173 m for the (Culatra) island length. The Brier Skill Score (BSS) exceeds 0.9, indicating excellent model performance (van Rijn et al., 2003). It is noted that the Armona island length (not shown in Figure 3; representing the rest of the domain) is simulated with similar precision.

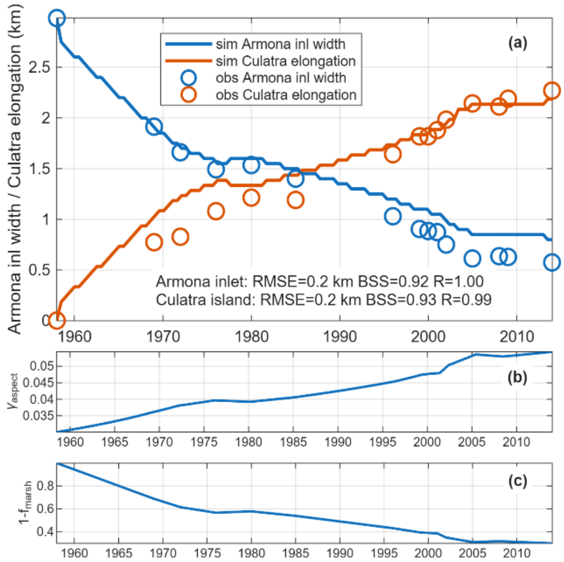

Figure 3. Simulated versus observed Armona inlet width and Culatra island elongation (a) for varying inlet aspect ratio (b; γ_{aspect}) and tidal prism reduction (c; 1-f_{marsh}) with time.

5. Discussion and Conclusions

The analysis shows that even though BRIE is an RCM that lacks explicit representation of ebb delta dynamics, it was able to reproduce the multidecadal adaptation of Culatra barrier island to the reduction of the tidal prism of the adjacent Armona inlet with good accuracy. Among the tuning parameters tested, the fraction of the backbarrier lagoon covered with marsh (f_{marsh}) was key to simulating the prism reduction and consequent narrowing of Armona inlet and elongation of Culatra island. Increasing values of the ratio of inlet depth to width (γ_{aspect}) with simulation time allowed to control the morphological adjustment of the inlet during prism reduction. By maintaining the value of the ratio constant, BRIE assumes that inlet depths and widths change in pace with each other. Sensitivity tests, however, showed that this approximation likely does not hold true for the Armona inlet, resulting to slower inlet narrowing than the observations. Setting a constant inlet depth value and calculating inlet aspect with time, allowed to accurately reproduce the morphological evolution for both the inlet undergoing tidal prism loss and the adjacent barrier islands. As the first real-world validation of BRIE to the authors' knowledge, these results are encouraging for its applicability over larger spatio-temporal scales and different barrier forcing conditions.

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