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Probabilistic Forecasting of Shoreline Evolution: A Case Study Using Genetic Algorithms

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Abstract. Sandy beach erosion is a pressing concern for coastal regions worldwide, driven by both natural processes and human-induced pressures. This study presents an ensemble modeling approach for predicting sandy shoreline dynamics using an equilibrium-based shoreline evolution model (EBSEM). A genetic algorithm (NSGA-II) was employed to calibrate multiple parameter sets, capturing the inherent uncertainty in model parameters. The method was tested with a publicly available dataset from Tairua Beach (New Zealand), spanning 14 years of high-resolution shoreline measurements. Results reveal a near-linear relationship between the slope and intercept parameters governing equilibrium wave energy, and demonstrate that the best-fit solution generally lies within the ensemble range. Comparisons of ensemble simulations with observed data indicate strong agreement in both calibration and validation phases, although certain extreme accretion and erosion events were underestimated. Overall, this ensemble framework provides a robust tool for medium- to long-term shoreline predictions, bringing coastal managers with stochastic/probabilistic estimates of shoreline change, which can be useful in the assessment of resilience of adaptive strategies for risk mitigation.

Keywords: Shoreline modeling · Coastal Morphodynamics · Cross-shore · Equilibrium Models

1 Introduction

Sandy beach erosion is a critical issue impacting coastal regions worldwide, driven by both natural processes and human activities. The dynamic nature of sandy shorelines—characterized by continuous sediment transport and changing geomorphology—poses significant challenges for coastal management and protection. Anticipating sandy beach erosion is crucial for understanding the complex, interacting processes and for planning effective strategies that mitigate impacts on coastal infrastructure, ecosystems, and human populations.

One of the essential tools for studying sandy beach erosion is shoreline modeling. Shoreline models aim to capture the interrelation among hydrodynamics (waves, currents, sea levels) and sediment transport, enabling researchers and practitioners to predict

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shoreline change under various environmental conditions. Equilibrium-based shoreline evolution models (EBSEM) are particularly significant for studying medium-to-long-term shoreline changes. These models assume that the shoreline seeks an equilibrium state under specific wave and sea-level conditions. They require low computational effort and effectively capture the shoreline's response to both gradual changes and episodic events, making them valuable for mid-to-short-term predictions [1].

Although these models are built on morphological concepts, they are highly dependent on calibration and have inherent uncertainty in their parameters, potentially leading to multiple valid solutions [2]. Given the versatility and simplicity of EBSEM, modeling the shoreline as ensembles can provide predictions based on the probability of shoreline position, thereby increasing confidence in these types of models. In this study, an ensemble technique is developed by using different sets of parameters for an EBSEM obtained via a genetic algorithm search.

2 Methods

To demonstrate the method's development, the Yates et al. (2009) [3] model is used. This model is widely referenced in the literature and is based on the concept that the incident wave energy influences the shoreline position. Specifically, it is assumed that for every possible shoreline position, there exists an incident wave energy at which no shoreline change occurs. This is termed the equilibrium wave energy. If the incident wave energy exceeds or falls below the equilibrium value, the beach will undergo erosion or accretion, respectively. The model's formulation is given by Eq. 1.

$$\frac{dY}{dt} = C^{+/-}E^{1/2}\left(E - E_{eq}\right) \tag{1}$$

where Y is the shoreline position, t is time, C^{+} and C^{-} are the accretion and erosion rates, E is the incident waves energy and $E_{eq} = aY + b$ is the equilibrium wave energy.

Since the equilibrium wave energy is assumed to have a linear relationship with the shoreline position, the model includes C^{+}, C^{-}, a and b as free calibration parameters.

Calibrating EBSEM typically relies on brute-force methods, optimization algorithms, or data assimilation approaches. In this study, the Non-dominated Sorting Genetic Algorithm (NSGA-II) [4] is used. The choice of NSGA-II is based on two key advantages. First, it is a multi-objective algorithm, meaning it can optimize more than one loss function simultaneously—an important feature when multiple statistical metrics are considered in the calibration process. Second, NSGA-II is designed to explore different parameter sets across the Pareto-optimal front, the region of the search space where no loss function can be improved without degrading another.

During the optimization process, the algorithm may also find solutions near the Pareto-optimal front. These can be considered valid solutions if they offer better metrics in future projections not captured in the optimization period. Consequently, all parameter sets with satisfactorily high metrics are considered possible solutions for the model. In this study, NSGA-II was applied to optimize four loss functions based on the following metrics: Kling-Gupta Efficiency (*KGE*), Mielke Skill Score (λ), Nash-Sutcliffe

Efficiency (*NS*) and Relative Root Mean Squared Error (*RSR*). Specifically, parameter sets were considered acceptable if $KGE > 0.5$, $\lambda > 0.5$, $NS > 0.25$, and $RSR < 1$.

To initiate the methodology, the parameter search space was defined. First, an initial run with a wide parameter range was conducted, using a population of 3000 individuals for 100 generations, repeated 1000 times—totaling 3×10^8 simulations. After that, the search space is refined, and the same number of simulations is repeated to obtain the ensemble of parameter sets.

2.1 Study Case and Data

As a pilot case for this method, publicly available data from Tairua Beach, provided by the University of Auckland, were used. The dataset contains time series of shoreline positions and wave forcing. The shoreline data were collected through a video-camera system that averaged one measurement every 16 h from 1999 to 2013. These measurements provide a high-resolution record of shoreline position; however, the model was applied using only the average shoreline position at each time step. Over the 14-year period, the first 7 years (1999 to 2006) were used for model calibration, while the subsequent years (2007 to 2013) served to validate the model's predictive accuracy. Tairua is a pocket beach of approximately 1.2 km of length in a microtidal environment, dominated by waves coming from NE and NEE. Figure 1 shows the study zone and the wave rose distribution of the wave climate timeseries.

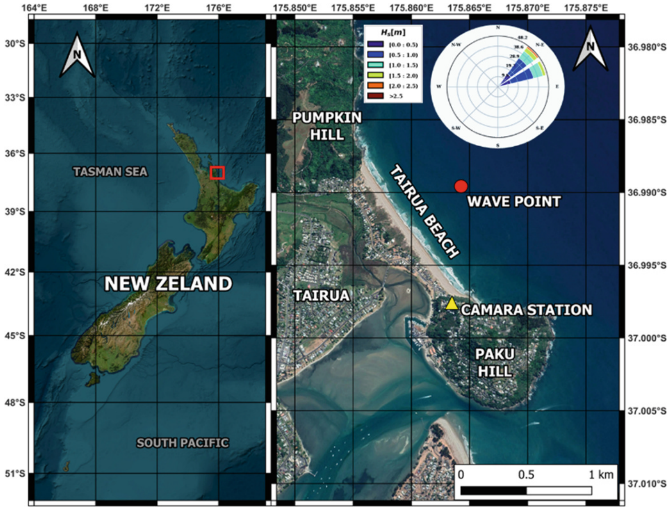

Fig. 1. Location of Tairua Beach on the eastern coast of New Zealand's North Island. The wave rose shows the directional distribution of the significant wave height from 1999 to 2014.

3 Results

3.1 Calibration

After the first run of NSGA-II and the search space was refined to the second run. The selected parameter sets are shown in Fig. 2. The values of the parameter a ranges from 0.03m to 0.32m, b from $2m^2$ to $24m^2$, C^+ from $10^{-3}m^{-2}h^{-1}$ to $10^{-1}m^{-2}h^{-1}$ and C^- from $10^{-3}m^{-2}h^{-1}$ to $5 \times 10^{-2}m^{-2}h^{-1}$.

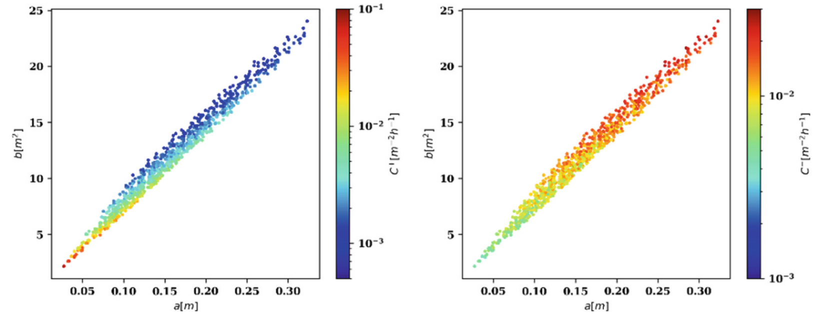

Fig. 2. Distribution of feasible parameter sets in the a-b space, color-coded by C^+ (left) and C^- (right).

Figure 2 shows the relationship among the calibration parameters, with a on the horizontal axis, b on the vertical axis, and color scales representing C^+ (left panel) and C^- (right panel). A clear near-linear trend emerges between a and b, indicating that increments in the slope parameter (a) are compensated by proportional shifts in the intercept parameter (b). The color gradients for C^+ and C^- further reveal how higher accretion or erosion rates align with particular regions of this $a - b$ space. This demonstrates the trade-off inherent in capturing beach responses to varying wave energy conditions and underscores the advantage of exploring a broad range of parameter sets in an ensemble framework.

3.2 Ensemble Simulation

With the obtained parameter sets, the ensemble simulations were carried out. Figure 3 shows the calibration and validation results. To validate the proposed methodology, we present histograms of the observed data, the ensemble simulation (Y_{ens}), best solution (Y_{bs}), and median of the ensembles (Y_{50}) are presented (see Fig. 3). The histogram coverage for Y_{ens} is 83% and 75% for the calibration and validation periods, respectively. For Y_{50}, these values are 79% and 74%, and for Y_{bs}, 75% and 77%, respectively.

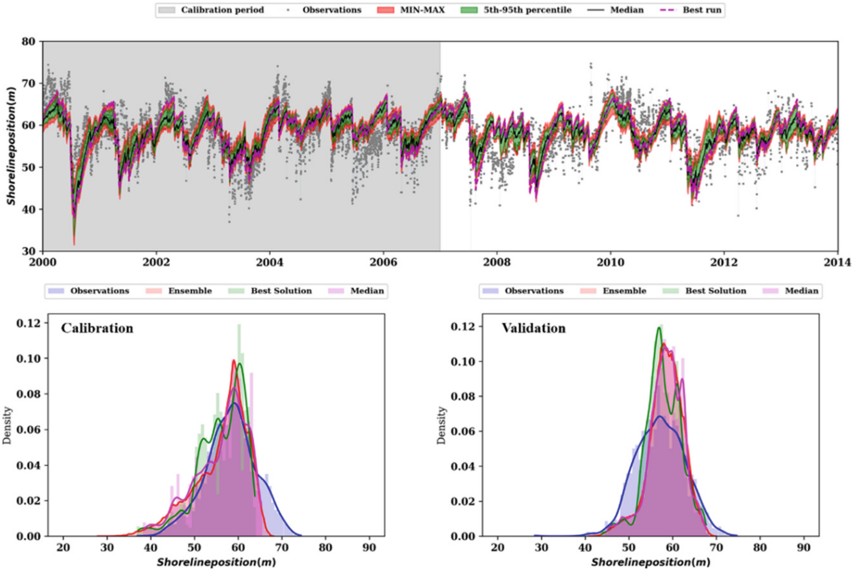

Fig. 3. Upper panel: Time-series comparison of observed shoreline positions (gray dots) and ensemble predictions for Tairua Beach, with calibration (shaded) and validation (unshaded) periods. Lower panel: density plots comparing observed shoreline data against the ensemble range, best solution, and median prediction for calibration (left) and validation (right) periods.

It can be observed that the best solution fluctuates primarily between the maximum and minimum values of the ensemble simulations. The model attempts to achieve the best possible agreement based on the density of available data. During the calibration period, higher shoreline values (i.e., accretions) appear to be underestimated, possibly due to the initial portion of the simulation in the early 2000s. In the validation period, accretions are well simulated, and the ensemble distribution remains close to the best solutions; however, several erosion events remain underestimated.

Notably, the ensemble encompasses most of the observed shoreline dynamics, capturing both episodic fluctuations and longer-term trends. In the lower panels of Fig. 3, the histograms indicate that the ensemble predictions align well with the overall distribution of observed shoreline positions, suggesting that combining multiple parameter sets can robustly characterize coastal evolution. Collectively, these results demonstrate that the ensemble method not only reproduces historical shoreline variability but also provides a credible range of future shoreline states, reinforcing its utility for medium- to long-term coastal management applications.

4 Conclusions

To overall, the ensemble approach applied in this study successfully demonstrated how equilibrium-based shoreline evolution models (EBSEM) can capture the variability and complexity of coastal processes over both calibration and validation periods. By leveraging a genetic algorithm (NSGA-II) to refine and explore multiple sets of parameters, the method addressed uncertainties inherent in the model and delivered a range of credible shoreline projections. In particular, using a video-camera dataset from Tairua Beach provided a robust case study, as the high temporal resolution allowed for detailed calibration and validation over a 14-year period.

The findings indicate that the best-fit solution typically remains within the bounds of the ensemble, suggesting that the ensemble approach can effectively reproduce key accretion and erosion events, despite a tendency to underestimate certain extreme values. Moreover, the relationships among the calibration parameters highlight how morphological and wave-energy factors interact to shape shoreline position. This underscores the importance of maintaining flexibility in parameter selection, particularly when addressing long-term or highly variable beach behavior.

Looking ahead, the probabilistic framework demonstrated in this work has significant implications for coastal management and planning. By generating ensemble forecasts rather than relying on a single deterministic output, stakeholders can better account for inherent uncertainties and identify strategies that are resilient under a wide range of possible future conditions. Ultimately, increasing the level of complexity of this problem using models with additional site-specific data—such as sediment characteristics or extreme storm events—could further refine model predictions and improve coastal risk assessments for vulnerable sandy beach environments.

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