

Developing a Process Driven Morphological Model for Long Term Evolution of a Dynamic **Coastal Embayment**

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How to cite this paper: O'Shea, M. and Murphy, J. (2020) Developing a Process Driven Morphological Model for Long Term Evolution of a Dynamic Coastal Embayment. Open Journal of Marine Science, 10, 93-109.

https://doi.org/10.4236/ojms.2020.103007

Received: March 7, 2020 Accepted: May 19, 2020 Published: May 22, 2020

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Abstract

Numerical modelling of coastal morphology is a complex and sometimes unrewarding exercise and often not yielding tangible results. Typically, the underlying drivers of morphology are not properly accounted for in numerical models. Such inaccuracies combined with a paucity of validation data create a difficulty for coastal planners/engineers who are required to interpret such morphological models to develop coastal management strategies. This study develops an approach to long term morphological modelling of a barrier beach system that includes the findings of over 10 years of coastal monitoring on a dynamic coastal system. The novel approach to predicting the long term evolution of the area combines a mix of short term hydrodynamic monitoring and long term morphological modelling to predict future changes in a breached barrier system. A coupled wave, wind, hydrodynamic and sediment transport numerical model was used to predict the coastal evolution in the dynamic barrier beach system of Inner Dingle Bay, Co. Kerry, Ireland. The modelling approach utilizes the schematisation of inputs to reflect observed trends. The approach is subject to two stages of validation both quantitative and qualitative. The study highlights the importance of considering all the parameters responsible for driving coastal evolution and the necessity to have long term monitoring results for trend based validation.

Keywords

Morphodynamic Modelling, Sediment Transport, Tidal Inlet, Ebb Tidal Bar, Long Term Process

1. Introduction

Numerical modelling is a very powerful tool when applied to the study of coastal

evolution as wave, current, sediment transport and morphological processes can all be simulated numerically. Coastal morphodynamic models can predict changes to a coastal system but in most cases the sediment transport element is not validated. Conclusions derived from model results on the future behaviour of a coastal cell can be made by utilising scenario modelling approaches such as simulating extreme storm events and morphological speed up techniques. Several software packages have been developed to represent the evolution of coastal systems in the simplest terms of elevation and cross-shore distance (1-D). These models such as S-Beach, Larson and Kraus [1], have been superseded by 2-dimensional profile models that expand the evolution model in an alongshore direction (2-D) such as X-Beach, Unesco-IHE [2] and LitPack, DHI [3]. These models predict the change in bed level and movement of sediment. Such models usually require a time series wave input from the nearshore zone and sediment characteristics. The X-beach model solves the equations for wave propagation and the Soulsby Van Rijn formula for sediment transport, Soulsby [4] and this is applied to a bed updating algorithm which results in a change in bed profile. Austin and Brown [5] created an X-beach model to examine the effect of cross section over a rip channel and a shoal of a transverse rip bar system. The breaching of Trabucador barrier beach system, in the Spanish Mediterranean Coast was modelled using X-Beach by Gracia et al. [6]. The study successfully reproduced 3 breaching events from the previous 25 years. The simulated breaching all occurred within an 8-hour timeframe and at high water.

Coastal area models such as DHI Mike 21, DHI [1], Delft 3D, Deltares [7] [8] and Telemac, Hervouet [9] typically simulate coastal processes on a cartesian or curvilinear grid that represents the bathymetry of the study site. It is common in such studies that the processes that drive coastal evolution (wind, wave, tidal elevation, sediment transport, and morphology) are separated into individual modules. After a specified time step the individual module outputs are then coupled and fed back to one another, to account for the effect of each model process on the others. These models are typically driven by spectrally resolved waves and 2 dimensional depth integrated flow.

Short term or event based modelling of morphology has been successfully undertaken in many cases using these types of models, Panigrahi *et al.* [10], modelled morphodynamics on the Arklow Bank off the East coast of Ireland, Herling and Winter [11] modelled the ebb tidal bar morphology of the East Frisian barrier islands in the North Sea. There have been several short term evolution modelling studies of Dingle Bay, the subject site for this study, including Sala [12], O'Shea and Murphy [13], Kristensen *et al.* [14], and Williams *et al.* [15].

However despite the proclivity of coastal modelling studies, complications arise when modelling of morphological changes over longer temporal scales is attempted. The model inputs required for this type of exercise are onerous, ranging from seasonal or multi annual scale to decadal scale. This is because when trying to assess the long term evolution of a coastal system, long term data sets of the environmental drivers are needed. In most situations this data has not been recorded. The current study aims to demonstrate a suitable approach to be applied to modelling morphology for inlet/barrier beach systems at the multi annual timescale range of morphological evolution. The ultimate aim of this research is to apply these same techniques to longer decadal timescales in the future.

De Vriend *et al.* [16] stated that there are two approaches to long term modelling; behaviour based and process based. A behaviour based approach is based on observations and empirical relationships but does not consider the coastal processes driving the behaviour. The process based approach seeks to understand the coastal processes driving the behaviour. The second approach is the preferred, however, detailing a simulation to include all of the contributory coastal processes in full is not feasible, due to both limitation on data collection, resolution and also computer processing capability. Williams *et al.* [17] states that a local conceptual understanding of sediment transport evolutionary behaviour is required for effective morphodynamic modelling at the decadal and centennial scale.

To address these issues an effective process based modelling approach should focus on the simplification of the driving coastal processes or as stated by Albert Einstein—*Everything should be as simple as it can be, but not simpler to the limit where no relevant features are lost.* This processes is referred to as schematisation and there are several common practises when considering morphodynamic modelling including utilising a morphological scaling factor (MORFAC), simplifying the effect of tidal variation and the manipulation of the computational time step.

The use of a MORFAC is a valid approach when tidal and wave driving processes occur on a significantly shorter timescale that the corresponding morphological changes. The model amplifies the sea bed updating process by a multiple of the simulated change over the model period e.g. a one month simulation of coastal processes could utilise a MORFAC of 6 to represent six months of morphological changes in the model domain. This was successfully undertaken by Latteux [18], to simulate changes on a single tidal diurnal tidal cycle albeit in dynamically moderate locations and not accounting for wave forcing. Cayocca et al. [19] applied a similar approach to model the evolution of a tidal Inlet, in the Archaron Basin, France and while this model successfully reproduced some of the long term evolution characteristics, it was ultimately unable to simulate storm driven changes including breaching. Xie et al. [20] used Delft 3D to successfully the model evolution of two tidal inlets in Hangzhou bay, China, over 30 years but this study did not require the inclusion and complexity of wave driven transport. Villaret et al. [21] implemented Telemac to model various hydrodynamic scenarios and morphodynamics at a meso spatial scale (10 -100 kM), but restricted test case studies to moderately dynamic locations including the Danube River. There is a recognised gap in studies attempting to model long term morphological evolution in dynamic coastal and estuarine settings where wind, wave and tidal forcings must be accounted for. The goal of the current research is to create a validated process based model that can be utilised to predict long term evolution in such an environment. This study focuses on developing a robust model to capture the key drivers of a dynamic coastal system at a complex stage of its evolution. The effectiveness of this model is demonstrated through comparing simulation results with field data in the short term as well as comparing modelled coastal processes trends with an understanding gained from long term observations of the system.

2. Study Site

The study site is Inner Dingle bay on the West coast of Ireland. The bay is westerly facing with a 3 mid bay barriers protecting low lying land to the east. The barriers are Inch, Rossbeigh and Cromane, the first two being barrier dune beaches and the latter of a glacial till base with extensive development. Due to the highly dynamic nature of the bay it has been subject to a number of previous studies examining topics including geology [22] [23], coastal processes [24] [25], storm surges [26], coastal evolution [12] [27], and numerical modelling [13] [28]. Several studies of storm impacts and wave patterns have been undertaken in Dingle Bay. [29] and [30] undertook further storm simulations in Dingle Bay, [26] simulated a 1 in 100 year storm in Dingle Bay.

The major event pertaining to evolution of the inner bay was the breaching of Rossbeigh barrier beach in 2008 and the consequent erosion and widening of that barrier breach. The evolution of the barrier and the hydrodynamic climate that developed thereafter are discussed in detail in [24]. Subsequent to this several experiments in describing the evolution of the system post breaching were undertaken including experiment utilising Wave Radar recording [31], and grain size trend analysis [13] [17] used an X beach model to simulate the 2008 breaching event and short term morphological response while [12] modeled 3 phases of evolution on Rossbeigh including pre-breaching (2000), breaching (2006) and post-breaching (2009) phases.

The Rossbeigh barrier itself can be divided into two distinct sections based on morphology, namely drift aligned section and swash aligned, **Figure 2**. The focus of this work is on the dynamic drift aligned section, for further information on the classification of these sections please consult [12] and [24]. Within the drift aligned section of Rossbeigh, there are three physical features to consider, an offshore ebb tidal bar, the drift aligned shore including the breached area and an ebb tidal channel separating the bar and shore. The monitoring and modelling analysis is concentrated on these features, as they have been previously identified as important factors in the evolution of the system overall.

3. Morphodynamic Modelling

3.1. Model Setup

The Mike DHI modelling software is used to undertake the morphodynamic

modelling; the model setup is described in [13]. In summary the domain, **Figure 1**, covers Dingle Bay to the open ocean beyond the mouth of bay; this model domain is represented on an unstructured mesh. The wave and tidal input data were applied at the offshore model boundary. The boundary was designed to ensure every possible wave direction incident in Dingle Bay could be simulated. A time series of water level elevation was applied at this boundary to simulate the tidal forcings in the bay. Likewise a time series of wave data was applied at the offshore boundary to generate wave forcings incident in the bay. Other model inputs include grain size data, bed roughness, wind data, directional spreading and eddy viscosity. The calibration of this model is described in [28].

3.2. Model Validation

The validation of this model is undertaken in two stages, firstly hydrodynamic, and then secondly morphodynamic. This validation consisted of comparing offshore boundary data to recorded data collected in the area of interest. A comparison of the real recorded dataset and a simulated dataset using the same boundary conditions was undertaken. The simulated tidal (current, directions, elevation) and wave (wave height, period and direction) statistics showed close agreement with the recorded data. The validation of hydrodynamics and waves is discussed in more detail [16].

The calibration and validation of sediment transport and morphodynamics was undertaken by running a 6 month equivalent simulation from March 2013 to September 2013 where the bed level volume changes were compared with the results of volume changes in bathymetric surveys over the 6 month period. The



Figure 1. Inner Dingle Bay model domain with bathymetry and mesh.

simulation was set up to include a morphological scale factor that accelerates the bed-level changes during updates at each hydrodynamic time step. This method reduced computational run time. A morphological acceleration factor (Morfac) of 6 is utilized with 1 month of input data which theoretically represents 6 months of morphological change. To assess the effectiveness of this approach, the results of both the simulated and measured bed level change in the ebb tidal channel location (**Figure 2**), was selected for comparison. This area has a high density of measured points and has been identified as an area where the key drivers of evolution act [12] [24]. **Table 1** details the amount of sediment movement in the channel both in the simulated and surveyed calculations.

The bed level sediment volumes calculated from the model are similar to the surveyed volume changes, **Table 1**. The volume eroded or transported out of the area were within 15% of the survey, while the fill volumes were within a 5% differential. The model tends to overestimate the erosion rate and underestimates the accretion or deposition rates slightly.



Figure 2. Coastal features of study site.

Table 1. Volume comparison of morphodynamic simulation and survey.

Mode	Volume Changes					
	Erosion	Accretion	Balance			
Survey	-60,212	120,106	59,894			
Model	-69,210	114,697	45,487			

3.3. Long Term Modelling Approach

The validated morphodynamic model of the Rossbeigh Barrier System enables longer term simulations to be undertaken. The inputs were schematized from recorded datasets similar to the datasets utilized at the calibration stage, in an effort to reduce computation time and increase the time scale length of the simulation. The long term models were developed using a longer multi seasonal dataset to enable multi annual simulation of evolution. A wave data time series of 2 months duration was used as the boundary input condition. This time series was derived from data collected in the summer of 2011, [24] concatenated with a month of wave data collected during the winter season of 2013. There were several storm events with wave heights of over 1.5 m. The dataset had a maximum significant wave height (Hs) of 2.6m. There were also periods of calm weather when the Hs was below 0.5 m. The wave direction recorded ranged from between 225° and 320°.

The modelling represents the sediment transport and morphological trends in the near future. To gain an understanding of the morphodynamics driving the evolution of the Rossbeigh breach, the simulation was run for two years giving morphodynamic results up to the end of 2015. The simulated changes in bathymetry, wave climate, tidal current regime and sediment transport patterns were examined.

4. Results

4.1. Modelling Results

The changes in bathymetry from 2013 to the end of the 2015 for both the surveyed and simulated are compared in **Figure 3**. Clear trends are evident including the ebb tidal bar beginning to merge with the beach of the Island section and a small section of the channel had become shallower. Erosion was also evident as the drift aligned section and Island reduce dramatically in size over this 2 year period. A section along the drift aligned beach south of the original breach undergoes severe erosion in this simulation.

Simulated significant wave heights, Hs, at high tide during a storm period in both 2014, and 2015 is shown in **Figure 4**. The wave height appears to have increased slightly for the same storm period from year to year in the area north of the distal dune section. This was a result of the increased erosion at this location and deepening of the inlet discussed previously. The increased depth leads to increased incident wave heights.

The mean wave direction for the same storm period is also plotted, **Figure 5**. It is significant to note that the difference in wave direction at high tide between drift and swash aligned zones was reproduced in the model. This phenomenon was previously documented in [23] where it is described as being a cause of the growth in drift aligned zone at the expense of swash aligned shore/dune. It is also significant that the ebb tidal bar has an effect on wave direction. The mean wave direction in the swash aligned zone was in the 250° - 275° sector while the













Figure 4. Significant wave height at high tide.





Figure 5. Mean wave direction at high tide.

ebb tidal bar and the drift aligned shore experienced wave action from the 275° - 300° sector. There was a noticeable change in the simulated mean wave direction between 2014 and 2015 at the entrance to the channel between the ebb tidal bar and the drift aligned shoreline. In 2014 a large area of the channel entrance shows wave direction in the 275° - 300° sector but in 2015 this changes to the 250° - 275° sector.

The tidal current regime at both mid flood and mid ebb shows little variation over successive years, **Figure 6**. The flood currents had a peak of over 0.8 m/s at the tip of island with strong currents also visible in the newly formed inlet north of the distal section. The increase in magnitude and shore parallel direction of these currents in the drift aligned section are in contrast with the smaller currents in the swash aligned section. The current accelerated at the narrow part of the channel between the ebb tidal bar and drift aligned shoreline.

At mid ebb in both 2014 & 2015, Figure 7, sections of the main tidal inlet









Figure 7. Tidal currents at mid ebb in drift aligned zone.

current turned south onto the bar. The observed pattern of the currents reinforces the concept developed in [24] that the ebb tidal bar is nourished by the main tidal inlet. As the water flows past the constriction caused by the northern tip of Rossbeigh in the inlet channel, the ebb current velocity slows down. The current jet then fans out in several directions with significant magnitude flows observed over the ebb tidal delta.

The accumulated sediment transport is represented in vector format at the end of each year long simulation. These vectors represent the total sediment load transported from each node. They are plotted on a background of bathymetry for both years, **Figure 8**. The sediment transport patterns from year to year did not change significantly with the exception of the island section and a small area to the south east of the ebb tidal delta. An increase in accumulated sediment transport was visible at both locations.



Figure 8. Accumulated sediment transport vectors simulated zone.

Globally in the study site domain, the sediment transport vectors followed similar patterns to that of the tidal current vectors. The sediment transport in the tidal inlet was dominated by ebb currents while the beach and ebb tidal bar was influenced by flood current driven sediment transport. The effect of wave driven sediment transport was also visible with sediment transport vectors shifted slightly to the east compared to the tidal current vectors on the bar and beach. This was due to the dominant westerly and north westerly wave directions driving sediment transport in this location.

At the northern edge of the Rossbeigh, a large magnitude vector running in a north westerly direction was evident in contrast to the north easterly vectors in the vicinity. This transport vector was in response to the dominant north westerly wave condition that is responsible for erosion at high tide. Sediment transport on the drift aligned beach is generally wave dominated although a tidal influence is visible in the centre of the breach area and at the edge of the island, where tidal currents are higher.

4.2. Morphodynamic Analysis

Similar to the validation of morphodynamic modelling, the volume of sediment movement was calculated by comparing volumes of bed level change. The change in volume from the 2013 survey to 2015 for both surveyed and modeled situations was compared in **Table 2**. This was presented in terms of cut and fill and balance. The surveys are interpolated on triangulated irregular networks (TINs) in AutoCAD Civil 3D [32] to create surfaces representing the topography of the study site. The survey points are connected with a series of edges to form a grid of triangles. The data is then interpolated on this grid utilising Delanauy [33] calculation method. To ensure accurate replication of the grids, the surveys follow the same track lines and acquisition rate. The entire 2015 survey areas along with three specific areas were examined to understand the performance of the model under different dynamic situations occurring in Rossbeigh. The three sub areas analysed were the ebb tidal bar, the channel between ebb tidal bar and the drift aligned shore.

The morphodynamic climate over the entire survey area was erosive in nature with both survey and model showing a net removal of sediment from the area, quantitatively the model under predicts the amount of sediment being removed or more specifically has a higher deposition amount. Cumulatively the survey shows that on average the bed level is reduced by approximately 540 mm whilst the model predicts 30% less of a bed level reduction. Examining the sub areas the trends shown by comparing the successive surveys are reproduced by model with the ebb tidal bar and drift aligned shore at 17% and 13% of the survey results.

In the drift aligned channel, the morphodynamic climate observed is contrary to the rest of the study site in that it is accretive but with large volumes of sediment movement in both erosion and deposition in both years. It is evident that

Location	Туре	Sq Area (m²)	Volume Changes				
			Erosion (m ³)	Accretion (m ³)	Balance (m ³)	Cumulative (mm)	% difference
Total Area	Survey	1,573,096	1,161,381	298,019	-863,362	-0.548	-29%
	Model		1,245,240	578,052	-667,188	-0.424	
Channel	Survey	287,024	35,732	167,785	132,053	0.460	55%
	Model		27,404	321,813	294,409	1.025	
Bar	Survey	916,717	622,465	94,125	-528,340	-0.576	-17%
	Model		670,390	220,151	-450,239	-0.491	
Shore	Survey	184,760	103,991	9015	-94,976	-0.514	13%
	Model		109,888	312	-109,576	-0.593	

Table 2. Volume calculations for model simulations.

the majority of the accretion was occurring due to the ebb tidal bar migrating shoreward. It is in this area where the model is least accurate, with over twice the amount of accretion shown compared with survey values, while the erosion is reasonably similar, it is also the only location where the model predicts less erosion than the survey showed.

It should be noted that fixed comparisons on plan may not capture the difference between survey and model as the channel has been shown to be migrating. Changes are ultimately captures on a more regional scale by the initial comparison of the entire survey area.

5. Discussion

The modelling has replicated the main hydrodynamic features considered to be the drivers of evolution such as the presence of a north westerly wave direction acting at high tide in the drift aligned zone as identified in [24] after a data collection campaign. The impact of this wave forcing on sediment transport was also observed. The bathymetry comparisons suggest that the ebb tidal delta is migrating and beginning to join with the drift aligned beach, starting at the neck of the channel.

The modelling has confirmed the presence of a north westerly wave direction acting at high tide in the drift aligned zone. The impact of this wave forcing on sediment transport was also observed. The bathymetry comparisons suggest that the ebb tidal delta is migrating and beginning to join drift aligned beach, starting at the neck of the channel.

Wave driven sediment transport appears to dominate seaward of the ebb tidal bar moving the sediment shoreward, tidal current sediment transport dominates into the channel with evidence of wave and tidally mixed sediment transport on the beach of the drift aligned zone.

Volume calculations confirm that the channel between ebb tidal bar and drift aligned zone is accreting while the beach continues to erode in the drift aligned zone. A cumulative average bed reduction of 500 mm was shown over a 2 year period in the drift aligned region of Rossbeigh.

The model generally predicts erosion and sediment mobilization in line with survey rates but displays a bias for accretive process at a ratio of almost 2 to 1. This is visible in almost all locations regardless of the dominant mode of sediment transport with the exception of the shore line where accretion rates are under predicted. In the complex multi mode transport environment that is the drift aligned section of Rossbeigh the simulations were not expected to be quantitatively exact, however a bias for accretion extrapolated over a longer term could ultimately lead to erroneous evolutionary trends being inferred, notwithstanding this, the model successfully replicates the general trends in this coastal cell. The contributing factors affecting this bias are increased storminess over the winter of 2014 as noted in Nuyts *et al.* (In press) and also a potentially more significant issue of under predicting tidal current driven erosion or sediment shear threshold. The impacts of such issues could be assessed by undertaking further simulations over longer period to assess the validity of schematization approach of using condensed dataset.

6. Conclusions

A 2-dimensional depth integrated hydrodynamic, fully coupled wave, sediment transport and morphological model has been created and validated for Dingle Bay, the primary use of this model has been in the prediction of the morphody-namic evolution of Rossbeigh and Inner Dingle Bay utilising a new approach to long term modelling.

The results of the modelling compared with survey results provide an insight into the complexity of the morphodynamics of Rossbeigh. The erosion trends in the drift aligned shoreline of Rossbeigh were reproduced in the simulations. The model however appears to simulate morphodynamic behavior better when sediment transport is wave driven or a combination of wave and tidal current e.g. in locations such as the seaward approach to the ebb tidal bar and on the drift aligned shore. When the tidal currents dominate sediment transport such as in the channel, morphology prediction is less accurate. This is possibly due to an over estimation of sediment fall velocities during higher velocity currents and sediments having a lower critical shields parameter than modeled.

The multi-annual modelling of evolution in Rossbeigh Drift aligned section has qualitatively reproduced the observed trends in changes. Quantitatively the volumes vary in accuracy depending on the mode of sediment transport that dominates. Analysis of the simulations revealed some potential bias in the process of schematization which requires further investigation and longer simulations. The results of the modelling provide a platform to undertake further study into the complexity of the morphodynamics of Rossbeigh and refine this approach to long term morphodynamic modelling of complex coastal systems.

This approach demonstrates that in dynamic coastal cells such as Rossbeigh, observational data and field measurements over a long period are required to build models capable of simulating the complex evolutionary trends. Even with such data, it is apparent that model tuning is required over a multiannual period to generate results in an order similar to that observed in the field. Therefore in the general context of coastal evolution modelling as it is currently undertaken, it would be expected that, without any measured data to validate the model, there can be significant discrepancies between real beach behavior and model predictions.

The next stages of this work will include such longer term modelling in two distinct phases; modelling the evolution over a longer multiannual period including and excluding the MORFAC approach. The method of schematization of input datasets will also be assessed to investigate their influence on long term simulation results.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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