Morphodynamics of a seasonal inlet

A case study using remote sensing and numerical modelling for cua dai inlet, central vietnam

Do, Anh T.K.; Kralli, Vasiliki E.; de Vries, S.; Nguyen, Viet T.; Stive, Marcel J.F.

DOI
10.1007/978-981-15-0291-0_58

Publication date
2020

Document Version
Final published version

Published in
APAC 2019 - Proceedings of the 10th International Conference on Asian and Pacific Coasts

Citation (APA)
Do, A. T. K., Kralli, V. E., de Vries, S., Nguyen, V. T., & Stive, M. J. F. (2020). Morphodynamics of a seasonal inlet: A case study using remote sensing and numerical modelling for cua dai inlet, central vietnam. In N. T. Viet, T. T. Tung, & D. Xiping (Eds.), *APAC 2019 - Proceedings of the 10th International Conference on Asian and Pacific Coasts* (pp. 417-425). Springer. https://doi.org/10.1007/978-981-15-0291-0_58

Morphodynamics of a seasonal inlet

A case study using remote sensing and numerical modelling for cua dai inlet, central vietnam

Do, Anh T.K.; Kralli, Vasiliki E.; de Vries, S.; Nguyen, Viet T.; Stive, Marcel J.F.

DOI
10.1007/978-981-15-0291-0_58

Publication date
2020

Document Version
Final published version

Published in
APAC 2019 - Proceedings of the 10th International Conference on Asian and Pacific Coasts

Proceedings of the 10th International Conference on Asian and Pacific Coasts (APAC 2019) Hanoi, Vietnam, September 25-28, 2019

MORPHODYNAMICS OF A SEASONAL INLET: A CASE STUDY USING REMOTE SENSING AND NUMERICAL MODELLING FOR CUA DAI INLET, CENTRAL VIETNAM

Anh T.K DO[1,2], Vasiliki E. KRALLI[1], Sierd DE VRIES [1], Viet T. NGUYEN[3] and Marcel J.F STIVE [1]

ABSTRACT: Cua Dai Beach located adjacent to Cua Dai Inlet is a typical, seasonally varying tidal inlet. This famous beach has suffered extreme erosion since 1995 due to an apparent irregular-periodic process, a decrease of sediment supply from the river and its estuaries and increased squeeze by coastal developments. The main objective of this study is to unravel the physical processes that control the morphological development of Cua Dai Inlet while challenged by the fact that it is a data-limited environment. In order to identify and quantify the main processes governing the evolution of Cua Dai Beach and thereby aiming to explain the morphological changes and extreme erosion in recent years, a new approach was developed. Historical shoreline positions and sediment budget changes were derived from satellite images using empirical engineering assumptions. In addition, numerical models were used to investigate in detail sediment transports and morphodynamics under the influence of seasonal waves and rivers as well as the anthropogenically-driven impacts. Results of shoreline change rates indicate that Cua Dai Beach (located on the northern side of Cua Dai inlet) experienced an average erosion of 12m/y during the period from 2000 to 2010 and erosion continued further to the north while the southern coast of the inlet accreted with a mean rate of 11m/y. The overall system showed a significant sediment loss of about 243,000–310,000 m3/y. The annual cycle of two past morphological periods has been numerically simulated to evaluate the behavior of the system without and with human interventions. The first morphological simulation without the impact of the resorts successfully reproduced an overall erosion trend at the northern coast while the formation of an ebb tidal bar was also reproduced. The second morphological simulation reproduced the impact of the resorts that have been constructed along Cua Dai Beach. Simulations indicate that the presence of the resorts has enhanced the propagation of the existing erosion further to the north. The new approach of remote sensing combined with process-based modeling has been essential to investigate the main processes that govern the morphological changes and extreme erosion at Cua Dai inlet.

Keywords: Seasonal inlet, coastal squeeze, Cua Dai Inlet, Cua Dai Beach

INTRODUCTION

Coastal erosion is a worldwide problem, generally induced by a combination of both, natural causes and human causes. Coastal erosion is problematic for the safety of inhabitants of coastal areas and is in need of further and continuous scientific attention, especially in complex coastal systems. Therefore, it is necessary to well understand these coastal systems to aid future improved management of these systems.

Cua Dai Inlet is a typical deltaic coastal formation on the central coast of Vietnam. Especially, this coastal system is associated with the biggest river system in Central Vietnam, e.g. The Vu Gia-Thu Bon river system. Downstream of Vu Gia River the flow discharges into Danang Bay through the Han estuary, while Cua Dai Inlet is the river mouth of Thu Bon River (Figure 1). The Vu Gia-Thu Bon river system is strongly seasonal and floods occur with higher and more frequent discharges in recent years. Moreover, the coastal area of central Vietnam especially Cua Dai beach is quite exposed to typhoons and other natural disasters. Apart from the rainstorms or typhoons it is highly vulnerable to river floods, flash floods, storm surges, salinity intrusions and tsunamis.

During the last ten years, several coastal structures were built in Da Nang Bay and at Cua Dai Beach, such as seawalls, breakwaters, dams and bridges, as well as other human interventions such as land reclamations for the construction of luxurious resorts and hydropower plants at upstream. These human activities along with the effects of climate change potentially pose a threat to the coastal safety of Da Nang Bay and Cua Dai Beach. As a result, at many places along the coast, especially for Cua Dai Beach extreme erosion has occurred causing immense damage.

The complex feedbacks between system forcing and response of inlet systems influenced by variations in a

[1] Faculty of Civil Engineering and Geosciences, Delft University and Technology, The Netherlands
[2] Faculty of Water Resource Engineering, The University of Da Nang- University of Science and Technology, Da Nang, Viet Nam
[3] Faculty of Civil Engineering, Thuyloi University, 175 Tayson Street, Dongda District, Hanoi City, VIETNAM

N. Trung Viet et al. (eds.), *APAC 2019*,
https://doi.org/10.1007/978-981-15-0291-0_58

seasonal wave climate combined with human interventions have received broad scientific interest. Moreover, the common occurrences of seasonal varying tidal inlets are often found in developing countries where data availability is mostly poor. Therefore, it is important to figure out a successful approach to understand the system behavior when dealing with a data limited environment.

In recent years, remote sensing and GIS techniques have been proposed as a relatively low-cost approach to coastal monitoring (Maiti and Bhattacharya 2009) especially for detecting coastline movement. Shoreline studies play an important role to understand a variety of component of dynamic beaches, for example shoreline mobility (Dolan et al. 1978), long-term erosion/sedimentation (Guillen et al. 1999), beach rotation and bay beach planform stability (Silvester 1960), changes due to human interventions (e.g., Grunnet and Rusessink 2005). Many applications of remote sensing and GIS on mapping shorelines and inlet dynamics demonstrate that satellite-based remote sensing can be used as a useful tool for mapping shoreline changes and the dynamic behavior of tidal inlets, rivers, and estuaries (Avinash et al. 2013), (Chen and Chang 2009), (Panda et al. 2013).

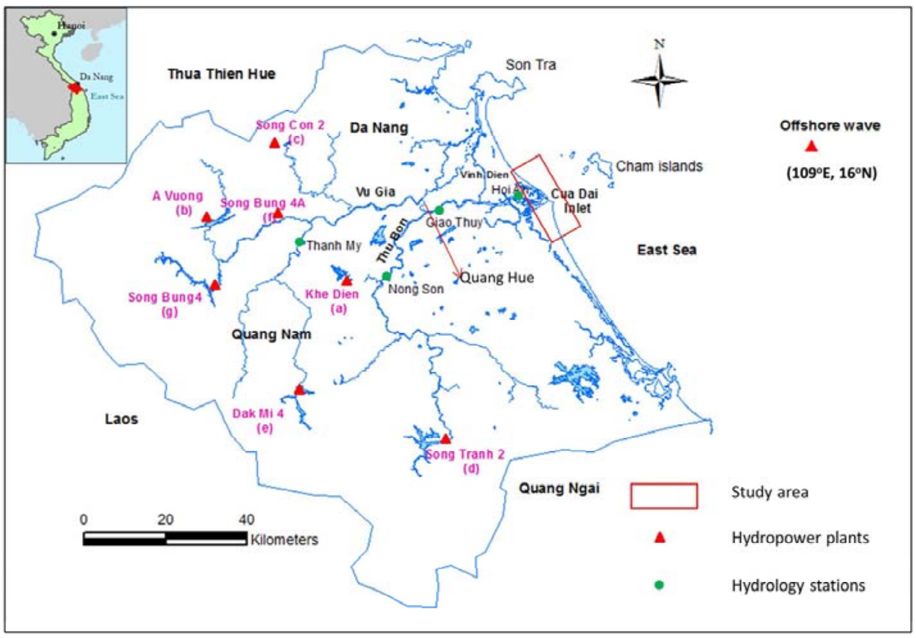

Figure 1. The Vu Gia –Thu Bon river basin including Cua Dai inlet

For complex coastal systems, such as tidal inlets further understanding can be obtained from process-based modelling describing the complexity of combined physical processes relevant to waves, tides, river flow and sediment transport processes, Many studies have shown that process-based modelling have been successful applied to study hydrodynamics, morphodynamics and morphological behaviour event in the complex coastal environments of tidal inlet systems (*e.g*. Bertin et al. 2009), (Chen et al. 2015), (Dissanayake et al. 2009), (Herrling and Winter 2014); (Nahon et al. 2012); (Ridderinkhof et al. 2016) In the absence of sufficient observational data, systematic and schematic numerical simulations are assumed to be able to provide insight into medium to long-term coastal evolution (Daly et al. 2011).

The general objectives of this study is to derive a better understanding of recent and present processes governing the evolution of Cua Dai Beach, while accepting it is a data poor environment. This understanding is expected to explain the reasons behind the morphological changes and extreme erosion at Cua Dai Beach in recent years, to aid in finding possible solutions for protection of the beach and to facilitate future coastal management.

METHODOLOGY

To investigate the erosion at Cua Dai Beach, the present work collected the available data concerning its past evolution. Satellite data and GIS techniques were used to estimate the trends in shoreline evolution and volume changes during recent decades. Then a 2DH process-based numerical morphodynamic model (Delft3D), which consists of Delft3D-WAVE and Delft3D-FLOW combined was applied to calculate the local longshore sediment transport rate (LSTR) and potential morphodynamics under influence of seasonal waves, seasonal rivers and human intervention. Based on the results of the LSTR and shoreline change rate as well as the background information of Cua Dai beach, this study aims to explain the prevailing transport mechanisms and especially those causing erosion problems in this system.

Satellite derived coastal volume changes

To detect the shoreline location in Cua Dai beach during the last decades, a total of six multispectral satellite images acquired on different dates were selected based on the lowest cloud cover (Table 1). The six orthorectified satellite images of the study area from the sensors Landsat-5TM, Landsat-7 ETM+ and Landsat-8 OLI-TIRS in the years, 1988, 1995, 2000, 2005, 2010, and 2015 were downloaded from U.S Geological Survey (USGS) Earth Explorer web tool. The methodology to extract the shoreline positions can be found in detail (Do et al. 2018, 2019). Then shoreline change rates are calculated following the End Point Rate (EPR) method using the Digital Shoreline Analysis System (DSAS) software version 4.3, an ArcGIS extension for calculating shoreline change developed by the USGS (Thieler et al. 2009). Following step, satellite derived volume change for each each coastal cell were estimated based on shoreline change rates using additional assumptions that the shoreline is translated horizontally without changing shape over a closure depth. Since no systematic measurements of the active beach profiles are available, this study used the method proposed by Hallermeier (1981) to estimated closure depth. The computed colure depth by Hallermeier (1981) is verified to some extend by using two available bathymetric maps of the area in 2009 and 2010.

Table 1. Characteristics of images analyzed.

Name	Acquisition Date	Path/Row	Resolution (m)	Type	Used bands
Landsat 5 TM	03/09/1988	124/049	30	Geo Tiff	2 and 4
Landsat 5 TM	19/06/1995	124/049	30	Geo Tiff	2 and 4
Landsat 7 ETM+	05/07/2000	124/049	30	Geo Tiff	2 and 4
Landsat 5 TM	16/07/2005	124/049	30	Geo Tiff	2 and 4
Landsat 5 TM	12/06/2010	124/049	30	Geo Tiff	2 and 4
Landsat 8 OLI-TIRS	10/06/2015	124/049	30	Geo Tiff	3 and 5

Numerical modeling

To investigate seasonal varying sediment transport and potential morphological changes of Chua Dai inlet and adjacent coasts, a 2DH process-based numerical morphodynamic model (Delft3D), which consists of Delft3D-WAVE and Delft3D-FLOW, is used in this study. The computational domain of the morphological model has been developed to represent the Cua Dai inlet which includes the open sea, the inlet and part of the river (Figure 2).

The boundary conditions of the regional model are extracted from the global ocean tide model TPXO8.0. This model is calibrated using the measured tide time series measured from the station at Da Nang near to Son Tra Mountain. Then the regional model is nested to generate the boundary conditions for the flow model. The results of the flow model are validated with water level and velocity measured at Cua Dai inlet. Wave forcing at the sea boundary in the wave model was extracted from the National Oceanic and Atmospheric Administration (NOAA) Wave Watch III archives at grid point (16.0^{o}N, 109.0^{o}E) in the period 2005-2013. Fresh water from Thu Bon River that flows into Cua Dai inlet was implemented at the river upstream boundary using the monthly average discharge during period 1977 to 2008.

To test the influence of seasonal waves and seasonal river flow on sediment transport and morphological changes at the inlet and its adjacent coasts, this study choose to simulate 4 different conditions (Table 2) that represent winter and summer. Two scenarios of morphodynamics are also simulated. The first morphological period depicts the system in the past which no human interventions. It means that no resorts that belongs to the simulation. The second morphological period that is going to be reproduced represents the evolution of the coast when human interventions took place.

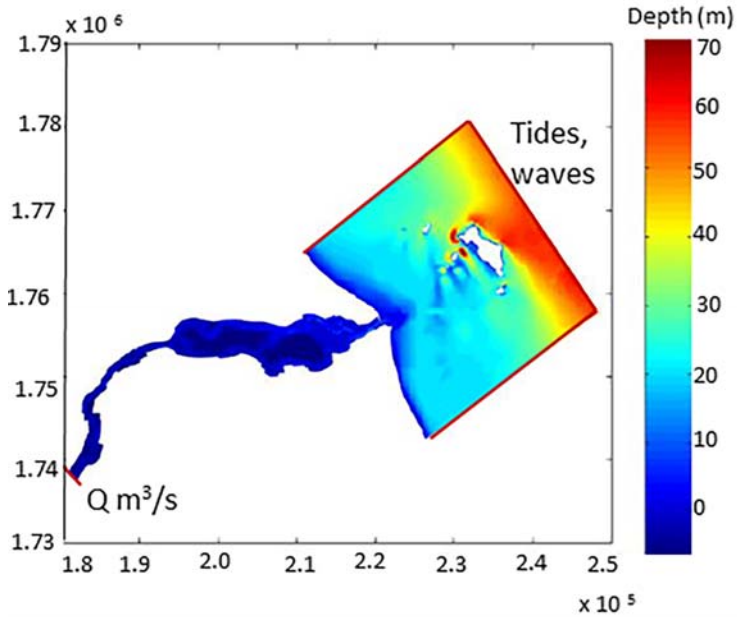

Figure 2. Model domain including wave model domain and flow model domain

Table 2. Overview of structure of the morphodynamic simulation considering seasonal waves and seasonal river discharges.

Season	Wave Direction (0)	Wave Height (m)	Period (sec)	Occurrence (%)	River Discharge (m^3/s)
Winter season	ENE (60^o)	1.75	7.57	11.3	1037
	ENE (60^o)	1.25	7.9	13.8	168
Summer season	ENE (60^o)	0.75	6.42	10.4	88
	SE (135^o)	0.75	6.4	17.18	88

RESULTS AND DISCUSSION

This section first presents and discusses the results of shoreline changes and volume changes during the period 1988 to 2015. Then the longshore sediment transport and morphological feedback are separately derived for the winter and the summer periods corresponding two scenarios are presented and discussed.

Shoreline changes and changes in sediment volume

Results of shoreline changes and sediment volume changes have been presented clearly in Do et al. (2018) with different periods from 1988 to 2015. Figure 3 indicates shoreline position around Cua Dai inlet and adjacent coast changing during period 1988 and 2016 taken from Do et al. (2018). Shoreline changes combine with volume changes have contributed to quantitative explain long-term morphological development of the system. According to Do at al. (2018) the development of Cua Dai inlet and its adjacent coast from 1988 to 2015 indicate a nonperiodic cyclic process which include the channel shifting from North to South and the welding of the ebb-tidal bar process. Before 1995, Cua Dai system did not experience any impact of human activities but only experienced natural processes. Resulting the volume change show the system was in very rich sediment with a total sediment gain of 481,000m^3/y (Do et al., 2018). After the bar welding, the main channel has shifted to the South and a new ebb shoal has been developed. Cua Dai system has started to rework to develop new equilibrium state, erosion has started to observe at Cua Dai beach since 1995. The most serve erosion has observed during period 2000 and 2010 (sediment lost 243,000m^3/y to 310,000m^3/y (Do et al., 2018)). Many human activities occurred during this period. Consequently, the further step to using numerical model to reproduce morphological development under human impact in the next section.

Morphodynamics in case absence of human intervention

The resulted intensity of the morphological changes is in accordance with the monthly duration of the simulation period. The morphology change in the areas of interest induced by ENE waves during the winter and by SE waves during the summer is displayed in Figure 4.

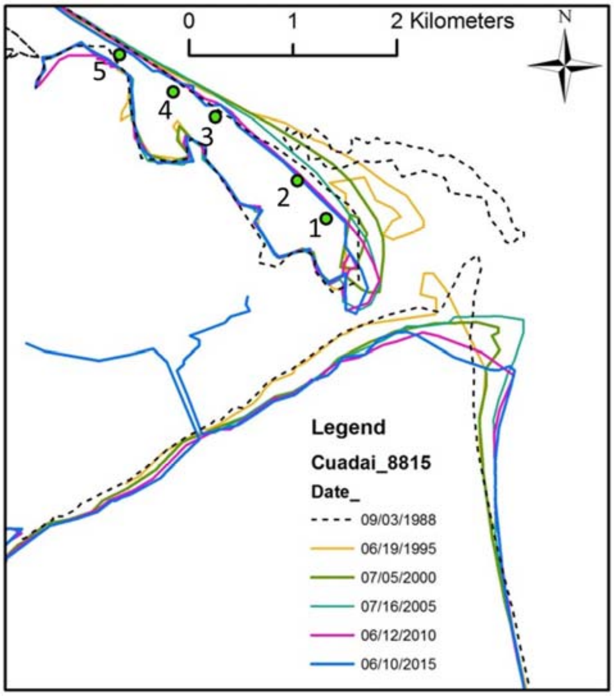

Figure 3. Shoreline positions including the ebb tidal bar welding at Cua Dai Beach from1988 to 2015 (From Do et al. (2018)).

The ENE wave conditions create a stronger impact in the north coastline compared to the south (Figure4a). In general, erosion is dominant along the north coast. In the location approximately 3 km from the inlet, significant local erosion exists, indicated by the darker blue color. There, a divergence point is formed, downdrift of which sediment is transported towards the inlet, forming a more complex pattern with local divergence and convergence areas over a distance of approximately 2 km. These explain the observed variations of the morphology. Mainly erosion is present, even though closer to the inlet side sedimentation develops, linked to the convergence point that is located approximately 1 km from the inlet. Further to the north, the level of erosion remains strong, highlighted by the steep gradient that can be observed in the corresponding alongshore sediment transport graph (Figure 4a). In this region, the transport intensity is largest during the winter flood season, as a result of the strong prevailing conditions. The magnitude of the observed patterns is lower during the winter dry season and becomes significantly milder over the summer ENE season, attributed to the lower forcing conditions. Along the south coastline during ENE conditions, sedimentation takes place. A more stable trend is observed compared to the north coast and no intense changes are present (Figure 4a). However, near the inlet over a 1 km distance, a strong southward transport gradient exists inducing larger sediment accumulation there with respect to the remaining coast. This southward transport is caused by sediment bypassing from the ebb tidal delta. In the summer, the sediment transport is more uniform with minimum gradients (Figure4b). The prevailing pattern of the south coast with minimum gradients, could be explained by the interaction of the local forcing conditions. In general, the ENE wave direction triggers a northward sediment transport. Sheltering effects due to the presence of the ebb tidal delta as well as the southward directed sediment bypassing from it, alter this trend influencing the resulted net southward transport pattern. The difference in the wave magnitude among the ENE seasons together with the level of bypassing, forms the intensity of the final southward pattern.

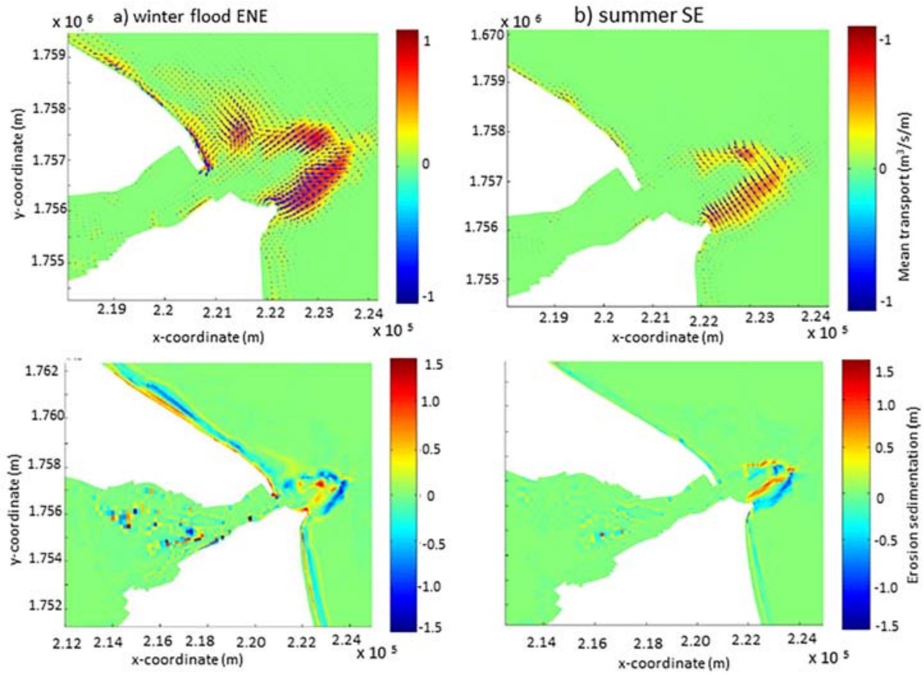

Figure 4. Mean sediment transport pattern and morphological changes during (a) winter flood and (b) summer (SE) seasons in the first morphological period.

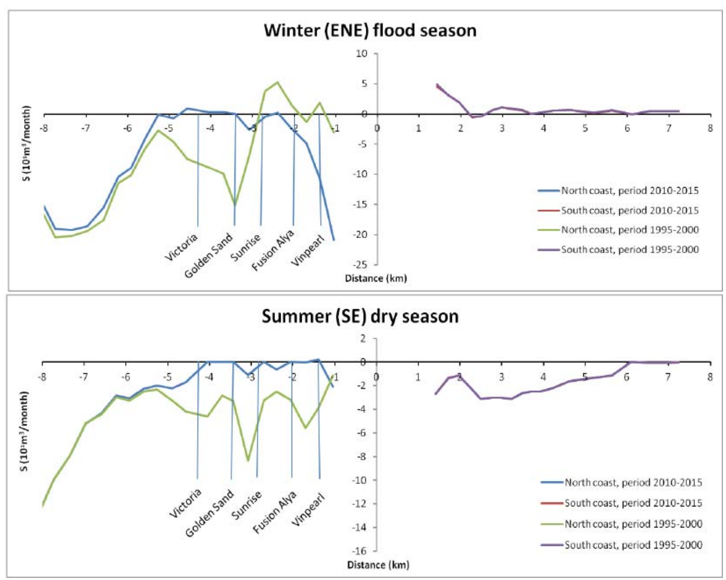

Figure 5. Alongshore sediment transport patterns during (a) winter flood and (b) summer (SE) seasons in the first and second morphological periods

Morphodynamics in case present of human intervention

The second scenario of morphology simulation is including the present of resorts along Cua Dai beach. The observed morphological pattern suggests that resorts start to behave as groynes when the beach is eroded in front of their location, creating an erosive pattern in the north that ultimately intensifies the erosion in Cua Dai. Over the period 2010-2015, the five resorts of the Cua Dai beach as shown in Figure 3, begin to have effect in the morphology of the north coast. The clearly influence of resorts can be seen through longshore sediment transport graph (Figure 5) that show the comparison between two morphological scenarios. The impact of resorts is restricted only in the north coast and the south coastline is steady over the two periods. The transport magnitude varies, introducing two locations have steeper sediment transport gradient, near the inlet and north of resorts. The resorts appear to create an impact in the coastline, inducing sedimentation in the region immediately downdrift of Vinpearl resort and erosion closer to the inlet. In the area north of the resorts, erosion is observed, causing a significant effect in the morphology there. Thus, it is obvious that the groyne effect in the morphology of the north coastline has been reproduced.

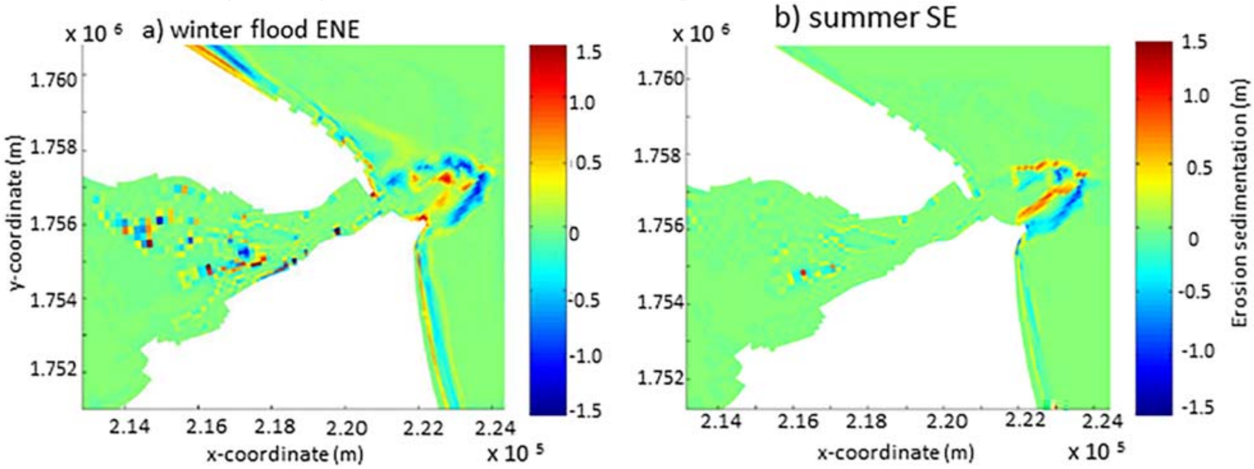

Figure 6. Morphological changes during (a) winter flood and (b) summer (SE) seasons in the second morphological period due to resorts

The morphology in the region among the resorts and around ebb tidal delta during the winter and summer season is indicated in Figure 6. Under ENE waves, sediment accumulation is present near the inlet over a distance of approximately 1 km. This region includes the Vinpearl and Fusion Alya resorts. In the regions between Fusion Alya and Golden Sand resorts a more complex pattern takes place with erosion and sedimentation locations. Assessment of the mean transport trend in the region shows that the divergence point has now shifted a bit to the south between Sunrise and Fusion Alya resorts, due to the construction of Sunrise in the location that was formerly observed during the assessment of scenario 1. In this area enough undisturbed coastline exists for the hydrodynamic pattern to form a new divergence point. There, erosion is formed downdrift of Sunrise resort and sedimentation updrift of Fusion Alya in accordance with the local alongshore sediment transport trend. From Victoria resort, the strong northward transport trend that starts there, inducing significant erosion.

When SE waves prevail in the summer, the morphological impact is mild. In general, the most significant transport takes place in the ebb delta. In the north coast the transport magnitude increases only at restricted locations. This is the case in the region updrift of resorts, where transport is directed to the north. Among the location of resorts, a northward constant pattern is present and no flow divergence takes place. This is also the case downdrift of the Vinpearl resort. In the area between Fusion Alya and Golden sand resorts erosion and sedimentation regions is present. Immediately downdrift of Vinpearl resort sedimentation is observed as sediment is transported towards the resort, but the feature is mild, while now the region between Vinpearl and Fusion Alya does not experience changes in morphology. An erosive pattern is formed north of the resorts, indicated by the presence of an alongshore gradient that increases in transport direction.

CONCLUSIONS

To derive a better understanding of recent and present processes governing the evolution of CuaDai Beach, this study has reconstructed the historical shoreline positions and has estimated volume changes derived from Landsat imageries. Then a process-based model is applied to investigate the influence of waves, tides, and river discharge on sediment transport and morphological changes. The results of this study indicate that the erosion of Cua Dai beach since 1995 was the result of a long-term geomorphological inlet development reflecting an irregular-periodic process that takes place over several decades. It appears that channel shifting from north to south, the bar welding processes, the decrease of sediment supply from river, estuary and squeeze by coastal development that caused significant geomorphological changes from 1988 to 2015.

The results from morphological changes around the ebb tidal and at adjacent coasts indicate that the model has successfully reproduced and explain the main phenomenon caused erosion at Cua Dai beach since 1995.

From the first morphological period that is simulated, where no interventions existed in the coast, the prevailing seasonal morphological pattern of the domain is identified. Common features are observed for ENE waves with a magnitude that varies with the forcing intensity, while a different result is formed for SE conditions. Under ENE wave conditions, divergence of sediment transport is observed in the north coast. Updrift of this location, an erosive trend is found. In the downdrift region the transport pattern is more complex with erosion and sedimentation areas, and the transport is southward directed. From there, sediment is transported to the north inlet side and a local sedimentation region is formed. A steady accretive trend is observed along the south coastline that has a net southward direction. The presence of SE wave conditions induces a net northward transport pattern in both coastlines. The erosive trend in the upper north coast is still present, while divergence of transport is absent.

The impact of resorts along Cua Dai beach is assessed in the second morphological scenario. Their presence affected only the morphology of the north coast, creating a more stable coastline among them with limited features. Due to their construction, the sediment transport divergence location shifted more south. It has been concluded that the resorts enhanced the propagation of erosion further to the north.

ACKNOWLEDGEMENTS

This study is part of the PhD dissertation of the first author and part of the master thesis of the second author. The PhD dissertation of the first author funded through an Erasmus Mundus Mobility Program with Asia (EMMAsia2014) and supported by Delft University of Technology. The authors gratefully acknowledge their co-author Dr Nguyen Trung Viet, Prof.Dr Marcel Stive and Dr.ir Sierd de Vries for contributing in discussion part and correct the manuscript of the paper.

REFERENCES

Avinash, K., Deepika, B., & Jayappa, K. S. (2013). Evolution of spit morphology: a case study using a remote sensing and statistical based approach. Journal of coastal conservation, 17(3), 327-337.

Bertin, X., Fortunato, A. B., and Oliveira, A. (2009). A modeling-based analysis of processes driving wave-dominated inlets. Continental Shelf Research, 29(5-6):819–834.

Chen, W. W., & Chang, H. K. (2009). Estimation of shoreline position and change from satellite images considering tidal variation. Estuarine, Coastal and Shelf Science, 84(1), 54-60.

Chen, J.-L., Hsu, T.-J., Shi, F., Raubenheimer, B., and Elgar, S. (2015). Hydrodynamic and sediment transport modeling of new river inlet (nc) under the interaction of tides and waves. Journal of Geophysical Research: Oceans, 120(6):4028–4047.

Daly, C. J., Bryan, K. R., Roelvink, J. A., Klein, A. H. F., Hebbeln, D., and Winter, C. (2011). Morphodynamics of embayed beaches: The effect of wave conditions. Journal of Coastal Research SI, 64(64):1003–1007.

Dissanayake, D., Roelvink, J., and Van derWegen,M. (2009). Modelled channel patterns in a schematized tidal inlet. Coastal Engineering, 56(11-12):1069–1083.

Do, A. T., de Vries, S., and Stive, M. J. (2017). Beach evolution adjacent to a seasonally varying tidal inlet in central vietnam. Journal of Coastal Research, 34(1):6–25.

Do, A. T., de Vries, S., and Stive, M. J. (2019). The estimation and evaluation of shoreline locations, shoreline-change rates, and coastal volumechanges derived from landsat images. Journal of Coastal Research (JCR), 35(1):56–72.

Dolan, R., Hayden, B., & Heywood, J. (1978). A new photogrammetric method for determining shoreline erosion. Coastal Engineering, 2, 21-39.

Guillén, J., Stive, M. J. F., & Capobianco, M. (1999). Shoreline evolution of the Holland coast on a decadal scale. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 24(6), 517-536.

Grunnet, N. M., & Ruessink, B. G. (2005). Morphodynamic response of nearshore bars to a shoreface nourishment. Coastal Engineering, 52(2), 119-137.

Herrling, G. and Winter, C. (2014). Morphological and sedimentological response of a mixed-energy barrier island tidal inlet to storm and fair-weather conditions. Earth Surface Dynamics, 2(1):363–382.

Hallermeier, R. J. (1978). Uses for a calculated limit depth to beach erosion. In Coastal Engineering 1978, pages 1493–1512.

Maiti, S., & Bhattacharya, A. K. (2009). Shoreline change analysis and its application to prediction: A remote sensing and statistics based approach. Marine Geology, 257(1-4), 11-23.

Nahon, A., Bertin, X., Fortunato, A. B., and Oliveira, A. (2012). Process-based 2dh morphodynamic modeling of tidal inlets: A comparison with empirical classifications and theories. Marine Geology, 291:1–11.

Panda, U. S., Mohanty, P. K., & Samal, R. N. (2013). Impact of tidal inlet and its geomorphological changes on lagoon environment: A numerical model study. Estuarine, Coastal and Shelf Science, 116, 29-40.

Ridderinkhof, W., Swart, H., Vegt, M., and Hoekstra, P. (2016). Modeling the growth and migration of sandy shoals on ebb-tidal deltas. Journal of Geophysical Research: Earth Surface, 121(7):1351–1372.

Silvester, R. (1960). Stabilization of sedimentary coastlines. Nature, 188(4749), 467.

Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L., and Ergul, A. (2009). The digital shoreline analysis system (dsas) version 4.0-an arcgis extension for calculating shoreline change. Technical report, US Geological Survey.