Processes of long-term coastal evolution and their mathematical modelling

Application to the Mozambican coast

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Different processes in response to the action of natural driven forces and the human interference on coastal systems act together, contributing to shape the coast. Coastal evolution models have been developed as useful tools to better understand the contribution of different processes on observed coastal changes, and also to anticipate future evolution in response to different actions and interventions taking place along the coast.

The predominant practice in coastal modelling is to have models that address separately the evolution as a result of cross-shore sediment transport processes from the ones caused by processes with main effects on the alongshore sediment transport. However, if longer time and spatial scales are to be covered by such models, a combination of cross-shore and longshore processes is crucial. In this context, the thesis explores the possibility of improving the mathematical modelling of long-term coastal evolution by integrating cross-shore evolution processes into a regional coastal evolution model.

The developed models were satisfactorily tested against available data, as they could reproduce the observed coastal evolution. The model development stage was followed by its application to simulate the long-term coastal evolution of selected coastal stretches of Mozambique's 2800-km-long coastline. Based on a literature review of different processes influencing the evolution of the Mozambican coast, the potential contribution of mathematical models to improve the local coastal planning and management was explored.

With the model application to the Mozambican coast, it was possible to estimate sediment transport rates, and to reproduce the long-term evolution of the coast, for a period up to nearly two decades. For that reason, mathematical models are considered a valid tool to improve the understanding of the historical long-term coastal evolution, and to anticipate how it will change in the future. The latter information would be valuable for the improvement of the protection of coastal sensitive systems, reinforcing the integration component, the use of soft approaches in coastal protection projects, and for the definition of setback lines.

Key words: coastal evolution, Mozambican coast, mathematical models, sediment transport, Macaneta

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Dedication

I dedicate this thesis work to my family and friends who have unconditionally supported me in different stages of my personal and professional growth.

May this work be an inspiration to my son, Akili, and to all my godchildren, nieces and nephews.

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In the lottery of life, I was blessed with an open mind which gave me a great opportunity to increase my knowledge, and to explore an always amazing world far beyond the borders of my country. For that reason, I am grateful to God.

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This thesis work is also a result of teamwork and cooperation. Thus, I would like to recognize collaboration of all co-authors of appended papers: Caroline Frediksson, Tiago Oliveira, Manel Grifoll, Cristina Viola, Bárbara Marinho and Carlos Coelho. I am equally grateful to Christofer Karlsson, Johan Liljedahl, Sofie Björnberg, Siri Wahlström, and Fátima Ismael for having conducted research work that gave inputs to appended papers.

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Popular science summary

All over the world, there is an increasing pressure and appetence for human settling and concentration of economic and recreation activities along the coast. This is equally a valid trend in Mozambique, a country with the fourth longest coastline in Africa, where two in each five inhabitants live in coastal districts.

This worldwide pattern of increasing population density towards the coast contrasts with the relative high exposure and consequent vulnerability of coastal areas to different climatic forces. Coastal strips are permanently exposed to waves, wind action, and cyclical variations in the sea water imposed by the tidal regime. During the occurrence of extreme climate events such as storms and cyclones the magnitude of these actions are amplified, disturbing even more the natural coastal environment.

Man is equally an important protagonist behind observed changes along the coast. Different houses, roads and many other infrastructures are built along the coast to accommodate the population living in these areas, but also to support different touristic and economic activities developed along the coast. Special focus goes to constructions of ports and subsequent dredging of the access channels and for the construction of coastal protection structures. These infrastructures, which are in permanent or temporary contact with the sea water, change the natural pattern of sediment (sand or gravel) transport observed along the coast. Numerous times, the resulting effects of human intervention in the coast is not limited to the project area, but are also extending into areas far outside the intervention areas, up to hundreds of kilometres. The interventions may also have an effect in time which can be felt decades after the causing intervention.

These and many other dynamics that can be observed along the coast justify the need for a proactive and conscious reaction to cope with changes that can occur along the coast, whether induced by natural forces or driven by anthropogenic actions. Conscious intervention demands a solid knowledge about the different processes behind the coastal evolution. This knowledge is critical to categorize effects of different natural actions and interventions taking place along the coast, as well as in a learning-by-doing process, to separate what works from what can result in complete disaster.

Nevertheless, often there is limited historical information available about past events and resulting evolution of the coast. It can be the case that rather than a simple qualitative description that the coast will erode and consequently the shoreline will recede towards the land, we need to know what will be the eroded volume and the range of expected recession. It can also be the case that we need to test the resulting effect of different coastal protection interventions, which is not feasible at large scale in the laboratory or in a real scale of the natural coast.

To address these demands, we need mathematical models which are a valid representation of a certain reality. In line with this conclusion, mathematical models were developed to simulate coastal evolution in periods extending from years to decades, and distances going from tens to hundreds of kilometres. The major research contribution from this model development is that the processes of sediment transport in the direction parallel (alongshore) and perpendicular (cross-shore) to the coast are simultaneously treated and their combined effects simulated at a regional scale.

The developed models comprise a collection of mathematical concepts based on physical insights that can reproduce observed changes in coastal areas, *i.e.*, main processes are identified and different governing factors are expressed through sets of variables that influence these processes. The conceptual relation between identified variables yielded equations which were solved using analytical or, for the most complex cases, numerical techniques.

Aiming for the integration of cross-shore processes with the alongshore sediment transport, the present study started by improving the long-term simulation of the sediment exchange in a direction perpendicular to the coast. This was made possible through review and improvement of modules that compute volumes of sediment mobilized by dune erosion on its seaward side, the transport of sediment to the landward side of the dune (known as overwash), dune growth due to wind-blown sand transport, and the exchange of sediments between the berm and the bar. Later these cross-shore modules, which in combination form the so called cross-shore (CS) model, were integrated into a longshore sediment transport model know as Cascade, yielding the Cascade-CS model.

Prior to application, the different components (modules) were tested and validated against existing high-quality data from different coastal locations around the world. This implies that the models in general will be robust and reliable, if they succeed to reproduce observed phenomena. The models were subsequently employed to simulate the long-term coastal evolution at Macaneta spit and to quantify the sediment transport along the Machangulo Peninsula in Mozambique.

Results from the models application in Mozambique indicated their high potential to improve the understanding historical evolution of the Mozambican coast, and consequently to predict the future development of similar coastal stretches. Therefore, they can give valuable inputs to improve the protection of coastal sensitive systems, reinforce the integration component, the use of soft approaches in coastal protection projects, and for the definition of setback lines.

Overall, the long-term modelling capability of the CS model in standalone mode, or of the Cascade-CS model that integrates both longshore and cross-shore processes, makes it possible to address wide variety of climate change scenarios of sea level rise, as long-term sea level variations can be accounted for. It is equally useful for risk assessment, as the results from long-term runs make it possible to identify critical scenarios when severe erosion occurs along the studied coastal systems. In addition, further statistical treatment may be adopted to assess recurrence periods of certain magnitudes of erosion which impose a high risk to the system. By providing more reliable empirical based predictions for longer periods, the developed models are valid tools for a more conscious decision-making process during the planning and development of coastal areas. Consequently, they stand as useful tools to improve the much-needed integrated coastal zone management.

Resumo ciência popular

Em diferentes partes do mundo, existe uma crescente pressão e apetência para o surgimento de aglomerados populacionais e concentração de actividades económicas e recreativas ao longo da costa. Esta é uma tendência igualmente válida em Moçambique, um país com a quarta linha de costa mais extensa de África, onde dois em cada cinco dos seus habitantes vive em distritos costeiros.

Este padrão global de uma crescente densidade populacional em direcção à costa contesta com a relativa grande exposição e consequentemente vulnerabilidade das áreas costeiras à diferentes acções climáticas. As faixas costeiras estão permanentemente expostas às ondas, acção do vento e variações cíclicas no nível do mar impostas pelo regime de marés. Durante a ocorrência de eventos climatéricos extremos, tais como tempestades e ciclones, as magnitudes dessas acções são amplificadas, perturbando ainda mais o ambiente costeiro natural. O Homem é igualmente um protagonista importante por detrás das mudanças observadas ao longo da costa. Habitações, estradas e muitas outras infraestruturas são edificadas ao longo da costa para acomodar a população residente nessas áreas, mas também para apoiar diferentes actividades turísticas e económicas desenvolvidas ao longo da costa. Enfoque especial vai para a construção de portos e subsequente dragagem de canais de acesso e para a construção de estruturas de protecção costeira. Estas infraestruturas, que estão em contacto temporário ou permanente com as águas do mar, alteram o padrão natural do transporte de sedimentos (areia ou cascalho) observado ao longo da costa. Muitas vezes, os efeitos resultantes de intervenções do homem na costa não se limitam à área de projecto, mas estendem-se para além da área de intervenção, podendo chegar às centenas de quilómetros. As intervenções podem igualmente ter um efeito prevalecente que pode fazer-se sentir décadas depois da acção geradora.

Estas e muitas outras dinâmicas que podem ser observadas ao longo da costa justificam a necessidade de uma reacção proactiva e consciente para lidar com as mudanças que possam ocorrer ao longo da costa, quer sejam induzidas por acções naturais ou antropogénicas. Intervenções conscientes exigem um conhecimento sólido sobre os diferentes processos por detrás da evolução costeira. Esse conhecimento é crítico para categorizar efeitos de diferentes acções naturais e intervenções que tem lugar ao longo da costa, bem como no processo de aprendizagem por experimentação, para separar o que funcional do que pode resultar num completo desastre.

Contudo, frequentemente, a disponibilidade de informação histórica sobre eventos passados e evolução da costa deles resultantes é limitada. Casos há em que mais do que uma simples descrição qualitativa de que a costa irá erodir e consequentemente a linha da costa irá retroceder, precisamos estimar qual o volume erodido e o alcance da expectável recessão. Casos há em que precisamos testar o efeito de diferentes intervenções de protecção costeira, o que não é viável em grande escala em laboratórios ou na escala real da costa.

Para solucionar estas exigências, precisamos de modelos matemáticos que sejam uma válida representação de uma determinada realidade. Em linha com esta conclusão, modelos matemáticos foram desenvolvidos para simular a evolução costeira em períodos que se estendem de anos a décadas, e distâncias que vão de dezenas a centenas de quilómetros. A principal contribuição desta acção de desenvolvimento de modelos reside no facto de processos de transporte de sedimentos na direcção paralela a costa (longitudinal ou ao longo da costa) e perpendicular (transversal) serem considerados em simultâneo, e o seu efeito combinado simulado numa escala regional.

Os modelos desenvolvidos compreendem uma colecção de conceitos matemáticos baseados em conhecimentos físicos que com sucesso explicam as mudanças observadas na zona costeira; isto é, os principais processos estão identificados e os diferentes factores regedores são expressos através de um conjunto de variáveis com influência nesses processos. A relação conceptual entre as variáveis identificadas resultaram em equações que foram resolvidas analiticamente ou com recurso à métodos numéricos para os casos mais complicados.

Perspectivando a integração dos processos de transporte transversal com o transporte ao longitudinal dos sedimentos, o presente estudo iniciou por aprimorar a simulação a longo termo da transferência de sedimentos na direcção transversal à costa. Tal aprimoramento foi possível através da revisão e melhoria de módulos empregues no cálculo do volume de sedimento mobilizado pela erosão dunar a barlavento (face exposta à agitação marítima), transportado para sotavento (face abrigada) através do processo de *overwash*, crescimento das dunas pelo transporte eólico, e na transferência de sedimentos entre a berma e a barra. A posterior, esses módulos de transporte transversal, que em conjunto forma modelo de transporte transversal (modelo CS), foram integrados num modelo de transporte longitudinal de sedimentos denominado Cascade, resultando num novo modelo Cascade-CS.

Antes da sua aplicação, os diferentes componentes (módulos) foram testados e validados com dados de elevada qualidade de trechos de costa de diferentes partes do mundo. Este exercício implica que no geral os modelos são considerados robustos e fiáveis se eles conseguirem reproduzir um fenómeno observado. Os modelos foram posteriormente empregues para simular a evolução costeira a longo termo na Restinga da Macaneta, e para quantificar o transporte de sedimentos ao longo da Península de Machangulo em Moçambique.

Os resultados da aplicação dos modelos em Moçambique indicaram o seu elevado potencial para melhor compreensão da evolução histórica da costa moçambicana e, consequentemente, para prever a evolução futura de trechos de costa similares aos estudados. Por conseguinte, os modelos podem dar subsídios valiosos para melhorar a protecção de sistemas costeiros vulneráveis, reforçar a componente de integração, promover o uso de soluções de protecção costeira mais leves, e para a definição de linhas de recuo da costa.

No geral, as capacidades de modelação do modelo CS no modo autónomo, ou do modelo Cascade-CS que integra ambos processos longitudinais e transversais de transporte, tornam possível o tratamento uma variedade cenários de mudanças climáticas de subida do nível das águas do mar por considerar as variações no nível do mar a longo termo. São igualmente úteis para avaliação do risco pois os resultados das execuções a longo-termo tornam possível a identificação de cenários críticos correspondentes a ocorrência de eventos de erosão severos ao longo dos sistemas costeiros estudados. Adicionalmente, um posterior tratamento estatístico pode ser empregue para avaliar os períodos de retorno de certas magnitudes de erosão que representam um elevado risco para o sistema. Ao proporcionar previsões com bases empíricas mais fiáveis para períodos longos, os modelos desenvolvidos são ferramentas válidas para um processo de tomada de decisão mais consciente durante a planificação e desenvolvimento de zonas costeiras. Consequentemente, eles sobressaem como ferramentas úteis para melhorar a tão necessária gestão integrada das zonas costeiras.

Abstract

Different processes in response to the action of natural driven forces and the human interference on coastal systems act together, contributing to shape the coast. Coastal evolution models have been developed as useful tools to better understand the contribution of different processes on observed coastal changes, and also to anticipate future evolution in response to different actions and interventions taking place along the coast.

The predominant practice in coastal modelling is to have models that address separately the evolution as a result of cross-shore sediment transport processes from the ones caused by processes with main effects on the alongshore sediment transport. However, if longer time and spatial scales are to be covered by such models, a combination of cross-shore and longshore processes is crucial. In this context, the thesis explores the possibility of improving the mathematical modelling of long-term coastal evolution by integrating cross-shore evolution processes into a regional coastal evolution model.

The developed models were satisfactorily tested against available data, as they could reproduce the observed coastal evolution. The model development stage was followed by its application to simulate the long-term coastal evolution of selected coastal stretches of Mozambique's 2800-km-long coastline. Based on a literature review of different processes influencing the evolution of the Mozambican coast, the potential contribution of mathematical models to improve the local coastal planning and management was explored.

With the model application to the Mozambican coast, it was possible to estimate sediment transport rates, and to reproduce the long-term evolution of the coast, for a period up to nearly two decades. For that reason, mathematical models are considered a valid tool to improve the understanding of the historical long-term coastal evolution, and to anticipate how it will change in the future. The latter information would be valuable for the improvement of the protection of coastal sensitive systems, reinforcing the integration component, the use of soft approaches in coastal protection projects, and for the definition of setback lines.

Resumo

Diferentes processos em resultado da acção de forças naturais e da interferência humana nos sistemas costeiros actuam em conjunto, contribuindo para moldar a costa. Modelos de evolução costeira tem sido desenvolvidos e empregues para antever a sua evolução futura em resposta às diferentes acções e intervenções que tem lugar ao longo da costa. Estes modelos são ferramentas úteis para melhorar a compreensão da contribuição de diferentes processos nas mudanças observadas na costa.

A prática comum na modelação costeira é o da utilização de modelos que descrevem separadamente a evolução resultante de processos de transporte de sedimentos na direcção transversal à costa dos causados por processos com efeitos principais no transporte de sedimento ao longo da costa. Contudo, se escalas temporais e espaciais mais extensas devem ser cobertas por tais modelos, um tratamento conjunto dos processos de transportes transversais e ao longo da costa é crucial. Nesse contexto, esta tese explora a possibilidade de aprimorar a modelação matemática de processos de evolução costeira a longo termo com integração processos de evolução transversais num modelo de regional de evolução costeira.

O desempenho dos modelos desenvolvidos foi satisfatoriamente testado por comparação com dados disponíveis, tendo os mesmos sucedido na reprodução da evolução costeira observada. A fase de desenvolvimento dos modelos foi seguida da sua aplicação para simular a evolução a longo termo de trechos seleccionados dos 2800 km de extensão da costa de Mozambique. Com base na revisão bibliográfica de diferentes processos com influência na evolução da costa moçambicana, a potencial contribuição dos modelos matemáticos para melhorar a planificação e gestão foi explorada.

Com a aplicação dos modelos à costa de Moçambique foi possível estimar taxas de transporte sedimentar e reproduzir a evolução a longo termo da costa, para um período de aproximadamente duas décadas. Por esse motivo, os modelos matemáticos são considerados uma ferramenta válida para melhorar a compreensão da evolução histórica a longo termo da costa, e para antecipar mudanças futuras. Esta última informação é de grande valor para melhorar a protecção de sistemas costeiros vulneráveis, reforçar a componente de integração e o uso de alternativas de protecção costeira leves, e para a definição de linhas de recuo da costa.

Appended papers

This thesis is based on the following papers which will be referred to by their Roman numerals in the body of the text. The papers are appended at the end of the thesis.

I. Viola, C.N.A., Grifoll. M., **Palalane, J.**, and Oliveira, T.C., 2014. Wave propagation to Maputo coast. Application to longshore sediment transport. *Water Science and Technology*, 69(12), 2438-2445. doi:10.2166/wst.2014.162

II. **Palalane, J.**, Larson, M., Hanson, H., and Juízo, D., 2015. Coastal erosion in Mozambique: Governing processes and remedial measures. *Journal of Coastal Research*, published online on 27 January 2015. doi:10.2112/JCOASTRES-D-14-00020.1

III. Larson, M., **Palalane, J.**, and Hanson, H., 2015. Sandy Spits and Their Mathematical Modelling, in: Randazzo, G., Jackson, D.W.T., and Cooper, J.A.G. (Eds.), *Sand and Gravel Spits*. Springer. doi:10.1007/978-3-319-13716-2

IV. Larson, M., **Palalane, J.**, Fredriksson, C., and Hanson, H., 2016. Simulating cross-shore material exchange at decadal scale. Theory and model component validation. *Coastal Engineering* (under revision).

V. **Palalane, J.**, Fredriksson, C., Marinho, B., Larson, M., Hanson, H., and Coelho, C., 2016. Simulating cross-shore material exchange at decadal scale. Model application. *Coastal Engineering* (under revision).

VI. **Palalane, J.**, Larson, M., 2016. A long-term coastal evolution model with longshore and cross-shore processes. *Journal of Coastal Research* (submitted).

Author's contribution to appended papers

Paper I The author participated in the writing, the discussion of the results of the wave propagation and the sediment transport calculations, and the final review of the paper.

Paper II The author did the literature review, conducted field visits to selected coastal sites, and was the main contributor to the writing of all sections and of the discussion with regard to the main findings of the paper.

Paper III The author participated in the model calculations, data compilation and analysis, and contributed to the writing of the paper as well to the discussion of the main findings.

Paper IV The author contributed to the discussion of the theoretical developments, model calculations, and participated in the writing of the paper.

Paper V The author conducted field work and data collection campaigns, performed adjustments to the original model formulations, implemented the model for one of the study sites, participated in the writing of different sections, and contributed with comments and the review of the whole article.

Paper VI The author participated in the conceptual discussion of the model structure and the model development, the implementation at the study sites, and in the discussion, writing, and final review of the paper.

Other related publications

Conference Proceedings

Palalane, J., Grifoll, M., and Oliveira, T., 2013. Monitorização e Modelação da Evolução Costeira em Moçambique. Práticas e Desafios (Monitoring and modelling coastal evolution on Mozambique. Practices and challenges). *Proceedings of the VII Congresso sobre Planeamento e Gestão das Zonas Costeiras dos Países de Expressão Portuguesa 2013.* Maputo, Mozambique (on CD).

Larson, M., Hanson, H., and **Palalane, J.**, 2013. Simulating cross-shore material exchange in long-term coastal evolution models. *Proceedings of Coastal Dynamics 2013*. Arcachon, France. pp. 1037-1048.

Palalane, J., Larson, M., and Hanson, H., 2014. Analytical model of sand spit evolution. *Proceedings of the 34th International Conference on Coastal Engineering* (Seoul, South Korea, ASCE).

Palalane, J., Larson, M., and Hanson, H., 2015. Modelling dune erosion, overwash and breaching at Macaneta spit, Mozambique. *Proceedings of Coastal Sediments 2015* (San Diego, California, ASCE).

Ismael, F., **Palalane, J.**, and Oliveira, T., 2015. Análise probabilística da vulnerabilidade da zona costeira da Cidade de Maputo à tempestades marítimas (Probabilistic analysis of the vulnerability of Maputo City coast to maritime storms). *Proceedings of the VIII Congresso sobre Planeamento e Gestão das Zonas Costeiras dos Países de Expressão Portuguesa 2015* (Aveiro, Portugal).

Co-supervised Master Thesis

Björnberg, S., and Wahlström, S.L., 2012. Coastal Erosion in Maputo, Mozambique. Governing processes and mathematical modeling. Master Thesis TVVR 12/5022, Lund University.

Karlsson, C., and Liljedahl, J., 2015. Coastal evolution at Macaneta Spit, Mozambique - an analysis of longshore and cross-shore processes. Master Thesis TVVR 15/5010, Lund University.

Co-supervised and supervised *Licenciatura* Thesis

Viola, C.N.A., 2012. Propagação da Agitação Marítima do Largo para a Costa de Maputo (Wave propagation to Maputo coast. Application to longshore sediment transport). Aplicação ao Transporte Longitudinal de Sedimentos. Universidade Eduardo Mondlane.

Francisco, C., 2013. Modelação Numérica da Interacção entre Ondas e Estruturas de Protecção Costeira (Numerical modeling of the interaction between waves and coastal protection structures). Universidade Eduardo Mondlane.

Ismael, F.F., 2014. Análise da vulnerabilidade de zonas costeiras à tempestades. Aplicação à costa da Cidade de Maputo (Probabilistic analysis of the vulnerability of Maputo City coast to maritime storms). Universidade Eduardo Mondlane.

Abbreviations and symbols

a – porosity [-]

A – coefficient expressing the ratio of overwash, parameter of the Dean equilibrium beach profile [-]

A_e, A_e^o, A_S – equilibrium spit area, initial A_e, spit cross-section area [m^2]

c_f – bottom friction coefficient [-]

C, C_g – wave celerity, group wave celerity [m/s]

C_B – coefficient for the equilibrium bar volume [-]

C_S – impact formula empirical coefficient [-]

CERC – Coastal Engineering Research Center

CS – cross-shore

D, D_o, ΔD – active spit profile height, initial D, increase in D [m]

D_B, D_C – berm elevation, depth of closure [m]

F – wave energy flux directed towards the shore [Nm/ms]

GEBCO - General Bathymetric Chart of the Oceans

GIS – Geographic Information System

h, h_b – water depth, at breaking

H, H_o – wave height, at deep water [m]

ICZM – Integrated Coastal Zone Management

K – transport rate coefficient at the CERC formula

K_β – spit shape factor [-]

L, L_o – wave length, at deep water [m]

LS – longshore

m – empirical coefficient for varying LS transport along a spit [-]

MSL, MHWSL – mean sea level, mean high water spring levels

n – porosity [-]

q_D, q_L, q_S, q_{SB} – cross-shore transport rate from dune face erosion, overwash (landward), backwash (seaward), bar-berm material exchange [m^3/m]

q_W, q_{WE} , q_{WL}, q_{WS} – wind-blown sand transport, at saturation, landward, seaward [m^3/m]

Q_L, Q_o – longshore sediment transport, potential Q_L [m^3/s or m^3/yr]

Q_{in}, Q_{out} – input, output sediment transport to the system [m^3/yr]

R – runup height [m]

s – dune height [m]

t, Δt – time, change in time [s or yr]

T – wave period [s]

$\overline{V}$ – surf-zone average longshore current velocity [m/s]

V_B , V_o, V_{BE}, ΔV_B – bar volume, at $t = 0$, at equilibrium, change in bar volume [m^3/m]

V_D – dune volume [m^3/m]

WW3 - wave model from the US National Centers for Environmental Prediction

x_S – location of the tip of the spit [m]

y_B, y_G, y_L, y_S – location of the berm, still-water, landward dune foot, seaward dune foot [m]

z_D – dune elevation (measured from MSL to the dune foot) [m]

β_F, β_L, β_S – foreshore, landward, seaward dune/spit slope [-]

δ – wind-blown transport growth coefficient [-]; incipient wave breaking correction coefficient [-]

γ_b – breaker depth ratio [-]

ε – empirical transport coefficient for LS sediment transport equation [-]

ρ, ρ_S – water density, sediment density [kg/m^3]

θ_b, θ_{bS} – breaking wave angle, θ_b relative to the shoreline [º]

λ – rate coefficient for changes in bar volume [m^3/m]; incipient breaking wave parameter [-]

ω – sediment fall speed [m/s]

Ψ – spit cross-section shape parameter [-]

Contents

1 Introduction

1.1 Background and identification of the problem

Coastal areas are dynamic zones which are in constant change due to different forces that induces cross-shore and longshore sediment transport. In contrast with its exposure, coastal areas exhibit the highest population densities and concentration of economic and recreation activities. This increasing pressure and development of coastal areas is accompanied by the placement of coastal infrastructure and stabilization interventions which contribute to further reshape the coast. The range of influence of different coastal projects exceeds the local project dimensions (inducing changes tens to hundreds of kilometers away from the intervention area), and extends in time for long periods (years to decades).

On a long-term basis, in the absence of sources and sinks of sediment, the cross-shore transport would be characterized by cycles of erosion and accretion, between more energetic and less energetic seasons. These cycles sustain the idea of cross-shore (CS) oscillations from an equilibrium profile, and that the longshore transport induced by varying longshore gradients are the most important factor to shape wave-dominant coasts (Bosboom and Stive, 2013). These are the principles behind the one-line theory introduced by Pelnard-Considere (1956). Models based on one-line theory, such as GENESIS (Hanson, 1989), Unibest CL+ (Townsend *et al*., 2014) and LITPACK (DHI, 2007), simulate shoreline evolution at large temporal and spatial scales assuming an equilibrium beach profile and ignoring cross-shore changes. However, a model which aims to cover a wider spatial extension should also be prepared to better account for local cross-shore material exchange processes such as beach nourishment, occurrence of overwash and breaching, dune build-up by wind-blown sand, dune and berm material exchange, etc.

Models for simulation of cross-shore sediment transport such as SBEACH (Larson and Kraus, 1989) and XBEACH (Roelvink *et al*., 2009) focus on short-term changes (hours to days). Existing 3D models which jointly address longshore and cross-shore transport and resulting evolution such as Delft-3D demands lots of computational resources to make it possible to run simulations which can extend in time to cover decades, and in space extending from tens to hundreds kilometers. Recent developed models to address large time-scales within acceptable computation times (e.g., Hanson *et al*., 2010; Hoan *et al*., 2011; Jiménez and Sánchez-Arcilla, 2004; Larson *et al*., 2002; Ranasinghe *et al*., 2013) come with the limitation of having a simplified representations of the cross-shore material exchange, such as the adoption of sources and sinks of sediments with schematized varying values in space and time.

Building on previous existing knowledge, this thesis contributes to address these issues. Special focus is directed to the improvement of a regional coastal evolution model, known as Cascade (Larson *et al*., 2002), to take into account processes of local cross-shore exchange of materials in a long-term perspective, while keeping models robustness and reasonable computation times. Cascade was developed to bridge the gap between shoreline evolution models and a sediment budget approach, in order to better predict coastal evolution in larger time and special scales associated with long-term processes. The Cascade model approach considers that processes at different spatial and temporal scales act simultaneously in what can be viewed as cascading of scales from regional to local. As part of this effort, the theory needed to develop the lacking cross-shore material exchange sub-models in Cascade is formulated and tested against laboratory and field data. In addition to that, a significant model development effort of the thesis is directed to better describe local processes of spit growth to be further incorporated in Cascade or other regional coastal evolution models.

Developed and improved models are employed to predict the resulting effect of coastal engineering projects in different study sites. A special focus of the modelling application is directed to the Mozambican coast, aiming to contribute to an increase of the limited available knowledge about the coastal processes which have been contributing to shape the coast.

1.2 Objectives of the research

The main objective of conducted research was to develop a mathematical model to simulate the sediment transport and long-term coastal evolution at the regional scale, with focus on the conditions along the Mozambique's coast.

In order to achieve the main objective of the thesis, the following specific objectives were deemed necessary:

1. Perform a literature review to document coastal evolution in Mozambique together with the governing processes. Summarize observed problems

concerning sediment transport, erosion, and accretion, and the solutions employed to deal with these problems.

2. Compile available data sets on long-term coastal evolution in the open literature of relevance for the modelling and review available data from the Mozambique coastline.
3. Formulate governing equations concerning cross-shore sediment transport and profile response, both for the subaerial and subaqueous portion of the profile, and test it against available data.
4. Develop a model of spit growth and test it against available data.
5. Integrate the sub-models for cross-shore transport and spit growth into a general regional coastline evolution model and simulate coastal evolution for compiled data sets in a validation procedure.
6. Simulate coastal evolution for selected areas along the Mozambique Coast, and explore the possibilities to integrate the results in a coastal zone management context.

1.3 Overall methodology

To fulfill the aim of the thesis, this research adopted different methods which helped to address all specific objectives as indicated below:

- Literature review to collect relevant data and information regarding coastal evolution in Mozambique, and to get a better insight about strengths and weaknesses of different coastal evolution models prior to the model development.
- Field work campaigns to collect samples to characterize sediment size, and to perform topographic surveys to describe emerged and immersed portions of the beach cross-section profile, and to map the shoreline positions.
- Generation of local wave data (in the absence of instrumental wave measurements covering the Mozambican coast) from offshore waves and wind

reanalysis data from different global repositories and locally available instrumental measurements. Generated waves were further used in different model applications along the Mozambican coast.

- Model development to improve calculation routines for spit growth and cross-shore sediment exchange, and their further integration into the main code of a long-term coastal evolution model.
- Model application as a useful mean to evaluate the performance of the developed models at selected sites, and their further application at different coastal stretches of Mozambique to get subsidies regarding their coastal evolution.

1.4 Limitations of the study

One important part of this thesis work complied the application of long-term evolution models to the Mozambican coast. These applications were limited by the availability of instrumental wave measurements, and good quality historical shoreline and beach profile records.

1.5 Thesis structure

This thesis consists of a thesis summary and a compilation of appended papers. The summary initiates with an introductory chapter which briefly presents the background, identifies the problems that are addressed, and the relevance of the study. The following chapters of the summary go through different issues retracted in the appended papers, and show how they contribute to fulfill the main and specific objectives defined for this thesis. Chapter 2 details the methodological approach. It is followed by Chapter 3 which explores relevant issues of the coastal evolution, planning and management in Mozambique. Chapters 4 and 5 focus on model development and application. At last, Chapter 6 presents the main conclusions of the thesis.

The research results are distributed as follows in the appended papers:

Paper I, in line with the specific objectives 1 and 6, explores a simple approach for initial estimates of sediment transport rates, the potential contribution from reanalysis waves, and bathymetric datasets from global repositories.

Paper II, in line with specific objectives 1 and 2, summarizes relevant aspects of the recent coastal evolution of Mozambique, identifies problems and challenges, and assesses the influence of different cross-cutting issues on coastal evolution.

Paper III, in line with specific objective 4, describes the state of the art of mathematical modelling of spit evolution with focus on linear spit growth and elongation, and tests it against available laboratorial data and field measurements.

Paper IV, in line with specific objective 3, describes the development of a model to simulate cross-shore sediment transport and profile evolution, and tests its performance with available data from a case of coastal evolution following shortening of a groin.

Paper V, in line with specific objective 6, simulates cross-shore sediment exchange and beach profile evolution in three different case studies, namely: Ängelholm in Sweden, Barra in Portugal, and Macaneta in Mozambique.

Paper VI, in line with specific objective 5, describes the integration of a sub-model for cross-shore transport into a general regional coastal evolution model and simulates coastal evolution for compiled data sets to validate it; in line with specific objective 6, applies developed model to simulate the evolution of a coastal stretch of Mozambique.

2 Methodology

The research methodology is best explained by exploring the adopted research strategy. As many engineering studies, the philosophical approaches adopted to build the knowledge presented in this thesis falls largely into the class of empiricism, *i.e.* acquisition of knowledge through experience or observation of a given phenomenon (Christensen *et al.*, 2010; Wenning, 2009).

Two main empirical methodologies were adopted throughout the performed research: induction and deduction. Induction consists on the generation of principles expressing general relationship between variables, and laws expressing specific relationships between certain observable quantities (Wenning, 2009). Deduction consist on the generation of predictions based on principles, laws, hypotheses, or theories (Wenning, 2009). These empirical methodologies made use of different methods and tools which are detailed in the following sections.

2.1 Literature review

The literature review was employed on two main fronts: (1) review of the state of the art of coastal erosion in Mozambique; and (2) critical review of relevant empirical research about coastal processes and their mathematical modelling. The first was undertaken to summarize the characteristics of coastal areas, and to identify the main factors that are contributing to shape the Mozambican coast, as detailed in **Paper II** and in Chapter 3, in a concise mode. This front of the literature review was also important for the analysis of information brought together about coastal planning and management, aiming to identify gaps and opportunities to achieve a better integration, and to assess the potential contribution of mathematical modelling as developed under Section 5.4.

The second front of the literature review was implemented to describe and evaluate how explored coastal evolution processes during this research are converted to different mathematical concepts and formulations, aiming at their final integration into improved models. Identified and analyzed significant contributions from the literature review, and further adopted in improved models, are mainly presented in **Papers III, IV** and **VI**, which describe the modelling development stages.

2.2 Model development

Model development falls into the induction methodology which comprise the integration of different mathematical concepts adopted to describe the complex processes driving the long-term coastal evolution observed in nature. Developed models are deterministic, implying that from observation or experiments we know in advance what to be expected. Thus, in line with the induction methodology, we go from the specific to a generalization as we look for mathematical expressions which can be valid to reproduce the observed and measured coastal evolution at different coastal locations.

The model development started with the identification of the processes that should be expressed in a mathematical way, i.e. by knowing the system. After that follows the identification of variables that together represent the observed evolution of the system. The subsequent step comprises the mathematical description of the relation between relevant variables, *i.e.,* derivation of mathematical equations. At a later stage, derived equations are solved using analytical and numerical techniques, and solutions are brought together into existing coastal evolution models. These model development stages are adopted in appended **Papers III, IV** and **VI**, and summarized under Chapter 4.

2.3 Data collection, processing and analysis

Empirical models are based on observations which are indispensable either to develop or to validate the model application. Data used in different phases of the study were obtained from four main sources: laboratory experiments, field work campaigns, climate reanalysis, and historical documents.

Laboratory experiments consist of tests conducted in physical models which are useful for improving the understanding of cause-effect relations in different coastal processes. Thus, data from laboratory experiments available from previous studies or shared by third parties were employed to derive the best mathematical relations between different variables. The range of values for different empirical model coefficients, expressing the mathematical relation between dependent and independent variables, were also estimated from laboratory data.

Field campaigns were an important source of data, mainly for the model application initiatives. Data from the field were used to optimize the model performance through a calibration and validation process, prior to its application to understand the past or to predict the future evolution.

Consistent instrumental wave data were not available for the Mozambican coast. Thus, the application of coastal evolution models to simulate the long-term evolution of the Mozambican coast made used of reanalysis wave data. The chosen source of reanalysis wave data was the Wave Watch III (WW3) model from NOOA/NCEP (Tolman, 2009). Extracted wave data for offshore wave points (bathymetry higher than 100 m) were later propagated towards the coast. In **Paper I**, wave propagation was performed using the SWAN model (Booij *et al*., 1999) and bathymetry data from GEBCO. **Papers V** and **VI** used a modified version of the EBED model (Nam *et al*., 2009), and a unified bathymetry which resulted from the merge of bathymetric data from GEBCO (Smith and Sandwell, 1997), the hydrographic map of Maputo Bay, and a bathymetric survey performed out of Macaneta and Costa do Sol coast.

The time span of long-term models varies from years to decades. Thus, historical description of the coastal morphologies and observations of shoreline position are a valuable resource to make possible the covering of such time span. Thus, data on historical shoreline positions were extracted from the digitalization of old maps and aerial photos. Historical studies and articles were also useful to obtain past sediment transport rates and reports of severe coastal erosion episodes useful for a qualitative, if not quantitative, evaluation of model application performance. **Papers III**, **V** and **VI** describe the use of historical records of shoreline position, and reports of coastal evolution, respectively.

2.3.1 Field surveys conducted as part of the thesis work

Field survey campaigns were performed as part of this research. They comprised: (1) collection of sediment samples and subsequent granulometric analysis to better characterize the coastal sediment variability at selected coastal locations described in **Paper II**; (2) topographic survey of the beach profiles and shoreline position at Macaneta spit and Costa do Sol using high precision GNSS (Global Navigation Satellite System) differential devices; and (3) bathymetric surveys off of Macaneta spit and Costa do Sol beach using a single beam portable echo sounder to improve the bathymetry description for subsequent wave propagation.

Collected georeferenced data from the field were processed before application using a set of tools from the free and open source GIS (Geographic Information System) software, Quantum GIS, and MATLAB. Data obtained from beach profile surveys, mapping of the shoreline position, and bathymetric surveys were used in model applications in **Papers V** and **VI**.

2.4 Model application

Model application falls into the deduction methodology as the generalized models developed under the thesis are applied to predict the long-term coastal evolution at specific coastal stretches. Model applications were also performed to assess how well the mathematical concepts incorporated in the developed models reproduce the empirical evidence provided by the natural coastal systems. This principle is applied in all model development and/or applications papers appended to this thesis, as summarized in Chapter 5.

3 Overview of the coastal evolution and its management in Mozambique

Mozambique is a country located in the southeast part of the African continent, between latitudes 10º82’70’’S and 26º85’20’’S and longitudes 30º81’20’’E and 40º85’10’’E. Its coast faces the Indian Ocean with an estimated length of 2770 km, being the fourth longest coastline extension in Africa (CIA, 2016; MICOA, 2007).

As detailed in **Paper II**, Mozambique follows the pattern of higher population density near the coast. In this paper, it was estimated that 44% of the country’s population were living in coastal districts in 2007 (year of the last population census), and that five out of the seven most populated urban centers are coastal cities.

The high anthropogenic pressure on coastal areas is a result of the concentration of economic activities along the coast. As the nucleus of developing are becoming stronger on coastal areas, and with the high population growth rate of 2.7% per year that the country is experiencing (INE, 2015), it is expected that the demographic pressure will continue to increase along the coast. The concentration of population and economic activities along the coast reflects and induces the development of different coastal infrastructures with potential to change the pattern of sediment transport and accumulation. It also increases the demand for new coastal protection interventions to defend infrastructured land against coastal erosion and inundation.

3.1 Coastal characteristics

The almost 2800-km extension of the Mozambican coast can be divided into three different geomorphological regions: northern, central and southern regions (Figure 1).

The northern region extends from the Rovuma River mouth down to the Zambezi River delta, with an approximate extension of 1000 km. This region is characterized by a narrow tectogenic band, along the margins of the plateaus of Cabo Delgado and Nampula provinces. The predominance of plateaus dictate that the elevated lands (altitude above 200 m) occur at shorter distances from the shore, with a minimum of 15 km, compared to distances of more than 100 km that can be observed in the other two regions. The dominant feature along this coast is small dunes alternating with cliffs and attached beaches. There is also occurrence of fringing reefs and coral islands on the narrow adjacent continental platform. (Chemane *et al*., 1997; INGC, 2009; Moreira, 2005)

The central region covers the extent between the Zambezi and Save River deltas, with an approximate extension of 980 km. In this region the major rivers, such as Zambezi, Save, Buzi, and Pungoé, drain the continent. For this reason it is also denominated the region of rivers. Thus, the central coast includes a wide fluvial-marine plain, with sandy-muddy soils and beaches. This region is also dominated by swampy depressions with mangroves and a series of low beach ridges. It is also in this region that the continental shelf reaches its maximum width of nearly 145 km in the bight of Sofala, narrowing southwards and northwards (Orme, 2005).

The southern region comprises the extension between the Save River Delta and Ponta do Ouro, with an approximate extension of 850 km. This region is characterized by the predominance of an extensive sandy plain. This sandy plain is accompanied by strips of beach attached to aeolian cliffs, or a system of recent dunes, inland lagoons, sandy barrier islands, and platform barriers of coastal sandstones (Chemane *et al*., 1997; INGC, 2009; Moreira, 2005).

3.2 Hydrodynamics

Due to the lack of continuous measurements, the availability of wave data for the Mozambican coast are very limited. As reported in **Paper II**, numerical models to simulate the offshore wave climate are used as an alternative. The two main sources of reanalysis wave data were from the NOAA Wave Watch III (WW3) model (Tolman, 2009), developed by the US National Centre for Environmental Prediction, and from the European Centre for Medium-Range Weather Forecasts' ERA-40 and ERA-Interim (Caires and Sterl, 2005; Dee *et al*., 2011). Wave data extracted from these reanalysis numerical models were later propagated to the coast, although the lack of good bathymetric data further limited the quality of the calculated propagated wave properties.

Papers I and **II** used data from the WW3 model to characterize the wave climate offshore of the Maputo coast (from 1997 to 2010), and of five other offshore locations along the Mozambican coast (from 2006 to 2013), respectively. As reported in **Paper II**, a general pattern of decrease in the average significant wave height (H_S) from south to north, with H_S = 1.8 m off Maputo to H_S = 1.1 m off the Cabo Delgado coast, and a maximum of H_S = 1.9 m off the Inhambane coast was identified. The maximum significant wave heights also decreased from 6.5 m in the south to a minimum of 3.6 m off of the Nacala coast. The results of decreasing wave heights towards the north confirms the significance of the sheltering effect provided by the Madagascar Island. This idea is strengthened by the fact that the most northern point analysed, located offshore of Pemba coast, had a maximum H_S = 3.8 m, giving an indication of an increase in wave height from Cabo Delgado coast northwards, where the sheltering effect starts to decrease.

Variations in wave conditions, includes changes in predominant wave direction pattern from north to south coast (see Figure 2). In the southern part of the country, waves come predominantly from the SE quadrant and have a bimodal behaviour. Towards the central region, the SSW component becomes more significant, and there is a slight change in direction to the west. In the northern coast, the predominant wave direction is south. Analysing the variability in time, the winter appears as the most energetic period as larger significant wave heights are observed during the winter months (from April to September), and smaller heights during the summer (between October and March). These results are in agreement with the findings from Guiloviça *et al*. (2011), Martins (2012), and Theron and Barwell (2012).

Tides along the Mozambican coast are semidiurnal. According to Theron and Barwell (2012), mean high water spring levels (MHWSL) vary from 1.4 m to 3.7 m above mean sea level (MSL). Overall, lower tide values are observed in the southern coast. The MHWSL was estimated to be equal to 2.9 m in Beira, and decreases southwards and northwards until Maputo where it reaches 1.5 m above MSL, and Mozambique Island where it reaches 1.8 m above MSL. From Mozambique Island, the MHWSL increases northwards reaching a maximum of 3.7 m above MSL in Mocímboa da Praia.

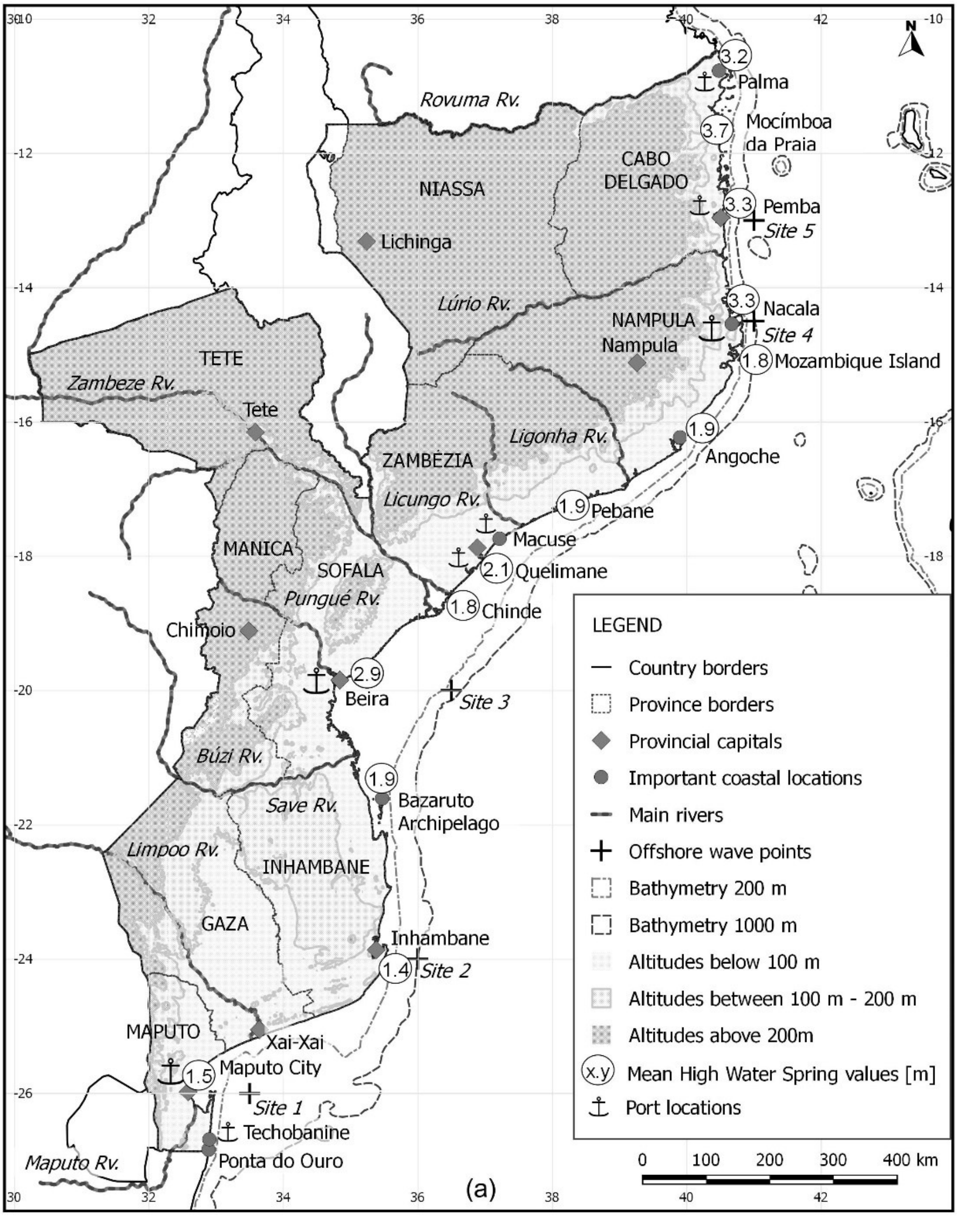

Figure 1. Mozambique's administrative division, port locations, altitude and bathymetric variation, and estimated mean high water spring values at different locations from Theron and Barwell (2012)

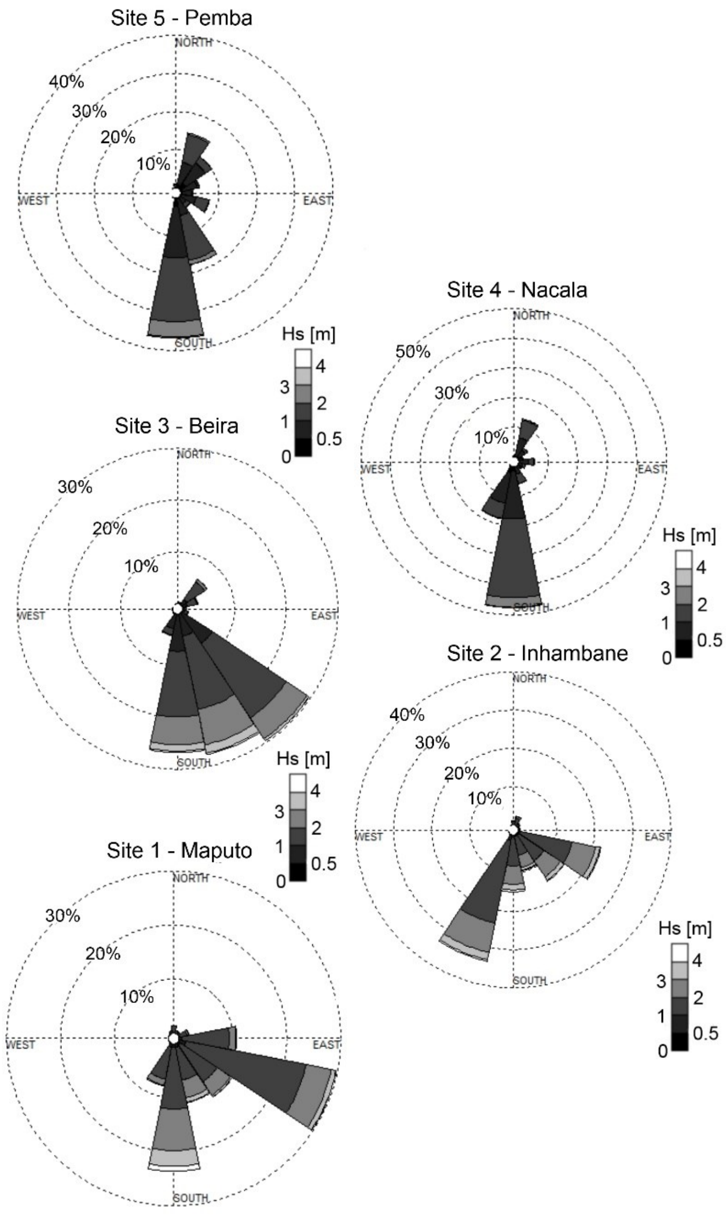

Figure 2. Wave climate variation along the Mozambican coast based on reanalysis data from the WW3 model from year 2006 to 2013

3.3 Sediment transport and morphological change

Different factors may influence the sediment transport and resulting morphological evolution of the Mozambican coast. Orme (2005) mentions that the swells from the Indian Ocean, locally generated waves, prevailing northeasterly and southwesterly winds, and seasonal high river discharges are the main driving forces.

Incident breaking waves generate longshore currents with velocities up to 2 m/s. They are the main agent for mobilizing and moving the sediment along the coast. However, morphological differences in the different coastal regions of the country suggests that there are other complementary processes with a high relevance. The presence of extensive dune fields in the southern coast gives an indication of the importance of wind processes. The central coast, region of rivers, characterized by the occurrence of vast areas fluvial-marine plains with sandy-muddy soils suggest that the influence of processes linked to tidal currents is more significant in this region. In the Save and Zambezi delta regions and in the northern coast the dominant processes depend on wave action.

Besides the sediment mobilization and transport caused by natural forces, humans have also a role to play in the sediment movement along the coast as direct and indirect anthropogenic interventions have a potential to influence the sediment transport pattern. Some examples of direct anthropogenic actions are the construction of coastal protection structures (*e.g.* groins), ports and dredging activities which contribute to intercept and block the sediment on the updrift side of these structures. The construction of houses on top of primary dunes and a few meters from the shoreline (Figure 3), and the unregulated circulation of vehicles (Figure 4) and pedestrians outside walkways and on beach sensitive areas constrain the natural variation of in shoreline position and profile shape. The effects of these direct anthropogenic actions on five coastal stretches are detailed in **Paper I**.

Figure 3. An example of recreational infrastructure exposed to the direct wave action in Maputo City (February 2016)

Figure 4. Unregulated circulation of heavy vehicles along a narrow stretches of the Macaneta spit (March 2015)

Human interventions that do not take place along the coast but have a high potential to affect the coastal sediment dynamics fall into the group of indirect anthropogenic actions. Human induced changes in the hydrological processes (*e.g.* land management, water abstraction for drinking and irrigation and flow regulation by dams) have a recognized significant impact on sediment supply to the coast as rivers are an important source of beach sand. Milliman and Syvitski (1992) estimated that the Limpopo River (the second largest river crossing the country) carries annually 33 million tons of sediment to the sea. The same author mentions that in the Zambezi River (the largest river crossing the country), the amount of sediment transported decreased from 48 million tons to 20 million tons after the construction of two upstream major dams, Kariba between 1955 and 1959, and Zambezi between 1969 and 1974.

The influence of natural and anthropogenic actions in the coastal sediment pattern mentioned in previous paragraphs demands local studies to advance from qualitative to quantitative descriptions of gross and net sediment transport rates. In some cases, the qualitative description of general patterns and recession rates are divergent (see Table 1, recession rates for Maputo). Thus, sediment budgets, at first instance, and regular monitoring initiatives should be initiated to increase the understanding of the sources, sinks and predominant transport direction, especially along more dynamic coastal stretches.

Tabel 1.Coastal recession at selected areas along the Mozambican coast (updated from Paper II)

Location	Recession rate (m/yr)	Period	Data source	Reference
Beira	1.0	Not specified	Not specified	Maansson (2011)
Maputo	0.30-0.35	1971-2004	Beach surveys	Moreira (2005)
	0.5-1.5	1970s-1996	Aerial photos and beach surveys	Langa (2007)
	1.06-5.34	2000-2008	Hydrographic maps and beach surveys	Ruby *et al.* (2008)
Ponta do Ouro	0.95-1.75	1974-2004	Beach surveys	Moreira (2005)
Xai-Xai	0.25-0.36	1971-1999	Land-based photographs	Moreira (2005)

3.4 Coastal management

3.4.1 Institutional arrangement

The responsibility of planning and managing the coast is split between different institutions in the central government and local institutions at district or municipal levels. At the central government the Ministry of Land, Environment and Rural Development (MITADER) is the key institution for policy making, promotion of education activities, and to enforce the application of existing legislation. **Paper II** reviewed the institutional arrangement for coastal planning and management. It found that responsibilities are split between institutions from different ministries, and that in some cases some overlap of responsibilities between institutions can be identified.

The former Department of Coastal Management, a sub-unit of the National Directorate for Environment, was previously the key unit for policy, legislation and regulation development, as well as to promote education and conservation activities on coastal areas (MICOA, 2005). However, in 2015, with the creation of MITADER (replacing the later Ministry for Coordination of Environmental Action) this department became a division, passing from a unit at the third level to the fourth level inside the ministry hierarchy (CIAP, 2015; MITADER, 2016). This gives an indication that coastal management might lose its visibility as there is no strong unit responsible for it. Another part of MITADER, the National Agency for Environmental Quality Control (AQUA), is at present the key unit for environmental management, monitoring, and auditing.

The National Institute of Hydrography and Navigation, as part of the Ministry of Transport and Communication, is the key unit to study, collect, and provide information about tides and currents, coastal processes, and bathymetry. These tasks are shared between two main sub-units: The Hydrography and Cartography Service and the Oceanography Service.

3.4.2 Legal framework

The Mozambican environmental legal instruments started to be developed during the last two decades. The first Environmental Law dates from 1997 (AR, 1997a), following the introduction of a right to a balanced environment by the 1990's Constitution. At present there is no specific legislation to regulate and control the erosion caused by anthropogenic actions.

However, **Paper II** reviewed different existing relevant legal instruments and found that two laws and an equal number of regulation laws contains clauses which can be used to control human negative interference in erosion processes.

The first of these laws is the Environmental Law which prohibits: (i) the practice of polluting activities, including activities that can accelerate erosion beyond the allowed legal limits (Article 9); and (ii) the placement of infrastructure for housing or other usages that can negatively impact the environment, with a special reference for is impediment in inland and coastal areas threatened by erosion (Article 14) (AR, 1997a). Besides the environmental Law, the Land Law (AR, 1997b) establishes that a coastal strip measured from the maximum spring tide to 100 m inland is a special, partial protection, and public domain area (Articles 7 and 8). The statute of total or partial protection areas should prevent the issue of land use rights for these coastal strips (as specified by Article 9) (AR, 1997b; CTV, 2012). However, there is a possibility to acquire special licenses for specific activities.

The Regulation Law for Pollution Prevention and Protection of Marine and Coastal Environments (CM, 2006a) specifies the need of consultation government entities before a special license is issued. The need for a consultation is later reinforced by the Regulation Law of Environmental Impact Assessment Process which requires Environmental Impact Assessments prior to the implementation of certain construction activities. This regulation law also specifies that special land use licenses for development of infrastructures on total or partial protection areas can only be granted for: (i) construction of basic infrastructures (e.g., for water and sanitation, electricity, and communication); (ii) infrastructures with recognized interest for the country development (roads, railways, ports, and oil and gas pipelines); and (iii) small constructions with temporary or removable material (AR, 1997b; CM, 2004; CTV, 2012).

Paper II found that existing legal instrument have an appellative character, giving more guidelines but lacking sanctions for prevaricators. They put more focus on pollution agents, consequently giving less attention to actions that can drive or lead to erosion. It is also important to mention that, different from many pollutants agents, the causes of erosion cannot always be assessed by field inspections, demanding in many cases studies to evaluate possible effects of interventions outside the primary affected areas. Positive progress were obtained with the approval of a Regulation Law for Environmental Inspection (CM, 2006b), and with the creation of an Environmental Quality Control Agency in 2010 (CM, 2010).

3.5 Practices in coastal protection

Coastal areas with medium and high development demands actions to protect existing infrastructures against observed erosion. This fact is clearly illustrated for the case of Mozambique in **Paper II**, which reports higher degrees of placement of coastal protection infrastructure in the most populated cities of Maputo and Beira, compared to the other three less populated and infrastructured studied coastal sites.

From the review of recent coastal protection interventions in Maputo, Inhambane and Beira, done in **Paper II**, it emerged that from 1970s until 2010s coastal protection interventions were more reactive (*i.e.* to correct problems) and less proactive (*i.e.* to prevent problems). These interventions were implemented following the occurrence of severe weather events or continuous erosion that put existing infrastructure at risk to become damaged. During the last five years, Maputo benefitted from a broader and more planned coastal protection intervention (from 2013 to 2015), as well as Beira (in 2013) although there at a lower scale due to lack of investment.

The dominant reactive character of coastal protection interventions dictates that adopted solutions are predominantly based on the principle of stabilization, and accommodation at a lower extent. Examining adopted coastal protection solutions in the past and during recent years, it can be clearly noticed that hard and semi-hard structures have primarily been employed, as seawalls, revetments, groins, and bulkheads are the commonly adopted protection measures. This fact shows that the principle that soft coastlines demand soft protection measures is not well disseminated among decision makers and coastal planners in the country.

3.5.1 Integrated coastal zone management

The National Report about the Coastal and Marine Environment (MICOA, 2007) points to the fact that Mozambique is lacking policies to control and regulate coastal erosion with anthropogenic origin, and that to revert this scenario, there is an urgent need to develop strategies to control and protect the coast against erosion. This action would be in line with the claim that Integrated Coastal Zone Management (ICZM) principles are only useful if a coherent integrated strategy is established (McKenna *et al*., 2009). An important step towards a better ICZM in the country was done with the approval of the first Strategy for Coastal Zone Management in February 2016.

As mentioned by McKenna *et al*. (2009), besides the existence of a strategy, a legal basis is also required to support and give priority to sustainable coastal practices and good management at eroding places. Thus, efforts to improve coastal management in Mozambique, in a more integrated way, should also focus (after the establishment of a consistent national strategy) on improving the existing legal instruments which tend to be more appellative and less punitive, with the introduction of regulatory measures, standards for permissible erosion, and incentives to mitigate the erosion problem. Competences for coastal management are spread between different institutions and decision levels, and in some cases with overlaps of mandates. Therefore, policies are also crucial to define the interaction and the coordination between institutions with administrative duties, and all stakeholders with environmental, social, and economic interests in coastal areas and environments.

Integration is also needed in coastal protection interventions. The coastal protection approaches lack or have limited integration components as they are implemented in response to the needs of restricted groups to solve local problems aiming at immediate protection of private or public infrastructure. Thus, their effects at wider temporal and spatial scales are left in a second plan or even ignored. In addition to that, economic interests tend to prevail when conflicting with social and environmental values. A possible compromise can be achieved by incrementing the number of coastal protection initiatives and projects which adopt interventions that do not induce or accelerate down-drift erosion being more environmental friendly and social acceptable. Some examples are beach nourishment and promotion of dune growth (Figures 5 and 6).

Figure 5. Beach nourishment action implemented as part of the the recent coastal protection works at Costa do Sol beach in Maputo City. From and by permission of Fátima Ismael.

Figure 6. Dunes growth in front of a building previous exposed to direct wave action in Ponta do Ouro beach (February 2014; Previous image of beach without dune available from Andrews, 2008)

ICZM requires active participation of different stakeholders when strategies are scaled down to local plans and during the decision making process. An effective participation can only be achieved if stakeholders are well informed. Thence, it is crucial to increase stakeholders' knowledge about coastal environments and processes. This can be made possible by increasing the number of research and monitoring activities, as well as by documenting and sharing information about the interaction between coastal uses and environments with the general public. Education is also crucial to change public perception of coastal management from a desirable to an essential activity. Scientific knowledge is an important solid base for development of coastal plans which specifies set-back lines, preferred coastal protection measures, and for definition of types of activities more suitable for different coastal stretches.

4 Processes of long-term coastal evolution and their mathematical modelling

4.1 General overview

Long-term morphological changes along the coast are a result of the reaction to different hydrodynamic forcing actions. At an engineering scale, long-term refers to periods going from decades to centuries (Hanson *et al*., 2003; Stive *et al*., 2002). At this time span, waves, wind, tidal currents are the main hydrodynamic agents responsible for mobilization and transport of sediments along the coast.

In the absence of sources and sinks, in a time perspective from years onwards and alongshore space between 100 to 1000 m the coastal profile shape oscillates inside an envelope of profiles that can be considerable stable over the years (Bosboom and Stive, 2013). The mean position of this envelop is constant in time. It represents the dynamic equilibrium profile which is one of the main principles behind one-line theory, and the basis for modelling of long-term shoreline changes due to longshore sediment transport along wave dominated coasts. If that equilibrium exists, the main cause for coastal evolution would be the varying longshore gradients.

Long-term models should be able to cover wider spatial scales from 10 – 100 km. Such spatial scales come with important variabilities which cannot be fully accounted for with the assumption of a dynamic equilibrium profile. Sources and sinks of sediment, and cross-shore processes such as beach nourishment, occurrence of overwash and breaching, dune build-up by wind-blown sand, dune and berm material exchange, become relevant on such scales.

Thus, to address wider time and spatial scales, the long-term coastal evolution model Cascade (Larson *et al*., 2002) was further developed to better account for cross-shore processes with the integration of a cross-shore (CS) material exchange modules; their development is described in section 4.3. The integration of the CS modules in Cascade is described under section 4.4. Although not yet integrated in Cascade, section 4.2 summarizes the development of a model for linear spit elongation that is solved analytically.

4.2 Analytical modelling of linear sand spit growth

Spits are accumulations of sediment caused by transport from a landmass or sediment source towards a water body. They commonly occur at river mouths, inlets, and at the down-drift ends of barrier islands. Linear spits develop if longshore sediment transport (Q_L) is dominant compared to other transport mechanisms.

Paper III details de development of a mathematical model for sand spit growth which offers a simple tool for quick and initial estimations of different factors affecting spit evolution. The model was developed based on the principle of mass conservation, coupled with different transport equations to represent the gains and losses (inputs and outputs) of sands to and from the spit, and equations to account for changes in cross-section spit shape.

Thus, the main governing equation is obtained by employing the principle of mass conservation to the spit sand volume, as represented by Eq. 1:

$$\frac{\partial}{\partial t}\left(\int_0^{x_s} A_s dx\right) = Q_{in} - Q_{out} \tag{1}$$

where A_s is the cross-sectional spit area at a distance x measured from the origin (x=0), x_s is the location of the tip of the spit, t is time, and Q_{in} and Q_{out} the boundary fluxes of sand. Q_{in} corresponds to the input of sediment for the system, representing the longshore sand transport at the updrift end of the spit, *i.e.* the spit origin. Q_{out} represents the output or the transport at the donwdrift end, *i.e.* the spit tip (see Figure 7).

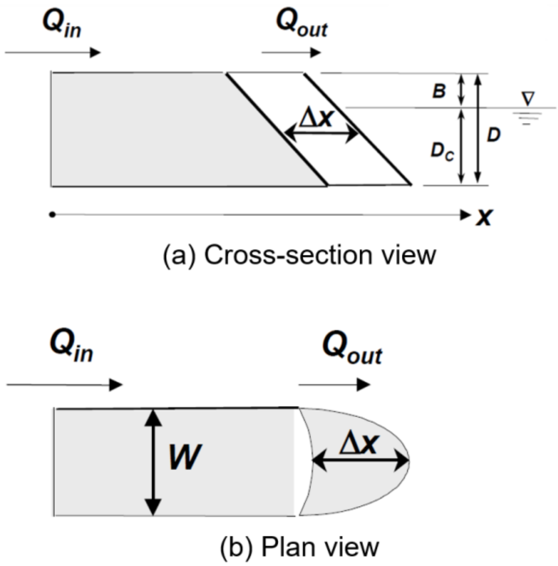

Figure 7. Schematization of spit growth and model variables (Modified after Kraus, 1999)

Building on the work from Kraus (1999), the cross-section spit shape was modified from a rectangular to a trapezoidal cross-section, with the introduction of a shape factor K_β, as described in the following equation:

$$A_s = DW_s\left(1 + K_\beta \frac{D_c - D_B}{2W_s}\right) \tag{2}$$

where D is the active profile height, and equals the sum of the berm elevation, D_B, and the depth of closure, D_c. The shape factor is $K_\beta = 1/\tan\beta_s + 1/\tan\beta_l$, where β_s and β_l are the slope on the seaward and landward side, respectively. Eq. 2 can be further simplified to $A_s = \psi D W_s$, in with ψ is a constant that represents a particular spit cross-sectional shape.

Analytical solutions were derived for the cases of: (1) unrestricted spit growth with Q_{out}=0; unrestricted growth combined with (2) time evolution of spit cross-section shape, and (3) changes of the active profile height; and a final case of (4) restricted spit growth with $Q_{out}=f(x)$.

For the simplest case of unrestricted spit elongation (Case 1), all sediment supplied to the spit results in growth as there is no transport at the tip of the spit. Thus, if Q_{in} and A_s are assumed to be constant (*i.e.* equals the equilibrium area A_e), Eq. 1 yields linear spit growth as:

$$x_s = \frac{Q_{in}}{A_e} t \tag{3}$$

When there is a gradual build-up of the spit (Case 2), a portion of Q_{in} is used to build up the cross section towards its equilibrium value (A_e) and the remaining portion is transported down-drift. Thus, A_s varies in proportion to Q/Q_{in} (*i.e.,* $A_s = A_e \cdot Q / Q_{in}$), where Q is the transport along the spit assumed to vary according to:

$$\frac{Q}{Q_{in}} = \left(1 - \frac{x}{x_s}\right)^m \tag{4}$$

where m is an empirical coefficient. Therefore, the cross-section changes can be represented as:

$$A_s = A_e\left(1 - \frac{A_e x}{(m+1)Q_{in} t}\right)^m \tag{5}$$

in which $0 < x < (m+1)Q_{in}t / A_e$. Substituting Eq. 4 into Eq. 1 yields for Q_{out}=0 and Q_{in} constant, the following elongation solution for Case 2:

$$x_s = (m+1)\frac{Q_{in}}{A_e} t \tag{6}$$

The increase in the active profile height in space (case 3) can be represented as:

$$D = D_o + \Delta D\left(1 - \exp\left(-\alpha x\right)\right) \tag{7}$$

in which D_o is the starting active height, ΔD is the increase in D, and α the rate coefficient quantifying the approach towards the final depth ($D_o + \Delta D$).

Substituting Eq. 7 into Eq. 2, and further its result into Eq. 1 yields an equation that can be solved analytically:

$$x_s + \frac{\Delta D}{D_o}\left(1 - \exp\left(-\alpha x_s\right)\right) = \frac{Q_{in}}{A_e^o} t \tag{8}$$

where $A_e^o = \psi_s D_o w_s$. The following analytical solution can also be obtained for the previous conditions, but also considering a varying spit cross-sectional width W_s (i.e. cases 2 and 3 combined), but only for m=1:

$$\frac{1}{2} x_s \left(1 + \frac{\Delta D}{D_o}\right) + \frac{\Delta D}{\alpha D_o}\left(\frac{1}{\alpha x_s}\left(1 - \exp\left(-\alpha x_s\right)\right) - 1\right) = \frac{Q_{in}}{A_e^o} t \tag{9}$$

The final case of restricted spit growth (case 4), can be solved introducing the following expression to represent the loss of sediment at the spit tip proposed by Larson *et al*. (2011):

$$Q_{out} = \frac{Q_o}{\left(1 - x_s / x_i\right)^2} \tag{10}$$

in which Q_o is the transport through the inlet before the spit starts growing and x_i is the initial inlet width. For a not varying spit cross-section shape ($A_s = A_e$), substituting Eq. 10 into Eq. 1 yields:

$$\sqrt{\delta}\,\text{arctanh}\left(\frac{\sqrt{\delta} x_s}{\left(1 - \delta\right) x_i - x_s}\right) + \frac{x_s}{x_i} = \frac{Q_{in}}{A_e x_i} t \tag{11}$$

where x_s is expressed as an implicit function of t, and $\delta = Q_o/Q_{in}$. At equilibrium Eq. 11 yields $x_{se} = x_i\left(1 - \sqrt{\delta}\right)$.

4.3 Simulation of cross-shore material exchange at decadal scale

The model developed to simulate CS material exchange at decadal time scales describes the evolution of key morphological features of the profile, specifically:

dune, berm and a longshore bar. The description is made through a set of geometric parameters (Figure 8). In the subaerial part, the dune is considered to have a trapezoidal shape. It is described by its height (s), the location of its landward (y_L) and seaward (y_S) ends, in conjunction with its seaward (β_S) and shoreward (β_L) slopes which are assumed to be constant, and by the dune volume (V_D). The berm is assumed to be horizontal and characterized by its width given by the difference between the seaward end of the dune and the berm crest location (y_B). The foreshore is sloping uniformly (β_f) from the berm crest to the still-water shoreline (y_G). In the subaqueous part, the bar is described by its volume (V_B). The subaqueous profile follows the Dean equilibrium profile.

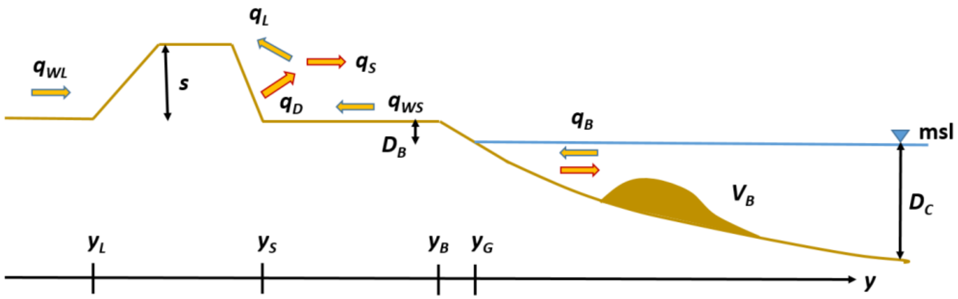

Figure 8. Schematic representation of cross-section profile used by the CS model

The following CS processes are included in the model: dune erosion, overwash and breaching, dune build-up by wind from both landward and seaward sides, berm erosion and accretion, and bar growth and decay. The modules developed to account for these processes are associated with sand conservation equations to simulate the evolution in time of beach morphological elements.

4.3.1 Sediment transport equations

The dune erosion is computed using a modified version of the impact theory from Overton *et al.* (1988), proposed by Larson *et al.* (2004). According to this theory, the volume of sediment mobilized by the incident wave impact can be calculated using the following expression:

$$q_D = 4C_s \frac{(R - z_D)^2}{T} \quad (12)$$

where q_D is the cross shore transport rate, R is the runup height, z_D is the distance from mean water level to the dune foot, T the wave period mean value, and C_s the impact formula empirical coefficient.

The runup height is calculated from the following expression (Larson *et al.*, 2004):

$$R = 0.158\sqrt{H_o L_o} \tag{13}$$

where H_o is the deep water root-mean-square wave height (m), and L_o the deep water wave length (m).

According to Eq. 12, the runup height must exceed the dune foot elevation ($R > z_D$) for erosion to occur. Hence, erosion will not occur if the runup height is lower than the dune elevation ($R < z_D$). A third scenario corresponds to the occurrence of overwash, observed when the runup height exceeds the dune height ($R > z_D + s$).

If overwash occurs, a part of the sediment mobilized by the wave impact (q_D) will be transported to the landward side of the dune (q_L) and the remaining part seaward by the backwash (q_S). To account for the landward and seaward transport rates an algorithm by Larson *et al.* (2009) was used. This algorithm introduces a ratio $\alpha = q_L / q_S$, which expresses the proportion of eroded dune material that goes offshore $q_S = q_D / (1+\alpha)$ and onshore $q_L = q_D \alpha / (1+\alpha)$, respectively.

As the impact force of the dune is reduced when overwash occurs, because of the additional momentum flux over the dune, a modified version of Eq. 12 was proposed by Larson *et al.* (2009),

$$q_D = 4C_s \frac{(R - z_D)s}{T} \tag{14}$$

The ratio α is given by,

$$\alpha = \frac{1}{A}\left(\frac{R - z_D}{s} - 1\right) \tag{15}$$

where A is an empirical coefficient assessed through comparison with field data to be around 3 by Larson *et al.* (2009).

A criterion equally introduced by Larson *et al.* (2009) establishes that breaching occurs due to erosion and overwash if 90% of the dune is eroded away.

Dune build-up and growth results from aeolian transport on the seaward and landward sides of the dune. An equation derived by Sauermann *et al.* (2001) which express the spatial growth of the potential wind-blown sand transport rate (q_W) towards equilibrium (q_{WE}, saturation state) was adopted, expressed as:

$$q_W(y) = q_{WE}\left(1 - \exp(-\delta y)\right) \tag{16}$$

where δ is the transport rate growth coefficient, and y the cross-shore distance measured from the berm crest towards the dune foot (*i.e.* $y_B \le y \le y_D$, for the seaward side).

The potential transport rate at equilibrium is a function of the wind speed and direction, and sediment properties. It is computed using a formula proposed by Lettau and Lettau (1977) for which the derivation is detailed in **Paper IV**. Prespecified values of the wind transport rate can be used if good quality wind data are not available for a certain location.

4.3.2 Bar and berm material exchange

Exchange of material between the berm and the bar is assumed to take place under conservation of mass, implying that no material is lost offshore. This exchange of material is computed using a model developed by Larson *et al*. (2013). According to this model, eroded material from the subaerial part is deposited in a longshore bar (or representative morphological feature), which strives towards its equilibrium volume (V_{BE}). The bar volume at any given time (V_B) will grow if is smaller than V_{BE}. Consequently, there will be a decay in bar volume if $V_{BE} < V_B$. A decay in bar volume will be followed by an increase in berm volume and shoreline advance. Conversely, a growth in bar volume will be followed by a decrease in berm volume and shoreline retreat.

The equilibrium bar volume is computed using the following empirical expression proposed by (Larson and Kraus, 1989):

$$\frac{V_{BE}}{L_o^2} = C_B \left(\frac{H_o}{wT} \right)^{4/3} \frac{H_o}{L_o} \tag{17}$$

where H_o is the deep-water wave height, L_o the deep-water water wave length, T the wave period, w the sediment fall speed, and C_B a dimensionless.

The change in bar volume (ΔV_B) during a time Δt is calculated from:

$$\Delta V_B = \left(V_{BE} - V_{B0} \right) \left(1 - \exp\left(-\lambda \Delta t \right) \right) \tag{18}$$

where V_{B0} is the bar volume at $t = 0$, and λ the rate coefficient which also depends on the waves and sediment properties as expressed by the following equation:

$$\lambda = \lambda_o \left(\frac{H_o}{wT} \right)^m \tag{19}$$

in which λ_o and m are coefficients with values to be calibrated. Considering seaward transport to be positive and if λ and V_{BE} are constants, the berm-bar transport rate (correspondent to change in bar volume) can be computed from:

$$q_B = \lambda \left(V_{BE} - V_{B0} \right) \exp\left(-\lambda t \right) \tag{20}$$

4.3.3 Sediment conservation equations

After calculating all sediment transport rates, the principle of sand volume conservation is applied, and resulting equations solved to yield the profile description parameters V_B, y_L, y_S, y_B, and s.

For the bar, the decay and growth in bar volume are coupled with the CS transport rate corresponding to the exchange of sediment between the berm and the bar according to:

$$\frac{dV_B}{dt} = q_B \tag{21}$$

The sand conservation principle applied to the berm takes into account the bar-berm material exchange (q_B), gains of sediment from dune erosion (q_S), and losses of sediment by wind-blown transport towards the dune (q_{WS}), and a gradient in longshore sediment transport rate (dQ/dx). Therefore the following equation will express the change in berm location:

$$\frac{dy_B}{dt} = \frac{1}{D_B + D_C}\left(-q_{WS} - q_B + q_S - \frac{dQ}{dx}\right) \tag{22}$$

The evolution of the dune may occur on the landward and seaward sides simultaneously. Consequently, two different mass balances are employed in the model. On the seaward side, dune erosion from wave impact will cause loss of sediment (q_D), and wind-blown sand (q_{WS}) will build-up the dune, yielding the following equation:

$$\frac{dy_S}{dt} = \frac{-q_D + q_{WS}}{s} \tag{23}$$

On the landward side, both the landward wind-blown (q_{WL}) sand and transport by overwash (q_L) will contribute to the dune growth, yielding the following expression:

$$\frac{dy_L}{dt} = \frac{-q_L - q_{WL}}{s} \tag{24}$$

4.4 Simulation of cross-shore material exchange in regional coastal evolution models

A regional model should be able to simulate coastal evolution processes which occur at different spatial scales. Cascade was created to provide such modelling framework, with the principle that in a cascading process, the coastal evolution at a larger scale should provide background conditions for the coastal evolution at the adjacent smaller scale (Larson *et al.*, 2006).

Larson *et al.* (2002) and Larson *et al.* (2006) reviews the different model components that integrate the Cascade model to constitute a representation of different spatial scales and the implementation of realistic boundary conditions (Figure 9). This section focus on improvements introduced in **Paper VI** in the computation of breaking wave properties and the coupling between cross-shore and longshore processes.

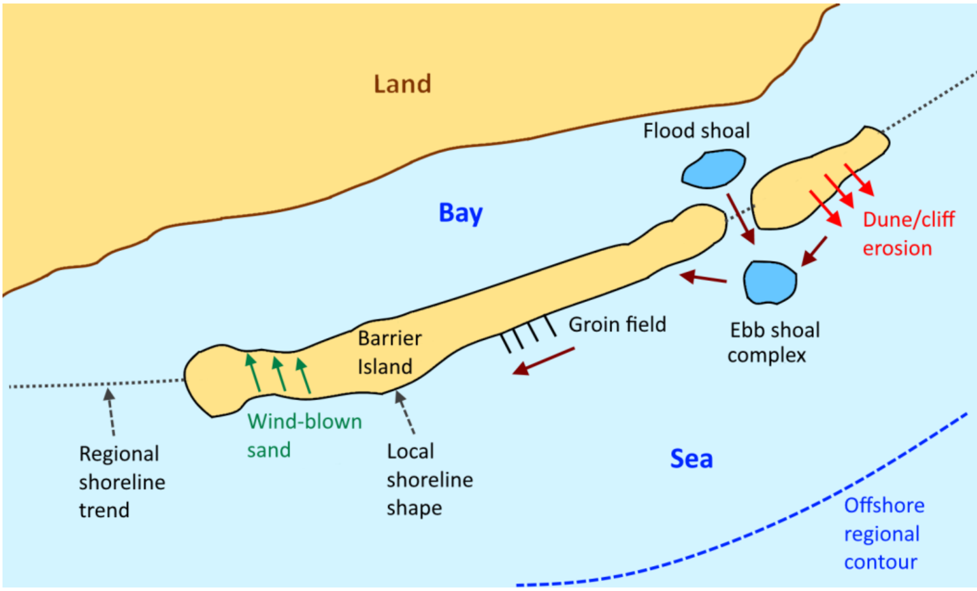

Figure 9. Scales and processes modelled by Cascade

The following sub-sections describe the shoreline change model, and the new subroutines integrated in Cascade to compute wave characteristics at incipient breaking and the integration of cross-shore processes, yielding an improved long-term model designated Cascade-CS.

4.4.1 Longshore sediment transport

The longshore sediment transport is a main mechanism for moving sediments and for causing shoreline change. To compute the longshore sediment transport rate (Q_L), Cascade-CS make use of the following expression derived by Larson and Bayram (2005):

$$Q_L = \frac{\varepsilon}{(\rho_s - \rho)(1-a)gw} F\overline{V} \tag{25}$$

where F is the wave energy flux directed towards shore, $\overline{V}$ the surf-zone average longshore current velocity, w the sediment fall speed, ρ_s the sediment density, ρ the water density, a the porosity, and ε an empirical transport coefficient.

Values for ε must be calibrated against data or by comparison with the CERC formula. The analogy with the CERC formula yields for small angle at breaking and $\gamma = 0.78$ that $\varepsilon = 0.77 c_f K$, in which K is the transport rate coefficient in the CERC formula, and c_f is the bottom friction coefficient (Larson and Bayram, 2005).

The mean longshore current velocity is computed from the following expression:

$$\overline{V} = \frac{5}{64} \frac{\pi\gamma\sqrt{g}}{c_f} A^{3/2} \sin 2\theta_{bs} \tag{26}$$

where A is the parameter of the Dean equilibrium beach profile ($h = Ax^{2/3}$) and θ_{bs} the wave angle at the breaking point relative to the shoreline.

4.4.2 Incipient wave breaking subroutine

Longshore transport is commonly estimated based on the breaking wave conditions. A new formula for incipient wave breaking derived by Larson *et al.* (2010) was introduced in Cascade-CS model to save time in the computation of breaking wave properties, up to 80% less than the iterative method previously used in Cascade.

The formula is based on a simplification of the solution to the wave energy flux conservation equation combined with Snell's law. For an input wave at deep water, if the wave angle at incipient breaking is small ($\cos\theta_b \cong 0$) the following expressions can be applied to compute the water depth at the breaking (h_b) and the breaking wave angle (θ_b):

$$\frac{h_b}{L_o} = \left[\left(\frac{H_o}{L_o} \right)^2 \frac{\cos\theta_o}{\gamma_b^2 2\sqrt{2\pi}} \right]^{2/5} \tag{27}$$

$$\theta_b = \arcsin\left(\sqrt{2\pi} \sin\theta_o \sqrt{\frac{h_b}{L_o}} \right) \tag{28}$$

where H is the wave height, θ the wave angle, h the water depth, L the wave length, γ_b the breaker depth ratio, and the subscripts o and b denote the deep water and breaking conditions, respectively. If the h_b is known, the breaking wave height can be calculated from $H_b = \gamma_b h_b$.

Larson *et al*. (2010) derived the following simplified equations to be applied when the input wave is at an arbitrary water depth, denoted by the subscript *m*:

$$\lambda = gh_b / C_m^2 \tag{29}$$

$$\theta_b = \arcsin\left(\sin\theta_m \sqrt{\lambda}\right) \tag{30}$$

where C_m is the wave celerity.

The parameter $\lambda = \delta\lambda_a$, in which $\lambda_a = \cos\theta_m / \alpha$, and δ is a correction coefficient approximated by the following empirical function

$$\delta = 1.0 + 0.1649\varepsilon + 0.5948\varepsilon^2 - 1.6787\varepsilon^3 + 2.8573\varepsilon^4 \tag{31}$$

valid for $0 \le \varepsilon \le 0.5$, with

$$\varepsilon = \frac{\sin^2\theta_m \left(\cos\theta_m\right)^{2/5}}{\alpha^{2/5}} \tag{32}$$

and,

$$\alpha = \left(\frac{C_m}{\sqrt{gH_m}}\right)^4 \frac{C_m}{C_{gm}} \gamma_b^2 \tag{33}$$

where C_{gm} is the group wave celerity.

4.4.3 Coupling of different model scales

At regional scale, coastline shapes and features can often have curved development that is not always possible to reproduce and maintain. Because of the longshore gradients in the coastline, existing coastal evolution models tend to diffuse such features towards a straight line. To mitigate this effect when such special features are present, Cascade-CS considers that the local shoreline evolves with respect to the regional shoreline, employing the following equation:

$$Q_L = Q_o \sin 2\left(\theta_b - \left(\arctan\left(\partial y / \partial x\right) - \arctan\left(\partial y_r / \partial x\right)\right)\right) \tag{34}$$

where θ_b is the wave angle at break point, y the shoreline position, y_r the regional shoreline shape, and Q_o the sediment transport amplitude from Eq. 25.

The coupling between the CS modules that compute episodic erosion by storms and dune build-up by wind with the long-term change is made by considering that gradients in the longshore transport ($\partial Q_L / dx$) cause a resultant movement in the shoreline position or some other contour chosen to represent it (*e.g.* the location of the berm crest). Thus, the sediment conservation equation may be expressed as:

$$\frac{\partial Q_L}{\partial x} + (D_B + D_C)\frac{\partial y}{\partial t} = \pm q_C \qquad (35)$$

where D_B is the berm height, D_C the depth of closure, y the shoreline position, and q_C is the cross-shore sediment exchange (with positive transport taken as onshore). Considering that the shoreline change is influenced by dune erosion (q_S; source), wind-blown sand (q_W; sink), and exchange of sediment between the bar and berm (q_B; source or sink), as illustrated in Figure 10, Eq. 35 can be re-written as:

$$\frac{\partial Q_L}{\partial x} + (D_B + D_C)\frac{\partial y_B}{\partial t} = q_S - q_W \pm q_B \qquad (36)$$

where y_B is the representative contour for the profile movement taking the berm crest as reference. The seaward and landward dune foot locations, denoted by y_S and y_L, respectively, are calculated from the dune sand conservation Equations 23 and 24, for the seaward and landward sides, respectively.

Other sources and sinks of sediment along the coast are taken into account by adding the corresponding transport rates on the right hand-side of Eq. 36. If it occurs on an immersed portion of the beach, the corresponding transport rate of sources and sinks are added to the right term of Eq. 21, which represents changes of bar volume V_B.

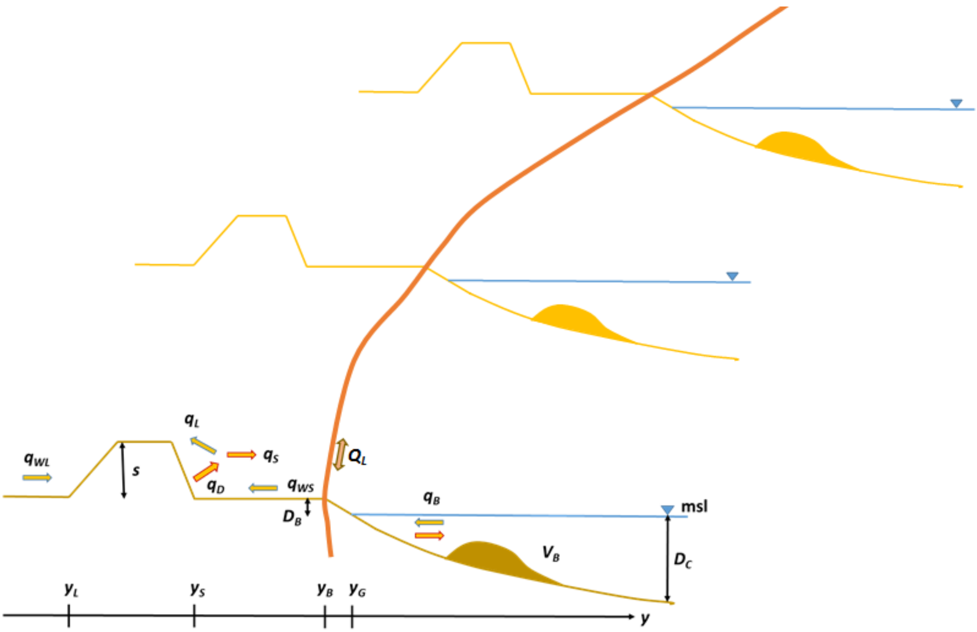

Figure 10. Schematic representation of integration of cross-shore and longshore sediment transport

5 Results and discussion

In this chapter selected results of the appended papers are reviewed. The potentials of adopted models are submitted to a critical analysis, and their potential application to improve coastal planning and management in Mozambique discussed in the last section of the chapter.

5.1 Simple model approaches to initial estimates

In situations when there is limited availability of data, less complex models and modelling approaches are valuable tools for initial and quick estimates of the coastal evolution in order to better understand how the coast is evolving.

In a scenario characterized by limited availability of data, **Paper I** explored the possibility of estimating the longshore sediment transport for a stretch of the southern coast of Mozambique, along the Machangulo Peninsula, with an extension of 21 km. The SWAN model (Booij et al., 1999) and linear wave theory were used to propagate offshore waves from the WW3 model (Tolman, 2009) towards the coast (until the breaking point), using a bathymetry extracted from GEBCO - General Bathymetric Chart of the Oceans (Smith and Sandwell, 1997). Since there was no information about the sediment size and beach slope, gross longshore sediment transported were estimated using the CERC formula (USACE, 1984):

$$Q = K \cdot H_b^{5/2} \sin\left(2\theta_b\right) \frac{\rho\sqrt{g}}{16\gamma^{1/2}\left(\rho_s - \rho\right)\left(1-n\right)} \tag{37}$$

where H_b is the breaking wave height, θ_b the breaking wave angle, g the acceleration of gravity, n the porosity, γ the breaking wave criteria, ρ the water density, ρ_s the sediment density. The parameter K is the CERC coefficient, and its value was calculated according to the following expression from (Mil-Homens *et al.*, 2013):

$$K = \left[2232.7\left(\frac{H_b}{L_o}\right)^{1.45} + 4.505\right]^{-1} \tag{38}$$

where L_o is the deep water wavelength.

The sediment transport rates obtained for the Machangulo Peninsula (Table 1) were lower than values from coastal locations with a similar wave fetch as detailed in **Paper I**. Nevertheless, the application of this simple approach was useful to validate the evident northwards directed net sediment transport, and to identify that SE and ESE are the most effective incident wave directions. Table 2 presents the results of the longshore transport rates computed for a CERC coefficient K=0.29, as reference, and for K values given by Eq. 38.

Table 2. Longshore sediment transport rates at Machangulo Peninsula

K	Q_L (x10^3 m^3/y)		
	Gross	Southwards	Northwards
0.29	429	46	383
0.04-0.22 (Eq. 38)	170	17	153

Paper III explores a simple approach of deriving analytical solutions to describe the elongation of linear spits. These analytical models proved to be useful for rapid quantitative estimates and predictions of sediment fluxes along the spit and its elongation (x_s; see Eq. 3), and therefore valid tools for initial estimates in engineering projects.

For the simplest case of unrestricted growth, the comparisons of the spit elongation given by the analytical model with observed data suggest that longer periods can be better represented by two or more elongation rates reflecting significant changes in transport rates (Figures 11 and 12). This observation is based on the fact that recorded spit elongation values tend to fall out of the best fit uncertainty estimates for longer periods. This pattern reflects the importance of changes in the system that occurs at longer time scales of decades (*e.g.* varying characteristics of the waves). It can also indicate the occurrence of important changes in the sediment input to the system with effects on the alongshore sediment transport rates.

The adoption of a more realistic trapezoidal cross-section (i.e., ψ = 2.5, with $A_s = \psi D W_s$; see Eq. 2) instead of a rectangular cross-section (i.e., ψ = 2.5) contributed to improve the model performance, leading to estimated longshore sediment input values (Q_{in}) closer to observed ones.

Paper III also explores the performance of analytical solutions of spit elongation accompanied by variations in spit cross-section with time, increase in active profile height, and restricted growth due to transport at the down-drift end of the spit. Because the comparison was done against laboratory data they are not reviewed in this summary.

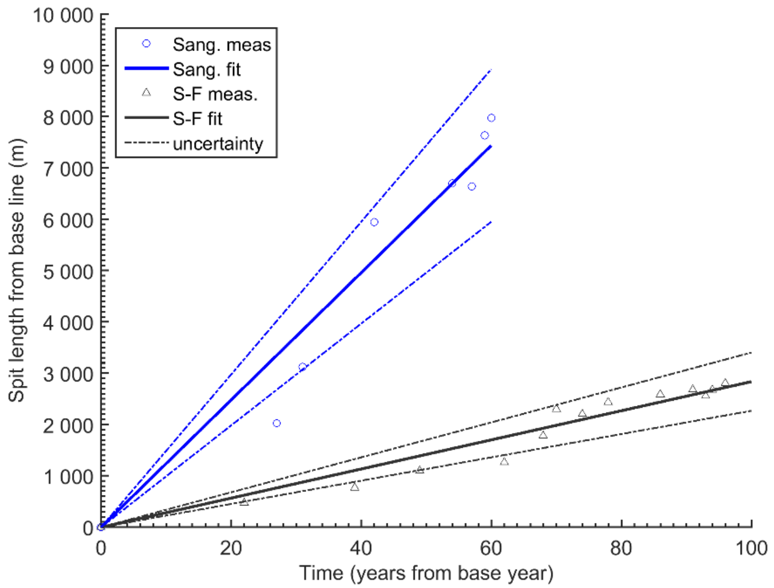

Figure 11. Unrestricted spit elongation at Sangomar spit (Sang.) from base year 1927, and Skanör-Falsterbo (S-F) Peninsula from base year 1916

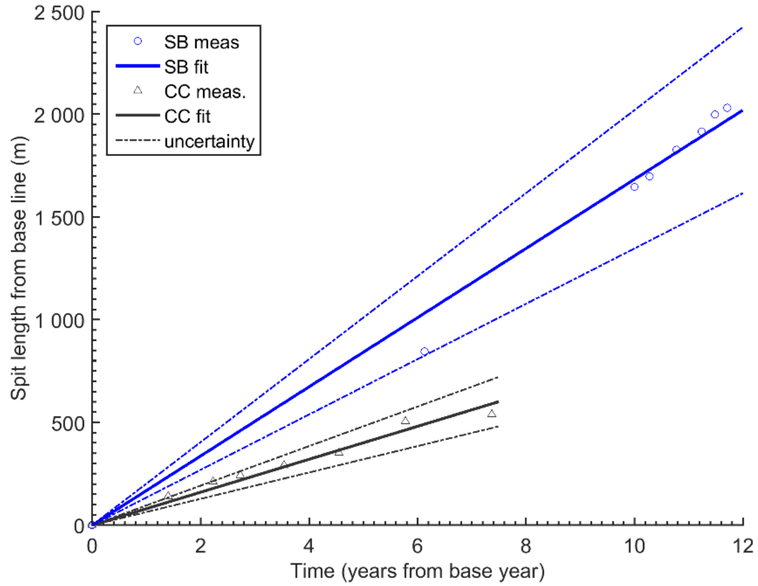

Figure 12. Spit elongation at San Bernard River Mouth from base year 1989, and at Corpus Christi (CC) North Beach from base year 1976 and

5.2 Long-term modelling of cross-shore material exchange

Paper IV described the theoretical development of a cross-shore model to simulate long-term cross-shore exchange of sediments and resulting profile evolution. In **Paper V**, the performance of the CS model was tested against data from the field, available for a stretch of the Portuguese coast influenced by beach nourishment, Barra beach. Besides this location, CS model was also implemented to simulate the cross-shore evolution of the Macaneta spit in Mozambique, a stretch of the coast affected by overwash and erosion, and in Ängelholm, a stretch of the Swedish coast experiencing dune development at different longshore sediment transport gradients.

The CS model was successfully implemented and proved to be a useful tool to model long-term cross-shore evolution at distinct situations. For Barra, a good agreement was observed between simulated and measured values of the seaward location of the dune foot (y_S), dune (V_D) and bar (V_B) volumes (see Figures 5 and 6 in **Paper V**). Although without a high degree of matching, the increase and decrease trends of the berm location (y_B) were equally satisfactorily reproduced.

The application to Macaneta and Ängelholm spit was limited by the availability of data from regular surveys. Thus, adopted values for model specific parameters were in the range of values suggested by previous studies. In addition to that, quantitative information available from old aerial images, and qualitative information available from reliable sources were equally useful to calibrate and evaluate the model performance, and to reach realistic results (see Figures 13 to 16 for the Macaneta results).

One of the model strengths lies in the simplified representative profile which allows saving computing time while keeping model stability. Still, results from the model application suggested that future improvements should be introduced in the schematized model profile to better account for sloping berms in the Ängelholm and Barra cases, and barrier shapes (inexistent or reduced berm widths) in the Macaneta case. Specific need for improvement for the Macaneta case includes assessing the potential aeolian transport rate which is between two and three times larger than at other two application locations. There is also a need to introduce sediment transport gradients along the river side of the spit to improve the results for the evolution of the landward side of the dune.

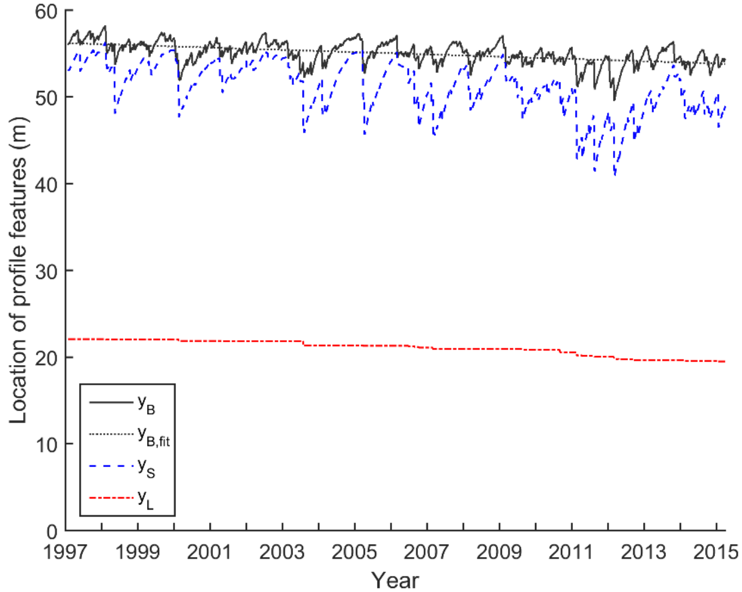

Figure 13. Resulting profile A with calculated location of the berm crest (yB), linear fitting for yB (yB,fit), seaward location of the dune foot (yS), and landward location of the dune foot (yL) at Macaneta spit

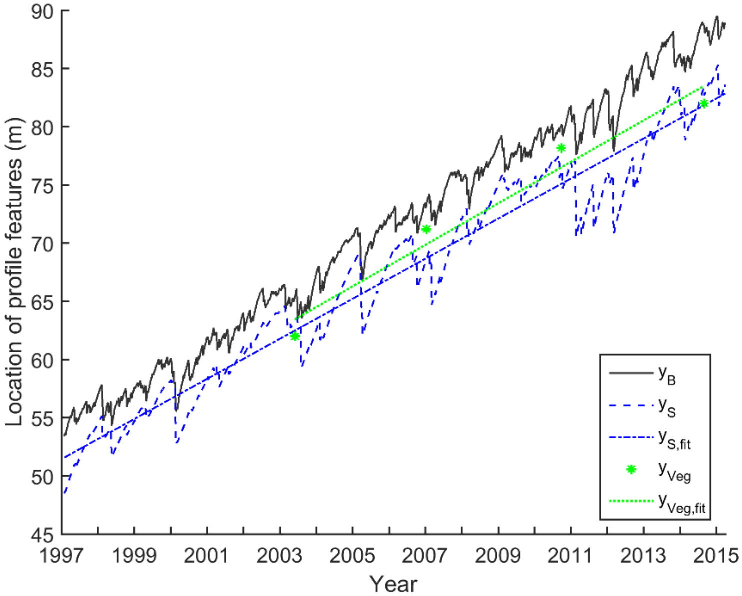

Figure 14. Resulting profile B with calculated location of the berm crest (*y_B*), seaward location of the dune foot (*y_S*), linear fitting for *y_S* (*$y_{S,fit}$*), estimated location of vegetation line (*y_{Veg}*), and linear fitting for *y_{Veg}* (*$y_{Veg,fit}$*) at Macaneta spit

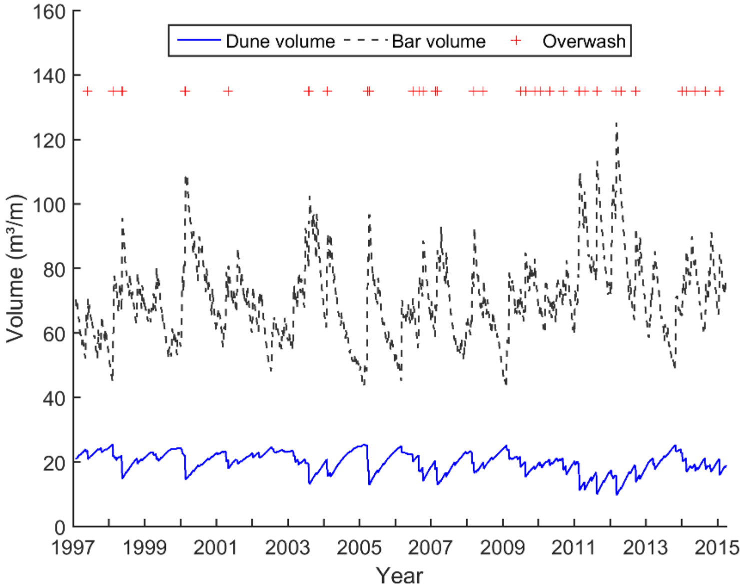

Figure 15. Overwash events (marked with + signs), dune and bar volume changes with time at Macaneta cross-section A

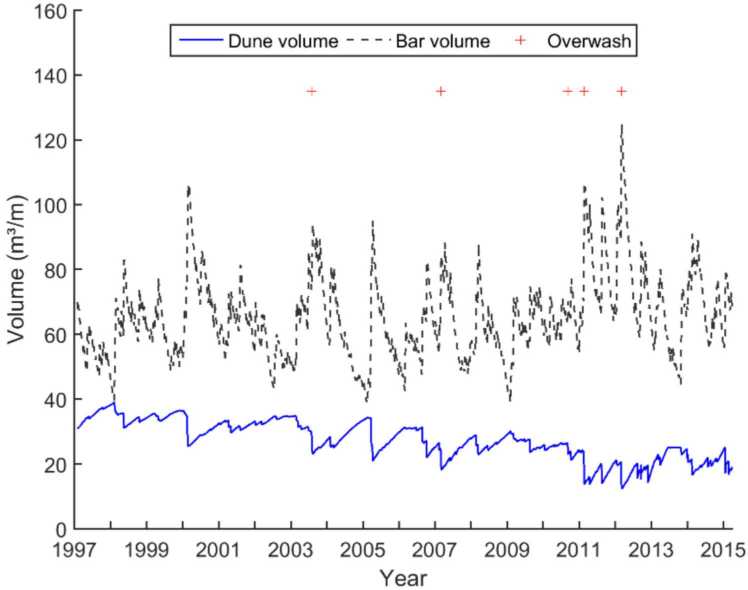

Figure 16. Overwash events (marked with + signs), dune and bar volume changes with time at Macaneta cross-section B

5.3 Coupling longshore and cross-shore processes in long-term coastal evolution models

In **Paper VI**, the Cascade-CS model was employed to simulate the combined longshore and cross-shore evolution of the Macaneta spit. In Figures 17 and 18, the time evolution of the landward and seaward dune locations at the two narrowest spit Sections A and E (see Figure 19) are presented and compared with available estimates from previous studies.

From Figure 17, it can be seen that both y_S and y_B fluctuate around a mean value involving a decreasing trend at the selected Section A+200m (section A is at the left boundary of model). The linear fit of the evolution of simulated y_B values in time points to an average recession of the berm crest of about 2 m during the 18 years simulation period. This finding agrees with the observation that on the seaward side the spit has been stable at this location during the last two decades as pointed out by DHI (2013) and Karlsson and Liljedahl (2015).

Similar behavior of y_S and y_B fluctuating around a mean value is observed at Section E (Figure 18), but with an increasing trend, which points to a more pronounced seaward advance of the shoreline at this section. This simulated trend of shoreline advance (around 1.25 m/yr), represented by the berm crest, agrees with the finding that the spit is migrating eastwards at this section as presented by Karlsson and Liljedahl (2015). Based on measurements of the location of the vegetation line from aerial images, these authors estimated a seaward advance of nearly 1.8 m/yr to be occur at Section E.

The recession trend observed at a lower rate at Section A+200m and the seaward advance of the spit at a comparatively higher rate identified for Section E, are also observed in Figure 20, which presents the spatial variation of the berm location and the yearly average net longshore transport along the spit. From this figure, it can be observed that a stretch of the coast nearly 2 km, starting from Section B (x = 3275 m) to C (x = 5170 m) is receding, while an advance of the coast occurs between Section C to E. From Section B northwards, and Section E southwards, the spit remains almost stable during the entire simulation (see Figure 19 for sections locations).

Figure 20 also indicates a negative (northward directed) longshore transport along the spit, with relatively higher net longshore transport rates occurring at the southern stretch of the spit, when compared with the values observed along the northern stretch. This finding of a northwards directed net transport goes intuitively against the southwards transport that justifies the current north-south development of the spit. However, it might be a valid trend if we consider that the spit has not elongated during the last decades. This northwards littoral drift was also found to be occurring from Section B to F by Karlsson and Liljedahl (2015), and from Section C to F by DHI (2013).

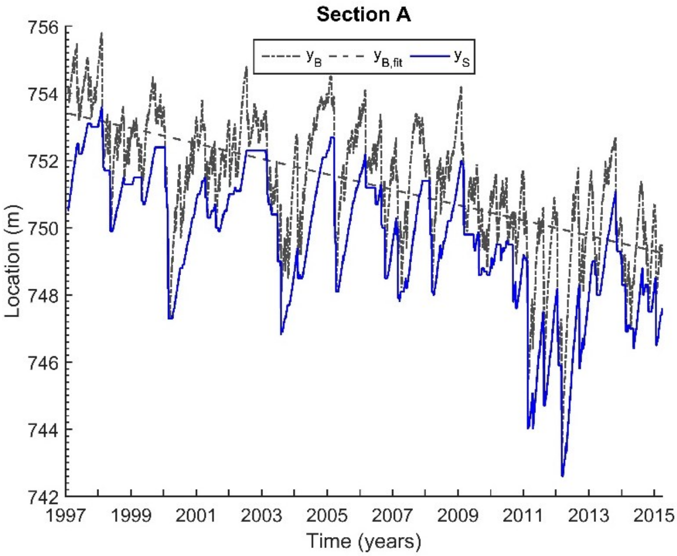

Figure 17. Resulting profile A with calculated location of the berm crest (yB), linear fitting for yB (yB,fit), and seaward location of the dune foot (yS) at Macaneta spit

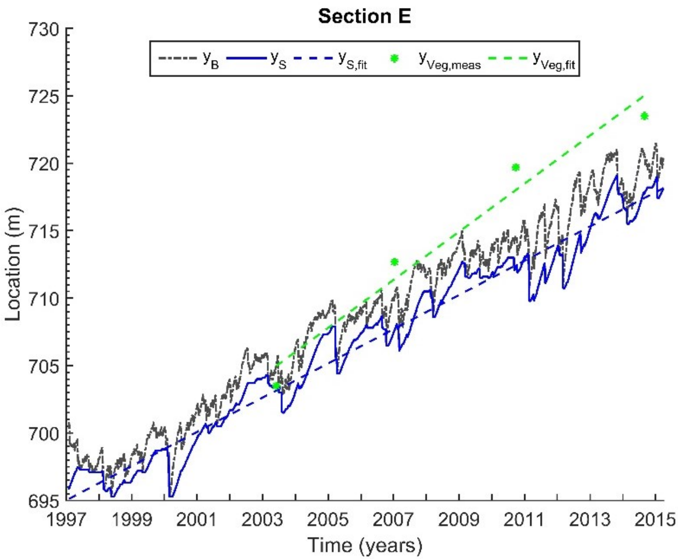

Figure 18. Resulting profile E with calculated location of the berm crest (y_B), seaward location of the dune foot (y_S), linear fitting for y_S ($y_{S,fit}$), estimated location of vegetation line (y_{Veg}), and linear fitting for y_{Veg} ($y_{Veg,fit}$) at Macaneta spit

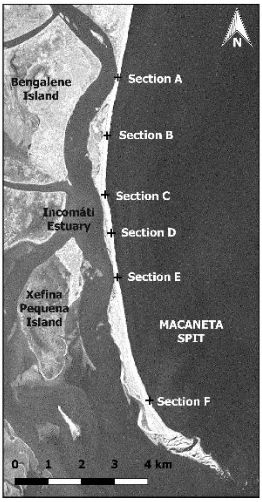

Figure 19 - Layout of Macaneta spit with indication of studied sections

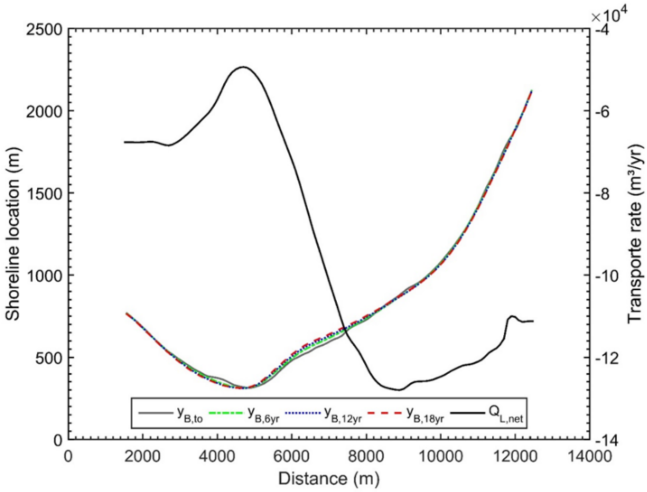

Figure 20 – Spatial variation of the berm location (y_B) at four selected times plotted together with the yearly average net longshore transport rate (Q_L) along the spit

5.4 Potential contribution of long-term coastal evolution models to improve coastal planning and management in Mozambique

The long Mozambican coast faces increasing challenges imposed by changes in the coastal morphology due to natural climate variability, and an increasing anthropogenic interference in a desired coastal balance. To better cope with such challenges, and to achieve an always sought after sustainability, there is a constant need for an improved understanding of how different processes contribute to the shape of the coast, and to anticipate future evolution trends. Thus, for such purposes, a collection of coastal evolution concepts are further developed into mathematical models, and applied to simplify and represent the complex coastal evolution processes observed in the real nature.

The application of coastal evolution models as part of the conducted research has proved to be a useful tool to better understand and describe the local coastal dynamics at selected study sites, from the offshore wave climate up to the resulting cross-shore and longshore sediment transport. Longshore sediment transport rates were estimated for coastal stretches along the Machangulo Peninsula and Macaneta spit. In addition, the shoreline and cross-shore profile evolution were simulated for the Macaneta spit, for a period extending up to two decades.

Longshore sediment transport estimates, and shoreline and cross-shore profile evolution, are useful to anticipate how the coast will evolve in the future. Therefore, the use of mathematical models provide valuable information, based on empirical evidence, for a more conscious decision-making process. In line with this statement, the following five potential contributions of coastal evolution models to improve the coastal planning and management in Mozambique were identified.

(1) Understand the recent coastal evolution

Different, somehow contrasting, coastal recession values based on the analysis of shoreline position in old maps and aerial photos are presented in Table 1. Moreira (2005) identifies erosion as a dominant process in the Mozambican coastal dynamics, and mentions that the change in more than 90% of the coast is due to natural agents. These are perceptions that need to be validated by field observations, or any other empirical based method. Long-term coastal evolution models can be valuable tools to reproduce the recent coastal evolution (from years to decades), and give insights to the identification of governing processes for such observed or described evolution.

Consequently, long-term models can be considered valuable tools to improve the understanding of the recent coastal evolution and validate different, and in some cases conflicting, perceptions. A solid knowledge about the dynamics of the coastal systems is a crucial requirement for the development and implementation of any coastal management plan.

(2) Protect sensitive coastal systems

Macaneta is a coastal system under threat of possible severe erosion and breaching, which could cause negative impacts to the Incomáti River estuary ecosystem. In **Paper V**, a CS model was employed to simulate the long-term cross-shore sediment transport at Macaneta. The application of the model was useful to identify scenarios of forcing conditions that can disrupt the delicate balance between erosion and deposition, which sustains the sensitive coastal system of Macaneta spit. Similar to this application, the CS model can be applied to other existing spits and barrier islands along the Mozambican coast.

(3) Improve the integration component in coastal protection projects

Paper II identified that coastal protection interventions are implemented in response to the needs of restricted groups, in specific places, and aiming at an immediate protection. Long-term coastal evolution models can contribute to improve the integration component in larger coastal protection engineering projects, with the introduction of the practice to model proposed interventions. This would make it possible to assess not only the local and immediate results of different protection interventions, but also their resulting influence far outside the project area and in a longer time perspective.

Thus, adopted protection measures should be the ones that are foreseen to result in the best compromise at different time and space scales. This approach is also valid to account for effects of interventions that are not even taking place directly at the coast (*e.g.* construction of dams, and its further blocking of sediment as reported to have occurred in the Zambezi River), but influences sediment transport and availability along the coast. It can also be a good and valid approach to introduce and defend the need for compensation mechanisms.

(4) Promote the adoption of soft coastal protection approaches

There is a lack of knowledge about the beneficial effects of the adoption of soft coastal protection approaches when comparing with hard and intermediate structures that do not solve but transfer the erosion problem to other areas. In order to revert this status, comparative studies of the performance of hard and soft coastal protection interventions should be promoted, and considered an essential requirement of all coastal protection projects. Such performance comparison can be made using long-term coastal evolution models that can handle the longshore and cross-shore sediment distribution after beach nourishment, as well the subsequent build-up of the dunes.

Beach-dunes are also an effective defense mechanism against coastal flooding. Their effective design requires long-term predictions of its performance against forcing actions of different magnitudes which can only be obtained from the application of long-term coastal evolution models with capacity to simulate the cross-shore sediment transport.

(5) Establish setback lines

Shoreline retreat rates and the future position of the shoreline in response to different forcing can be anticipated with the use of long-term coastal evolution models. The current legislation prohibits the placement of infrastructures on a strip of the seafront measured from the maximum spring tide level to 100 m inland (AR, 1997b; CTV, 2012). Nevertheless, along more dynamic eroding and vulnerable coastal stretches (e.g. Beira coast), the100 m from the maximum spring tide criteria can be combined with a prediction of the shoreline position in *N* years (project life) to define the most appropriate widths of coastal protection strips, as well as setback lines.

5.5 Final considerations

The contribution to better planning and management in coastal areas does not come only from deterministic models such as the long-term coastal evolution model retracted in this thesis work. Further contribution can be obtained by the adoption of probabilistic approaches, and probabilistic models, to communicate and express risk and vulnerability of systems to different hazards. Probabilistic approaches are equally useful during the design process making it possible to express the frequency and recurrence period of a specific event identified as a potential threat to a specific coastal system.

Thus, results from developed deterministic models can be further treated in a probabilistic way. For instance, the time series of eroded dune volumes given by the application of the deterministic CS model can be fitted to a probability model, and be further used to estimate the risk of occurrence of a specific severe erosion event identified to have caused a severe erosion or breaching of the spit.

Results from the model simulations should be accurate, *i.e.* model outputs should be close to observations to render them useful. In the Mozambican context, there is limited availability of data for different input parameters used to model long-term coastal evolution. This scenario suggest that an investment should be made to establish an institutionalized coastal monitoring system, and/or to promote more independent monitoring initiatives. It is equally important that collected data can be made easily available for any potential users.

6 Conclusions

This research work reviewed different processes of long-term coastal evolution and their further development into concepts employed in the development of mathematical models. Also, as a part of this research, governing processes affecting the evolution of the Mozambican coast were critically reviewed, and the potential contribution of developed mathematical models to address identified challenges in coastal planning and management explored.

Results of the review of documented coastal evolution in Mozambique point to the occurrence of erosion driven by natural actions, and incremented by direct and indirect anthropogenic actions. To mitigate the negative effects of the observed erosion, soft coastal protection approaches are relegated to a second level, as hard and intermediate structures are commonly adopted to achieve the desired protection.

A long-term, cross-shore (CS) evolution model with the capacity of modelling cross-shore sediment transport and resulting profile response was successfully developed, and further integrated into a long-term shoreline evolution model (Cascade), yielding an improved Cascade-CS model. Cascade-CS makes it possible to account for different cross-shore processes which cannot be ignored when modelling the coastal evolution at temporal scales extending up to decades, and spatial scales on an order of tens to hundreds of kilometres. From the standalone model application of the CS module, good agreement was observed between simulated and observed values available for one of the locations. Descriptions of the coastal evolution from reliable sources were equally useful to validate the model performance on two other locations with limited data availability. Results from this initial integration of the CS module in Cascade-CS look promising as both time evolution of the shoreline and cross-shore beach profiles could be satisfactorily reproduced for selected application sites. The combined model was also stable during all the simulation period extending for up to nearly two decades.

Besides the more complex model development and implementation, simple approaches to describe coastal evolution were equally explored. Thus analytical solutions were derived to simulate the elongation of linear spits under restricted and unrestricted conditions, and successfully tested against data from the field and from laboratorial experiments for more complex cases representing increase in active spit height and changes in cross-section spit area. Another simple approach adopted to assess coastal sediment transport using wave and bathymetric data data from global repositories, made it possible to estimate alongshore sediment transports along the Machangulo Peninsula, and to identify a northward directed net transport.

Overall, results from the application of developed models to simulate the long-term evolution of selected locations of the Mozambican coast indicated their high potential to contribute to improve the coastal planning and management, as they gave valuable insights to better understand the recent coastal evolution. They also showed to be valuable tools to anticipate the future coastal evolution, and hence to the selection of the best coastal protection interventions that can meet the needs of immediate and long-term protection, as well as to ensure a balance between local benefits and possible negative influences at distant locations from the project area.

One critical factor that influence the use of mathematical models is the availability of data. This was a limitation in the application studies conducted for the Mozambican coast. More than being seen as an excuse not to act, this situation constitutes a strong incentive to multiply the number of monitoring initiatives and studies addressing the coastal dynamics of the extended Mozambican coast.

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Paper III

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Paper IV

Larson, M., Palalane, J., Fredriksson, C., and Hanson, H., 2016. Simulating cross-shore material exchange at decadal scale. Theory and model component validation. *Coastal Engineering* (under revision).

Paper V

Palalane, J., Fredriksson, C., Marinho, B., Larson, M., Hanson, H., and Coelho, C., 2016. Simulating cross-shore material exchange at decadal scale. Model application. *Coastal Engineering* (under revision).

Paper VI

Palalane, J., and Larson, M., 2016. A long-term coastal evolution model with longshore and cross-shore processes. *Journal of Coastal Research* (submitted).

Different processes in response to the action of natural driven forces and the human interference on coastal systems act together, contributing to shape the coast. Coastal evolution models have been developed as useful tools to better understand the contribution of different processes on observed coastal changes, and also to anticipate future evolution in response to different actions and interventions taking place along the coast.

The predominant practice in coastal modelling is to have models that address separately the evolution as a result of cross-shore sediment transport processes from the ones caused by processes with main effects on the alongshore sediment transport. However, if longer time and spatial scales are to be covered by such models, a combination of cross-shore and longshore processes is crucial. In this context, the thesis explores the possibility of improving the mathematical modelling of long-term coastal evolution by integrating cross-shore evolution processes into a regional coastal evolution model.

The model development stage was followed by its application to simulate the long-term coastal evolution of selected coastal stretches of Mozambique's 2800-km-long coastline. Based on a literature review of different processes influencing the evolution of the Mozambican coast, the potential contribution of mathematical models to improve the local coastal planning and management was explored.

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