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Nunes De Brito Junior, Almir

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Tidal Inlets Hydraulics and Morphological Modeling

An application to Mundaú Lagoon, Brazil

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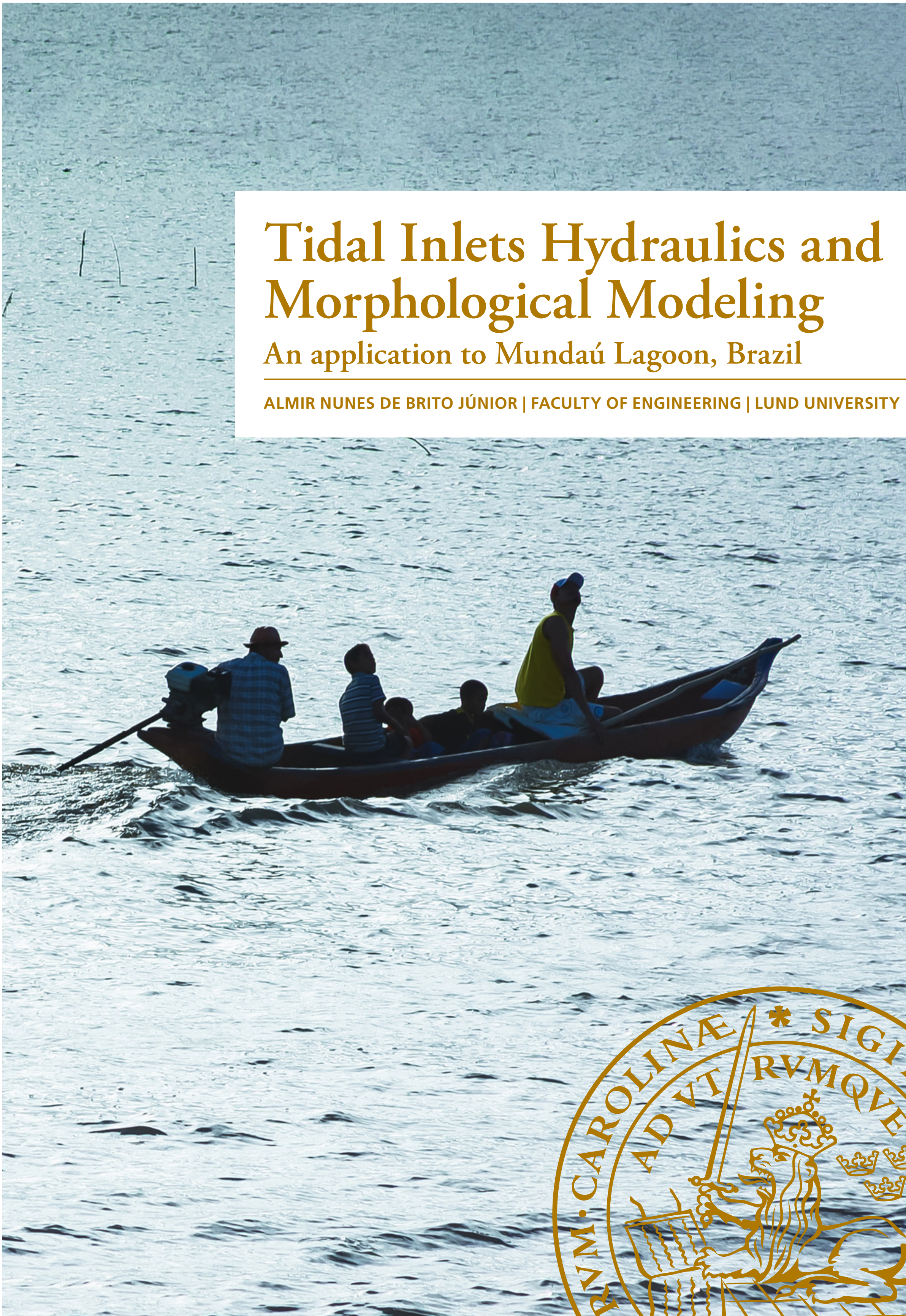

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Tidal Inlets Hydraulics and Morphological Modeling: An application to Mundaú Lagoon, Brazil

Tidal Inlets Hydraulics and Morphological Modeling

An application to Mundaú Lagoon, Brazil

Almir Nunes de Brito Júnior

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Full Professor in Coastal Engineering & Management
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Water Resources Engineering
Box 118
SE-221 00 Lund, Sweden

Author: Almir Nunes de Brito Júnior

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Abstract

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The present thesis advances the development of new numerical and analytical models to be used in preliminary studies and to serve as useful tools for qualitative and quantitive assessment of tidal inlet hydraulics and morphology. The study validated the developed approaches to a natural and dynamic inlet-lagoon system: the Mundaú Lagoon (northeastern Brazil). Furthermore, the research investigated internal processes of this lagoon that are affected by the flow through its inlet, such as the water exchange, during the critical dry season scenario, and the impacts of the tidal exchange on the lagoon salinity dynamics and population of its characteristic mussels.

A semi-analytical approach was developed based on the classical Keulegan equations, resulting in a series of expressions in non-dimensional form describing key characteristics of the inlet flow as the lagoon levels response to tides, tidal prism, and inlet velocities, having as the main independent variable the repletion coefficient. These flow expressions were then used in a sediment balance equation for the inlet evolution resulting in diagrams of inlet equilibrium for different scenarios related to inlet geometry configurations.

The numerical model for the inlet morphology was applied in the Mundaú lagoon inlet long-term (decadal) and validated through schematic simulations and an application to a complex set of forcing conditions. In this way, the inlet evolution was estimated through the inlet width based on a geometrically-similar idealization of the cross-section. The approach taken resulted in a satisfactory description of the inlet evolution through fast simulations and showing potential for long-term assessment of the inlet morphology.

In conclusion, the developed models demonstrated the ability to reproduce the main characteristics of the inlet flow and morphological evolution, requiring only key information about the inlet and lagoon geometries as well as the main forcing. Furthermore, the fast execution times required by the numerical model is promising for applications in a probabilistic manner exploring multiple future scenarios.

Key words Tidal inlets; Numerical modeling; Coastal Lagoons; Mundaú Lagoon; Sururu; Sediment transport

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To the people of Mundaú Lagoon

Table of Contents

Abstract

Tidal inlets are narrow channels connecting coastal lagoons to the sea and in this way controlling the exchange of water while serving as navigational pathways. These important components of the coast are also very dynamic environments, having their morphology determined by multiple sediment transport processes, making tidal inlets difficult to model. Expected future sea level rise imposes an added challenge to the management and maintenance of the inlets and also of the connected lagoons, in particular for poorly studied regions that often lack data to support more detailed morphological models.

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Popular Science Summary

Coastal lagoons are aquatic environments located between sea and land; thus, receiving water and nutrients from both sources. These nutrient loads create a water quality that is affected by the often slow and barely noticeable water renewal of coastal lagoons. These conditions, on one hand, provoke a nutrient enrichment that makes coastal lagoons one of the most productive aquatic environments in the world, providing many ecosystems services. On the other hand, however, they make lagoons vulnerable to eutrophication and accumulation of pollutants and sediments. Among different kinds of coastal lagoons, classified by shape and level of connection with the sea, the choked lagoons are the most critical, exhibiting very limited water exchange. The main feature controlling the water renewal of coastal lagoons is the tidal inlet. Therefore, the lagoon-inlet system and how it influences water exchange, and ultimately the environmental conditions in the lagoon, is the focus of the present study.

Tidal inlets are like gates that connect the lagoons to the sea and control the water exchange between the two water bodies. Inlets are often very dynamic environments, changing constantly between wider and narrower opening conditions and some possibly closing during parts of the year. These so-called morphological changes are driven by the competition between the sediment transport along the coast, tending to close the inlet, and the flow in the inlet channel, striving to keep it open. Morphological changes in inlets are some of the most complex phenomena happening in coastal areas due to the flow conditions that reshape the morphology, that, in turn, alter the flow conditions. Thus, feedback between the forcing (e.g., waves, currents), the sediment transport, and morphological change is pronounced, highly nonlinear, and acting on many scales in time and space.

There are already many empirical and computational methods to quantify both the changes in the inlet morphology and the inlet flow. However, these methods can be either too complex, demanding high-quality input information and high computational costs, or too simple, failing to assess important factors, for example, the coupling between inlet flows and morphological response and long-term changes in the forcing (e.g., sea-level rise). In the present study, different methods were developed to quantify and assess the inlet hydraulics and related morphological changes, with the purpose of producing robust and reliable estimates of the evolution and its impact on lagoon water exchange. The method development emphasized the study of regions lacking detailed information about the inlet and adjacent lagoon, which is a common situation in many engineering projects. The methods included both analytical approaches, resulting in new mathematical expressions of key inlet and lagoon parameters, and numerical approaches, resulting in new computational models of more general applicability. In addition, models were developed to describe the interaction between the sea and the lagoon to assess how the water renewal occurs and its impact on the salinity dynamics and the ecosystem for choked lagoons.

The developed methods and their use for the assessment of lagoon dynamics were applied to the Mundaú Lagoon (northeastern Brazil), a choked coastal lagoon of crucial importance for the communities living around it due to its role as a source of food and income provided by the fishing activity, particularly the harvesting of the Sururu mussel. This lagoon has a very dynamic tidal inlet and water quality problems such as eutrophication and sedimentation. Also, salinity variations have been identified as the primary cause of its characteristic mussel disappearance observed for long periods.

The developed methods applied in the Mundaú lagoon resulted in a satisfactory description of the flows and morphological changes in the inlet, requiring only key information about the inlet and lagoon geometries as well as the main forcing. These methods demonstrated the potential to be applied in other similar coastal lagoons and to serve as tools for the successful management of such environments.

Resumo em Linguagem não Técnica

Lagunas costeiras são ambientes aquáticos localizados entre o mar e a terra; assim, recebendo água e nutrientes de ambas as fontes. Essas cargas de nutrientes criam uma qualidade da água que é afetada pela lenta renovação desses ambientes. Essas condição, por um lado, provoca um enriquecimento de nutrientes que torna as lagunas costeiras um dos ambientes aquáticos mais produtivos do mundo, oferecendo muitos serviços ecossistêmicos, mas, por outro lado, torna as lagunas vulneráveis à eutrofização e acúmulo de poluentes e sedimentos. Entre os diferentes tipos de lagunas costeiras, classificadas por forma e nível de conexão com o mar, as lagunas sufocadas apresenta a condição mais crítica, exibindo uma renovação da água muito limitada. A principal característica que controla essa renovação nas lagunas costeiras é o canal de entrada. Portanto, mudanças no canal de entrada da laguna e como essas influenciam a troca de água e, finalmente, as condições ambientais da laguna, é o foco do presente estudo.

Os canais de entrada são como portões que conectam as lagunas ao mar e controlam a troca de água entre os dois corpos hídricos. As entradas geralmente são ambientes muito dinâmicos, mudando constantemente entre condições de abertura mais amplas e mais estreitas e algumas fechando durante partes do ano. Essas chamadas mudanças morfológicas são motivadas pela competição entre o transporte de sedimentos ao longo da costa e o transporte no canal de entrada. Alterações morfológicas nas entradas representam um dos fenômenos mais complexos que ocorrem nas áreas costeiras devido às condições de fluxo que remodelam a morfologia, que, por sua vez, alteram as condições de fluxo. Assim, o feedback entre o forçamento (por exemplo, ondas, correntes), o transporte de sedimentos e a mudança morfológica é pronunciado, altamente não-linear e atua em muitas escalas no tempo e no espaço.

Já existem muitos métodos empíricos e computacionais para quantificar as alterações na morfologia da entrada e no fluxo da entrada. No entanto, esses métodos podem ser muito complexos, exigindo dados de entrada de alta qualidade e altos custos computacionais, ou muito simples, deixando de avaliar fatores importantes, por exemplo, o acoplamento entre fluxos de entrada e resposta morfológica e mudanças de longo prazo no forçamento (como o aumento do nível do mar). No presente estudo, diferentes métodos foram desenvolvidos para quantificar e avaliar a hidráulica de entrada e alterações morfológicas relacionadas, com o objetivo de produzir estimativas robustas e confiáveis da evolução do canal de entrada e seu impacto nas trocas de água da laguna. O desenvolvimento do método enfatizou o estudo de regiões carentes de informações detalhadas sobre a entrada e a adjacente laguna, o que é uma situação comum em projetos de engenharia. Os métodos incluíram abordagens analíticas, resultando em novas expressões matemáticas dos parâmetros de entrada, e abordagens numéricas, resultando em novos modelos computacionais de aplicabilidade mais geral. Além disso, foram desenvolvidos modelos para descrever a interação entre o mar e a laguna para avaliar como ocorre a renovação da água e seu impacto na dinâmica da salinidade e no ecossistema de lagunas sufocadas.

Os métodos desenvolvidos e seu uso na avaliação da dinâmica das lagunas foram aplicados à Laguna Mundaú (situada no nordeste do Brasil), uma laguna costeira sufocada de importância crucial para as comunidades que a rodeiam devido ao seu papel como fonte de alimento e renda fornecida pela atividade pesqueira, principalmente a colheita do mexilhão Sururu. Esta laguna tem uma entrada muito dinâmica e problemas de qualidade da água, como eutrofização e sedimentação; além disso, variações de salinidade foram identificadas como a causa primária do desaparecimento do mexilhão por longos períodos.

Os métodos desenvolvidos aplicados na Laguna Mundaú resultaram em uma descrição satisfatória dos fluxos e das alterações morfológicas na entrada, exigindo apenas informações sobre as geometrias da entrada e da laguna, bem como as forças principais. Esses métodos demonstraram o potencial de serem aplicados em outras lagunas costeiras semelhantes e de servir como ferramentas para o gerenciamento de tais ambientes.

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My deepest gratitude to my supervisor Magnus Larson for the guidance. His professionalism and dedication while being a generous and attentive person are inspiring. Thanks to my co-supervisor Ruberto Fragoso, who I have had the pleasure to work with since the beginning of my studies and first steps as a researcher. Thanks for always encouraging me to follow this path. Thanks to my co-supervisor Hans Hanson for the wise pieces of advice and good discussions.

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Papers

Appended Papers

I. **Nunes de Brito**, A., Fragoso Jr., C. R., and Larson, M. (2018). Tidal exchange in a choked coastal lagoon: A study of Mundaú Lagoon in northeastern Brazil. *Regional Studies in Marine Science*, 17. 133-142. https://doi.org/10.1016/j.rsma.2017.12.005

II. Larson, M., **Nunes, A.**, and Tanaka, H. (2020) Semi-analytic model of tidal-induced inlet flow and morphological evolution. *Coastal Engineering*,155:103581. https://doi.org/10.1016/j.coastaleng.2019

III. **Nunes, A.**, Larson, M., and Fragoso Jr., C.R., (2020). Morphological modeling of long-term inlet channel evolution with an application to the Mundaú Lagoon inlet, Brazil. *Estuarine, Coastal and Shelf Science Journal*. https://doi.org/10.1016/j.ecss.2020.106618

IV. **Nunes, A**., Larson, M., Fragoso Jr., C.R., and Hanson, H.. (Manuscript submitted). Modeling the salinity dynamics of a choked coastal lagoon and its impacts on the Sururu mussel (*Mytella Falcata*) population. *Ocean and Coastal Management Journal*.

The Author's Contributions to the Appended Papers

I. The author contributed to the theoretical conception of the study, data compilation and analysis, the model implementation and application, and the discussion of the results. The author was the main writer of the manuscript.

II. The author contributed to the examination and discussion of the theoretical developments, assessment of the model results, writing, and final review of the paper.

III. The author contributed to the theoretical conception of the study, implemented and applied the model, and conducted the data compilation and analysis. The author was the main writer of the manuscript.

IV. The author contributed to the conceptual development of the study, the model implementation and application, and the discussion of the results. The author was the main writer of the manuscript.

Other Related Publications

Nunes, A., Fragoso Jr., C. R., and Larson, M. (2017). A study on the water exchange in Mundaú Lagoon, northeastern Brazil, during the dry season. *Coastal Dynamics Conference*, 2017. Paper n. 123. Pages 1251-1260.

Souza, A., **Nunes**, **A.**, and Fragoso Jr., C.R., (2018). Influência do assoreamento no tempo de residência de uma laguna costeira tropical. *XIII ENES - Encontro Nacional de Engenharia de Sedimentos e I PiA - Partículas nas Américas (Particles in the Americas)*

Larson, M., **Nunes, A.**, Tanaka, H., and Hanson, H. (2018). A semi-analytic model of tidal inlets and their evolution. *36th International Conference on Coastal Engineering*.

Santos, G. B., **Nunes, A.**, and Chaves, M. B., (2019). Calibração de Modelo Hidrodinâmico para Simulação dos Níveis da Água da Laguna Mundaú – AL. *XXIII SBRH - Simpósio Brasileiro de Recursos Hídricos*.

Nunes A., Fragoso Jr., C. R., and Larson, M. (2019). Morphological Modeling of Tidal Inlet Evolution: An Application to Mundaú Inlet, Brazil. *Coastal Sediments Conference*, 2019.

Wang, S. and **Nunes A.**, (2019). Modelling Water Exchange in the Flommen Lagoon, Southern Sweden. *VATTEN – Journal of Water Management and Research*. 75:4. 331-343

Master Theses Related to this Doctoral Research

Souza, A.P. de M., 2017. Avaliação do efeito do assoreamento no tempo de residência e na hidrodinâmica de um complexo estuarino lagunar tropical. Universidade Federal de Alagoas.

Wang, S., 2019. Modelling Water Exchange in the Flommen Lagoon, South Sweden. Lund University. TVVR19/5008.

Lay, K., Ångbäck, K., 2020. Modelling of Water Exchange in Flommen Lagoon System in Skanör-Falsterbo, Sweden. TVVR 20/5003.

Abbreviations

ANA	Brazilian National Agency of Waters
CHM	Brazilian Navy Hydrographic Center
CR	Control Region
CSTR	Continuously Stirred Tank Reactor
GFS	Global Forecast System
IMA-AL	Environmental Agency of the State of Alagoas
MMELS	Mundaú-Manguaba Estuarine-Lagoon System

List of Symbols

A_o	Normalized inlet cross-sectional area
A_B	Lagoon surface area
A_I	Inlet channel cross-sectional area
a_o	Sea level amplitude
a_B	Amplitude of the bay water level
$\hat{a}_B$	Non-dimensional amplitude of the bay water level
B	Barrier island width
b	Return flow factor
C	Concentration of tracer or number of water parcels
C_0	Initial concentration of tracer or number of water parcels
C_M	Coefficient differing the obtained solution for criteria 1 and 2
f	Coefficient of bottom friction
g	Gravitational acceleration
H	Undisturbed channel depth
k	Dimensionless friction coefficient
K	Repletion coefficient
K_E	Equilibrium repletion coefficient
K_I	Inlet friction coefficient including entrance, exit and head losses
K_w	Empirical coefficient of transport

L	Inlet channel length (Hydraulics); Distance from the farthest location to the inlet (Salinity)
m	Coefficient defining the salinity profile shape
m_I	Inlet sediment transport rate
m_L	Longshore sediment transport rate
$\widehat{m}_L$	Non-dimensional longshore sediment transport rate
m_{max}	Theoretical maximum sediment transport rate in the inlet
n	Coefficient for the assumed inlet geometric schematization (Morphology); Coefficient for describing the decay based on the salinity influence (Salinity)
N	Mussel population
η_L	Lagoon water level, following Hill (1994) description
η_m	Average lagoon level
η_B	Lagoon water level, following Keulegan (1967) description
η_o	Tidal levels
N_E	Population equilibrium state
$\hat{\eta}_B$	Non-dimensional lagoon water level
$\widehat{N}_E$	Non-dimensional population equilibrium state
P_{max}	Maximum tidal prism
$\hat{P}$	Non-dimensional tidal prism
Q_R	River runoff
Q_T	Tidal flow
$\bar{s}$	Average salinity concentration in the lagoon

s_o	Sea salinity concentration
T	Tidal period
t	Time
$\hat{t}$	Non-dimensional time
T_f	Flushing time
u_{cr}	Critical velocity for the sediment entrainment
$\hat{u}_{cr}$	Non-dimensional critical velocity for the sediment entrainment
u_I	Inlet velocity
u_{max}	Normalized maximum inlet velocity
u_I^m	Inlet average velocity
u_I^{max}	Inlet maximum velocity
V	Lagoon volume at mean sea level
W	Inlet width
x	Position along the lagoon originating from the most upstream location
α	Mussel population growth rate
β	Mussel population decay rate
δ	Population model parameter.
ε	Phase difference between water level peaks in the sea and the lagoon
Ψ	Derived expression representing both the non-dimensional tidal prism and bay amplitude

1 Introduction

This introductory chapter outlines the problems investigated in this thesis research, as well as, the approach and goals. The chapter closes presenting the thesis structure and briefly describing the appended papers and their interconnection.

1.1 Background

Coastal inlets are narrow water bodies connecting estuaries, lagoons, and bays to the ocean. Inlets serve as conduits for commercial and recreational navigation, and their channels are typically dredged and maintained for this purpose. When the flow through the inlet is primarily due to tidal motion the inlet is named a tidal inlet (Kraus, 2009). The flow through an inlet is the main mechanism for water renewal in a lagoon ensuring satisfactory water quality, including the salinity levels necessary for the maintenance of the aquatic ecosystems.

Changes in the morphology of inlets alter the inlet flow and they are important to consider as they impose challenges for the management of the navigational conditions and the water quality in the lagoons. For example, sediment infilling of an inlet channel, and the resulting reduction in cross-sectional area, weakens the water exchange between the lagoon and the sea, causing deterioration of the water quality. On the other hand, the opening of new inlets, whether artificially, as a tentative measure to enhance the water conditions in the lagoon, or naturally, through breaches in the coastal barrier, has consequences for the adjacent coastline and also for pre-existing inlets.

Coastal lagoons, present along about 13% of the world's coasts (Barnes, 1980), contain highly productive aquatic ecosystems due to the high input of nutrients from the watershed and the sea. The lagoons classified as choked coastal lagoons (Kjerfve, 1986) have reduced water renewal rates and, consequently, are more sensitive environments. Thus, the understanding of the effects of inlet morphological changes on the water flow is a crucial factor for the management of choked lagoons.

To address these challenges, mathematical models are needed to reproduce the main processes involved and their complex interactions. Models that are able to accurately reproduce the morphological evolution of inlets and the effects on lagoons and bays are highly useful tools for understanding and managing inlet lagoon systems. As important as predicting and quantifying the morphological changes in tidal inlets, is to assess the impacts caused by these changes in the inland water bodies, lagoons, or bays.

The present study investigates both inlet processes (hydraulics and morphological changes) and the coastal lagoon processes (water exchange, salinity dynamics, and ecology) through a series of numerical and analytical modeling approaches newly developed. These models may be applied, especially in regions with a lack of data, to support the formulation of inlet and lagoon management strategies.

1.2 Objective and Procedure

The overall objective of this thesis is to develop and validate new simple approaches to simulate the hydraulic and morphological changes in tidal inlets considering the essential forcing and general environmental conditions. These new approaches should be able to generate robust and reliable estimates of key parameters describing inlets and lagoons and their evolution. Also, the models should be applicable to areas with limited data available and support coastal managers in the development of strategies for coastal inlets and lagoons.

The lagoon-inlet system adopted as the study region for model development, calibration, and validation is the Mundaú Lagoon located in northeastern Brazil. This lagoon has, despite its great importance for the population living in its surroundings, concerning its physical processes, still scarcely been studied and is poorly understood. Mundaú Lagoon is a choked coastal lagoon where the inlet dynamics has marked impacts on several key aspects such as water exchange, salinity levels, navigation conditions, and erosion of the adjacent coast; all requiring further investigation.

The procedure followed in this thesis, to address the objective, included the following steps:

1. Perform a literature review to document the state-of-the-art regarding the modeling of hydrodynamics, sediment transport, and morphological changes at inlets connected to lagoons and bays.
2. Compile available data from the Mundaú Lagoon with a focus on waves, currents, sediment transport, and the observed morphological evolution at the inlet. Document existing problems related to inlet morphological evolution at the site.

3. Investigate the physical processes affecting the hydrodynamics of the study region through the application of a hydrodynamic model and qualitative assessment of the morphological changes through satellite images.
4. Formulate the governing equations concerning the hydraulics and sediment transport at inlets, including the effects of waves and currents, and develop analytical solutions for inlet hydraulics and evolution, allowing a general assessment of tidal inlets.
5. Develop a numerical model of inlet cross-sectional area evolution that couples the hydrodynamic and sediment transport models. Test the model against schematized simulations for assessment of the model representation of the inlet behavior, as well as against observations derived from satellite images for qualitative and quantitative assessment of the model predictions in a complex setting.
6. Employ the inlet hydraulics model to investigate the impact of tidal exchange and river flow on lagoon water quality with focus on the salinity conditions. Use the salinity model for a qualitative assessment of the evolution of the mussel population in a lagoon.

1.3 Thesis Structure

This thesis follows the format of a compilation of papers introduced in the present thesis summary. These papers are appended just after this summary. A brief description of the appended papers and their interconnection is presented below:

Paper I presents a detailed investigation of the hydrodynamics and the processes involved in the water exchange of a choked coastal lagoon (Mundaú Lagoon) with the sea. The understanding of these processes was fundamental for the design of the inlet hydraulics models developed in the subsequent studies **Paper II** and **Paper III**, especially for this latter study in which the methods developed were applied in the Mundaú Lagoon.

Paper II and **Paper III** explore new methods of estimating inlet hydraulics and using it to describe the inlet morphological changes. **Paper II** presents a semi-analytic approach based on the Keulegen (1967) description of the tidal inlet flow, generating expressions for the key parameters of the inlet flow. These expressions are then used to develop a modeling approach of the inlet evolution and equilibrium conditions based on the repletion coefficient.

Some of the limitations present in the **Paper II** approach are then relaxed in **Paper III**, where a numerical approach for the inlet hydraulics and evolution is developed considering the complexities of the real natural inlet in which the model was applied in a long-term simulation.

Finally, **Paper IV** brings the focus back on the effects of the connection and water exchange with the sea on the lagoon processes. This study investigates the implications of the tidal water exchange and water balance for the salinity dynamics of the lagoon and then develops a coupled model between the salinity and the population dynamics of the *Mytella Falcata*, a characteristic bivalve mussel that is common in this lagoon. The inlet hydraulics model explored in **Paper III** was applied in **Paper IV**.

This thesis summary is composed of six chapters: **Chapter 2** (Theoretical Background) presents a brief theoretical background introducing the main concepts and references that the appended studies were based on. **Chapter 3** (Methods) presents the procedure followed for the development of the appended studies. **Chapter 4** (Study Area) presents Mundaú Lagoon and its inlet, as well as, the data used. **Chapter 5** (Results and Discussion) highlights the main findings of the studies and discusses them**.** Finally, **Chapter 6** (Conclusions and Future Steps) presents the main conclusions of the thesis and future steps.

2 Theoretical Background

This chapter describes the theoretical background to the thesis development and presents the main references on which the thesis is based. The first two sections focus on the inlet processes and the last two sections focus on the coastal lagoon processes.

2.1 Inlet Hydraulics

The flow through tidal inlets is a classical research topic and has been investigated in a considerable number of studies (Brown, 1928; Escoffier, 1977; Keulegan, 1967). The pioneer studies of inlet hydraulics are based on the application of the one-dimensional dynamic (momentum) equation in combination with the continuity equation, considering a dampening effect on the lagoon levels controlled by the friction in the channel. These approaches produce simple, insightful yet effective solutions, as described in depth by classic coastal engineering texts as Bruun *et al*. (1978) and Dean and Dalrymple (2001). More recently a new generation of numerical models has demonstrated ability to solve the inlet hydraulics in more detail (de Vriend *et al*., 1993b; der Wegen *et al*., 2010; Sánchez and Wu, 2011). However, the use of simple solutions is still advantageous when applied in regions with limited data available or in studies where the computational efforts need to be minimized. The simpler methods for inlet hydraulics description were explored in this thesis work, therefore the present theoretical background focuses on them.

The initial approaches for estimating the inlet hydraulics used analytical solutions to calculate the key elements of the flow as the average and maximum velocities (u_I^m, u_I^{max}), and the response of the lagoon levels (η_B) due to tides. The input information these approaches require are easily determined parameters of the inlet-lagoon system (Figure 2.1) as the tidal levels (η_o) and period (T); the lagoon surface area (A_B); the channel length (L); and the channel cross-sectional area (A_I). The basic balance equations were in the first studies solved in terms of non-dimensional variables. Other recurrent solution strategies involved are: the assumption of only one harmonic constituent of the tidal signal; neglection of the local acceleration (inertia) term of the dynamic equation (Keulegan, 1967; Oliveira, 1970; van de Kreeke, 1967); and linearization of the dissipation term (Brown, 1928; Dean, 1971).

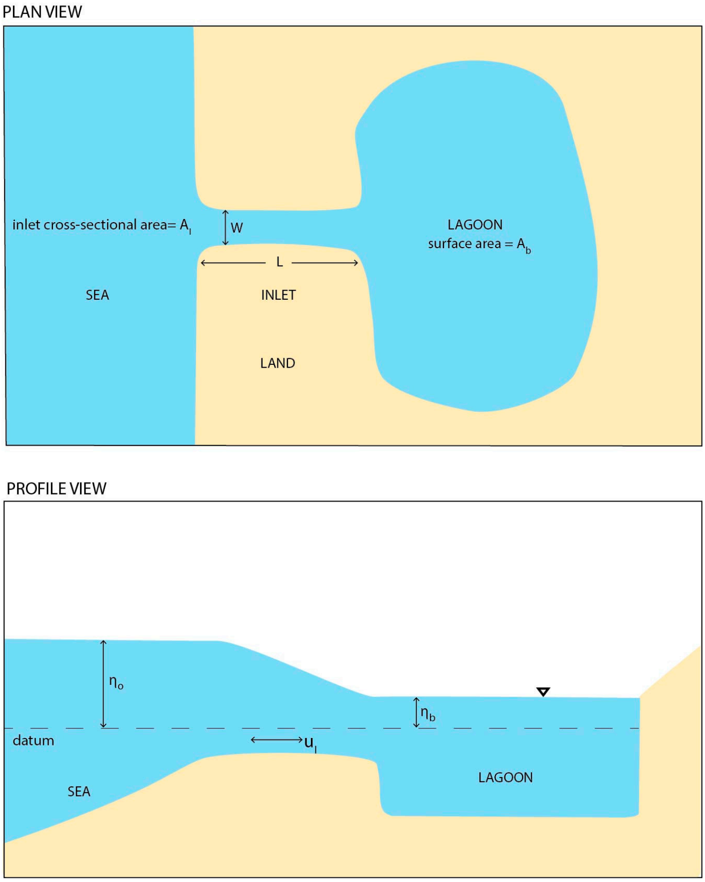

Figure 2.1
The Inlet-Lagoon system and its characteristic dimensions.

This thesis work used as main references for the inlet hydraulics, in a first approach (**Paper II**), the equations developed by Keulegan (1967) and later (**Paper III**) the equations proposed by Hill (1994) regarding the flow through choked inlets, in which the depth variation becomes more important. These two solutions are described below.

Keulegan (1967) developed a one-dimensional depth-averaged solution for the inlet hydraulics, neglecting the inertial term of the dynamic equation, which is a reasonable assumption for a forcing frequency significantly smaller than the Helmholtz frequency of the system (van de Kreeke and Brouwer, 2017). For the lagoon level variation in time, this solution can be expressed as:

$$\frac{d\eta_B}{dt} = \frac{A_I}{A_B}\sqrt{\frac{2g}{K_I}}\sqrt{|\eta_o - \eta_B|}\,sgn(\eta_o - \eta_B) \qquad 2.1$$

where K_I is a friction coefficient that includes entrance losses, exit losses, and head loss due to friction in the channel; t is time; and g is the gravitational acceleration. Considering a sinusoidal level variation, with the amplitude of a single tidal constituent, together with the non-dimensional form of Eq. 2.1, the following expression is obtained:

$$\frac{d\hat{\eta}_B}{d\hat{t}} = K\sqrt{|\hat{\eta}_o - \hat{\eta}_B|}\,sgn(\hat{\eta}_o - \hat{\eta}_B) \qquad 2.2$$

where $\hat{t} = 2\pi\frac{t}{T}$; $\hat{\eta}_o = \frac{\eta_o}{a_o}$; $\hat{\eta}_B = \frac{\eta_B}{a_o}$. From this non-dimensional equation a coefficient K, known as the repletion coefficient, arises, where:

$$K = \frac{A_I}{A_B}\sqrt{\frac{2ga_o}{K_I}}\frac{T}{2\pi a_o} \qquad 2.3$$

The repletion coefficient indicates the response in the lagoon level given by the tidal level, in terms of dampening and phase difference (Figure 2.2). The $\hat{\eta}_B$ curve has a symmetric sinusoidal-like shape, indicating that the duration of the ebb and flood flows are the same, also the amplitude of the bay response is the same both during high and low water (*cf.*, Oliveira, 1970).

Besides the neglected inertial term this solution assumes head losses in terms of the averaged velocity along channel; representative cross-sectional area; constant lagoon surface area; and constant inlet area.

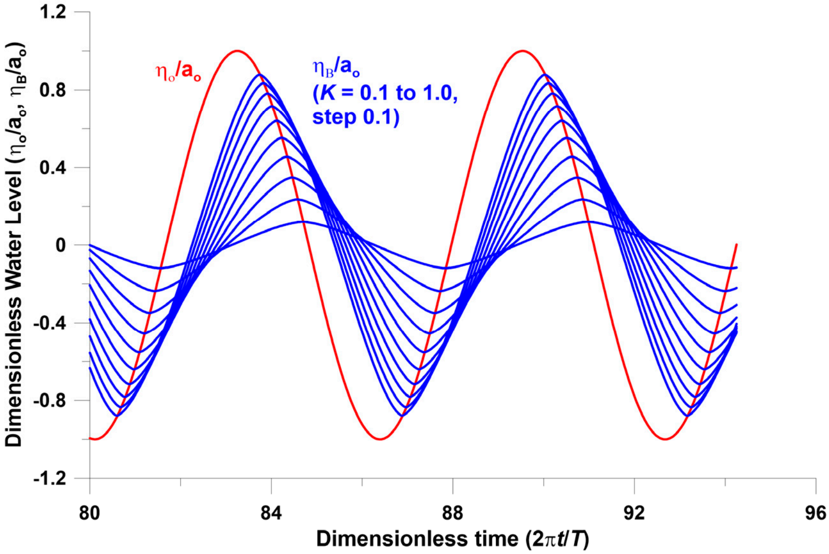

Figure 2.2
Dimensionless tidal level variation (red) and the lagoon response (blue) for different values of the repletion coefficient (*K*).

For the case of choked inlets, friction asymmetry processes become relevant and cause a set-up in the average levels. Thus, in these inlets, the depth variation needs to be represented (Dean and Dalrymple, 2001). Therefore, another solution based on Hill (1994) was also explored in this thesis. Hill (1994) follows the same principles of the Keulegan (1967) solution but differing essentially in the use of an average level in the channel ($n_m = (n_o + n_L)/2$). This other solution expresses the lagoon level variation by:

$$\frac{dn_L}{dt} = \left(\frac{gW^2}{{A_b}^2 kL}(H + n_m)^3\right)^{\frac{1}{2}} \frac{n_o - n_L}{\sqrt{|n_o - n_L|}} \qquad 2.4$$

where W is the inlet width; H is the undisturbed channel depth and k is a dimensionless friction coefficient. This equation can be solved numerically having the advantage to consider all the tidal constituents.

2.2 Inlet Morphological Changes

Composed of different morphological elements, such as the inlet channel, the ebb and flood shoals that interact and exchange sediments between each other through and with the adjacent coastlines, tidal inlets are one of the most complex elements of the coastal zone (Hayes, 1980). This interaction is mainly controlled by the reversing currents caused by tides, seasonally controlled river flow currents, and wave activity along the coast (Komar, 1996). This complex interaction of different elements and competing transport processes results in the morphological changes at coastal inlets.

Morphological changes in the coastal zone are a result of a variety of processes acting and interacting on different space and time scales (de Vriend *et al.*, 1993a). These changes may be described by morphological models grouped in different types, for example, physical, empirical or semi-empirical, deterministic or process-based, and behavior-based models. In the study of tidal inlet morphology, the empirical and the process-based modeling approaches stand out.

The stability of tidal inlets and its morphological changes has been studied first through empirical equilibrium relationships, the most famous relating the cross-sectional area of the inlet with the hydrodynamics represented by the tidal prism (Hughes, 2002; Jarrett, 1976; O'Brien, 1969, 1931). This is a useful approach to estimate a bulk property of the inlet such as the equilibrium volume of the ebb shoal (Walton and Adams, 1976) or the already mentioned equilibrium cross-sectional area of the inlet. However, this approach does not describe the inlet processes in a more general way. Instead, the results are heavily dependent on the data and are not necessarily applicable at different inlets; thus, the lack of data of a study region is an important limiting factor in applying this kind of models (Roelvink *et al.*, 2016). Another limitation of empirical models to be considered is when analyzing changes in the forcing conditions, such as future sea levels. The applicability of these model approaches is not obvious; changes in the historical tidal prisms may cause uncertainty in the new morphology to be estimated (der Wegen *et al.*, 2010).

More recently, with the advances in computational capacity, the process-based type models have become increasingly popular and widely used (Nahon *et al.*, 2012; Ranasinghe *et al.*, 1999; Stive and Wang, 2003; Van de Kreeke, 1996). These models attempt to resolve the small-scale physics and integrate the resulting changes over larger time and space scales. Process-based models have obtained some success in qualitatively representing inlet mechanisms such as closure, migration, and evolution after breaching. One common characteristic of process-based inlet morphological models is the feedback of the new estimated morphology on the hydrodynamics. Although empirical approaches have historically been more used for the long-term evolution, process-based models have demonstrated relative success also at this time scale in recent years (Cayocca, 2001).

The difficulty in applying a process-based morphological model is to find a proper balance in the level of complexity assumed in the process representation. A very general model considering the detailed mechanisms involved in the morphodynamics of the inlets has an associated high computational cost, decreasing model usability and limiting the number of scenarios that can be explored. Also the high demands on input data in terms of quantity and quality limit the applicability in most inlet cases (Cayocca, 2001). On the other hand, for some applications, certain physical processes cannot be disregarded without losing representativity of the results produced, for example, the effects of varying depth in choked inlets. In this way, the most suitable process-based morphological model for a specific application or study case is a balance determined by the level of complexity needed to represent relevant physical mechanisms in view of data availability and computational resources.

This thesis work was based on and further explored the potential of a process-based model proposed by Kraus (1998) for representing tidal inlet evolution; similar approaches were taken by Ogawa *et al*. (1984) and Tanaka *et al*. (1996). The principles and idealizations on which this approach is based, as well as its limitations, will be described in more detail below.

Kraus (1998) focused on the response of the inlet channel volume to the two main competing sand transport fluxes at tidal inlets: the transport due to scouring in the inlet channel and the longshore transport contributing to deposition in the channel. Formulated this way, the following balance equation results:

$$\frac{d(A_I B)}{dt} = m_I - m_L \qquad 2.5$$

where A_I is the inlet cross-sectional area; B is the barrier island width; m_I is the sediment transport rate in the inlet; and m_L is the longshore sediment transport rate. Eq. 2.5 yields for the case $m_I > m_L$ that the inlet channel is scoured, thus, increasing its volume, whereas for the case $m_I < m_L$ sediment deposition is predominant and the channel volume decreases. This model was further developed in this thesis work, first in the semi-analytic solution and then numerically. Limitations and idealizations involved in both these solution approaches are presented in more detail in the Methods chapter.

Replacing the sediment transport rate in Eq. 2.5 by the transport formula proposed by Watanabe *et al*. (1991) with a critical shear stress estimated from the Shields theory for initiation of motion, the following expression is obtained:

$$B\frac{dA_I}{dt} = \frac{K_w f}{8g}(u_I^2 - u_{cr}^2)u_I W - m_L \qquad 2.6$$

where u_I and u_{cr} represent, respectively, the inlet velocity and the critical velocity for the sediment entrainment; K_w is an empirical coefficient of transport and f is coefficient of bottom friction. The inlet velocities and the coefficient f arise from the use of the Darcy-Weisbach equation in the transport formula by Watanabe *et al.* (1991).

2.3 Water Exchange and Renewal

The water quality deterioration, eutrophication, and sediment infilling processes are considerable concerns in coastal lagoons that are often related to reduced water renewal times (Kjerfve and Magill, 1989). The relationship between the water renewal time scales and the quality of the water and the ecosystems for coastal lagoons have been investigated in many previous studies regarding, for example, phytoplankton eutrophication. (Lucas, 2010; Lucas *et al.*, 1999). The flow through the inlet that connects the lagoon to the sea is often the main water renewal mechanism for these coastal water bodies.

There are several concepts in the literature for estimating the water renewal times in coastal lagoons; some of these concepts have different names for similar methodologies or the same names for different approaches when estimating such times, which may cause confusion. For example, the residence time definition used by Takeoka (1984) relies on a different concept than the one used by Monsen *et al.* (2002). Thus, it is crucial that the studies on water renewal establish precisely the definition and method used to avoid misunderstandings (Bolin and Rodhe, 1973).

Another common source of confusion when applying different concepts is that they can lead to considerably different values. In addition, these values are event dependent. The scenarios of the environmental conditions investigated need to be considered carefully and the results are only valid considering the context they were estimated under, for example, different river runoff seasons, tidal cycles (spring and neap), and lagoon inlet morphology (Oliveira and Baptista, 1997).

The water renewal time scale methods can be divided into two types of measures: (a) lumped or integrated approaches, and (b) the spatially distributed or local time scales (Monsen *et al.*, 2002). The former type, the integrated measures, obtain a bulk value of water renewal time scale for the lagoon, considering the environmental forcing of the flow during a specific period. Integrated water renewal time scales are useful to easily compare different lagoon systems.

Local time scales are estimates of the renewal potential of different regions within the lagoon and effect of the different hydrodynamic processes on the renewal or stagnation of these regions. As the spatial distribution of the processes is relevant for this methodology, 2D or 3D hydrodynamic models are commonly applied differing basically in whether a Eulerian or Lagrangian perspective of the transport is adopted based on the flow field generated. Following these two transport perspectives, the concentration decay of a conservative tracer, such as salt or the movement of buoyant virtual particles, is often used in estimating spatially distributed time scales. This approach is useful to identify zones sensitive to pollution events or algae blooms.

The water exchange in this thesis work was estimated both regarding the entire water body (flushing time) and the spatially distributed (residence time) scales. The main concepts explored are presented in detail in the Methods chapter.

2.4 Salinity and the Coastal Lagoons Ecosystems

Together with temperature, salinity is an important abiotic parameter that regulates the aquatic ecosystems in coastal lagoons. In tropical coastal lagoons, presenting lower seasonality of the temperature conditions, salinity becomes the most important abiotic factor. Several studies have already pointed to the crucial role of salinity levels in ecological processes as controlling fish variety and abundance (Franco *et al.*, 2019; García-Seoane *et al.*, 2016); richness and biomass of submerged aquatic vegetation (Rodríguez-Gallego *et al.*, 2014); plankton distribution (Araújo *et al.*, 2015; Dube *et al.*, 2010); and trophic state shifts (Jeppesen *et al.*, 2007; Moreira-turcq, 2000). In coastal lagoons, the salinity variation is an important condition determining which species survives and is often a critical factor limiting for the populations of these organisms, as is the case for the bivalve mollusks (Gosling, 2015).

The mechanisms affecting the salt balance are the advective transport, the tidal diffusion, and the shear effects (Smith, 1994). The advective transport is related to the river runoff and sea-level fluctuations. Over periods of days or longer, a consistent freshwater flow may dominate the advective process, causing a seaward transport. On the other hand, the diffusive mechanism of transport caused by tides will present a quasi-steady landward transport. Finally, salt transport due to shear effects is induced by the spatial variations in concentration and current velocity.

Lagoon processes affecting changes in salinity levels in coastal lagoons are changes in the water balance and the morphology that, together with the water exchange, alter salt transport mechanisms. These changes can occur due to anthropogenic interventions or through natural seasonal or extreme events in the lagoon system, including the contributing watershed. Regarding the morphological changes affecting the salinity dynamics, most common changes are related to the inlets, restricting or enhancing the water exchange with the sea (Panda *et al.*, 2013; Rynne *et al*., 2016). Human interventions in coastal inlets are often related to the opening of new inlets (Rivera *et al*., 2019) and dredging operations (García-Oliva *et al*., 2019). Examples of natural morphological processes are inlet closure as well as breaching of barrier islands and formation of new inlets. Important morphological changes not related to the inlet also occur in coastal lagoons; for example, sedimentation processes aggravated by soil erosion processes in the watershed can alter coastal lagoon volumes, causing substantial long-term changes (Duck and da Silva, 2012; Souza, 2017).

A change in the water balance of a coastal lagoon is another important external factor affecting its salinity dynamics. Lagoons with marked seasonality in the freshwater inputs and outputs can present drastic differences in salinity concentrations throughout the year. Besides the interannual variability in the hydrology of coastal lagoons, other phenomena such as climatic variability and climate change affect the salinity dynamics, for example, the El Niño-Southern Oscillation (ENSO) (Blanco *et al*., 2006; Fichez *et al*., 2017).

The different salinity modeling approaches have evolved from box models to distributed approaches. This thesis work explores the use of the former method for describing the salt balance. Some of the pioneer modeling investigations of the salinity levels in coastal lagoons and estuaries were done by Pritchard (1960, 1958, 1954). Pritchard (1960) developed an integrated salt balance considering the hydrological and meteorological information to estimate the annual salinity variation in Chincoteague Bay and inferred water renewal rates. The integrated approach for salinity modeling has demonstrated effectiveness in many other studies regarding coastal lagoons (Babson *et al*., 2006; Martínez-Alvarez *et al*., 2011; Obrador *et al*., 2008) and is particularly suitable as a basis for management decisions.

3 Methods

This chapter highlights the model development for both the inlet processes (hydraulics and morphology) and coastal lagoon processes (water exchange, salinity and mussel population) through analytical and numerical approaches. For a more extensive methodology description, the appended papers are referred to.

3.1 Inlet Hydraulics and Morphological Changes

The inlet hydraulics and morphological changes were primarily explored through modeling approaches based on Keulegan (1967) and Hill (1994) for the hydraulics and Kraus (1998) for the inlet morphology. However, the present formulations developed these approaches further to achieve the goal of obtaining robust and reliable tools for engineering applications. These previous methods were enhanced through the semi-analytic (**Paper II**) and numerical approaches (**Paper III**).

3.1.1 Semi-Analytic Modeling

Here, a semi-analytic model refers to a solution that is valid while satisfying specific criteria for the original equation, in opposition to an analytic model that produces a more general solution to the equation. Here, this semi-analytic approach was used to solve Keulegan's Eq. 2.1, obtaining explicit expressions for the main inlet flow properties. General analytical solutions of this equation do not exist even when considering a simple tidal level variation. Previous solutions derived to this equation produce convenient results in graphic and tabulated form for simple forcing and boundary conditions (e.g., Bruun, 1978; van de Kreeke and Brouwer, 2017); however, explicit expressions describing the inlet flow have considerable advantages of applicability, for example, in the subsequent analysis of inlet morphological changes. As described below, the explicit expression developed in the present study included amplitude of lagoon water level, tidal prism, and inlet velocity. These flow expressions were then used to explore inlet evolution and stability.

As is common in many approaches to the Keulegan equation, the present semi-analytic solution neglected depth variations and adopted a representative depth for the inlet. Furthermore, a dimensionless simple sinusoidal response of the bay level variation was adopted:

$$\hat{\eta}_B = \hat{a}_B \, sin(\hat{t} - \varepsilon) \qquad 3.1$$

where $\hat{a}_B$ is the non-dimensional amplitude of the bay response ($\hat{a}_B = a_B/a_o$) and ε is the phase difference between the water level peaks in the sea and the bay (Figure 3.1). By replacing the bay response (Eq. 3.1) in the non-dimensional form of the Keulegan (Eq. 2.2), considering a period of flood tide and considering the geometric relationship $\hat{a}_B = cos\, \varepsilon$, the following expression is obtained:

$$cos\, \varepsilon \, cos(\hat{t} - \varepsilon) = K\sqrt{sin\, \hat{t} - cos\, \varepsilon \, sin(\hat{t} - \varepsilon)} \qquad 3.2$$

As there is not a solution that satisfies this equation during an entire tidal cycle, two criteria were applied to ensure agreement between the exact and semi-analytic solution, so that in each case the equation becomes analytically solvable: (1) maximum inflow from the sea to the lagoon ($\hat{t} = \varepsilon$); and (2) integrated squared flow through the inlet. Both criteria result in basically the same solution differing by a multiplier that was optimized and compared to the numerical solution for the inlet flow. A general expression for the dimensionless bay amplitude is obtained. Based on this expression the other inlet flow properties were formulated in non-dimensional form. The performance of the new expressions derived was assessed against the numerical solution of Eq. 2.2.

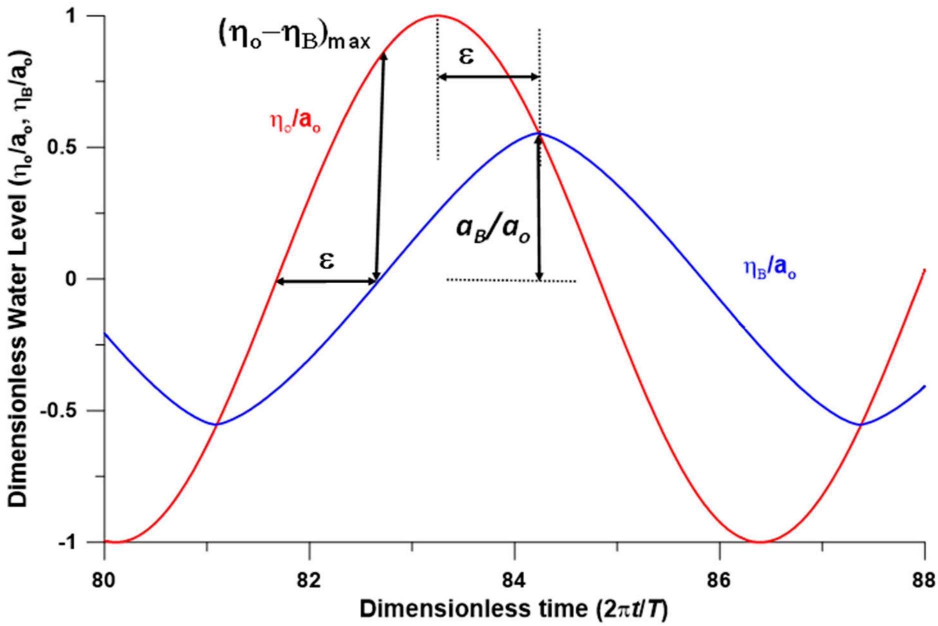

Figure 3.1
Dimensionless water levels (red for tide and blue for the lagoon response) and definition of the key parameters.

The new explicit expressions of the inlet hydraulics obtained for the flow were then used in the Kraus (1998) inlet evolution model given by Eq. 2.6. An equation for the changes in the repletion coefficient of the inlet over time ($\frac{dK}{dt}$) due to the morphological processes was derived (the repletion coefficient includes the cross-sectional inlet area, which is the primary unknown in the evolution equation). The inlet dynamic equilibrium can then be assessed by letting $\frac{dK}{dt} = 0$.

For an analytic solution, the other parameters involved in the morphological processes must be represented with reasonable simplicity. Thus, the critical shear stress and the longshore transport were assumed constant, whereas the inlet channel geometry and velocity were described schematically. Three schematized geometries of the inlet cross-section were explored (*cf.*, Larson *et al.*, 2011): (1) constant width (e.g., a jettied inlet); (2) constant depth (e.g., hard bottom in the inlet); (3) geometrically similar inlet with a constant ratio between width and depth (Stive *et al.*, 2009).

The equilibrium conditions for the different inlet schematizations were displayed in the form of diagrams of the equilibrium repletion coefficient related to the longshore sediment transport, with different curves for specific critical shear stresses values. Inlet evolution simulations were also executed and the changes in the equilibrium repletion coefficient with the time were estimated.

3.1.2 Numerical Modeling

The second approach explored by this thesis work was the numerical modeling of the inlet hydraulics and evolution. The semi-analytic solution derived in the previous section produced expressions for key inlet flow parameters and allowed for the determination of the equilibrium conditions of tidal inlets for simplified input and boundary conditions; however, more complex forcing and boundary conditions could not be handled. Thus, there are clear advantages in generalizing the solution of the governing equations, relaxing some of the previous assumptions, and allowing for long-term modeling of the tidal inlet evolution under very general conditions.

A modeling structure similar to the semi-analytic approach was used with some fundamental differences allowed by the numerical solution: the inlet hydrodynamics considered depth variation and the model proposed by Hill (1994) was used instead of Keulegan (1967); the complete tidal harmonic constituents and the river runoff were used as drivers of the inlet flow; the stirring and sediment transport in the inlet was expressed by Watanabe *et al*. (1991) with critical shear stress estimated from Shields theory for initiation of motion; and the longshore sediment transport was estimated using the CERC equation having as breaking wave conditions input estimated through the wave transformation model by Larson (1995), which was also used to account for the wave breaking and energy reduction caused by reefs present at the study site. A diagram of the model structure is presented in Figure 3.2 that includes the main parameters in the modules representing the different processes involved.

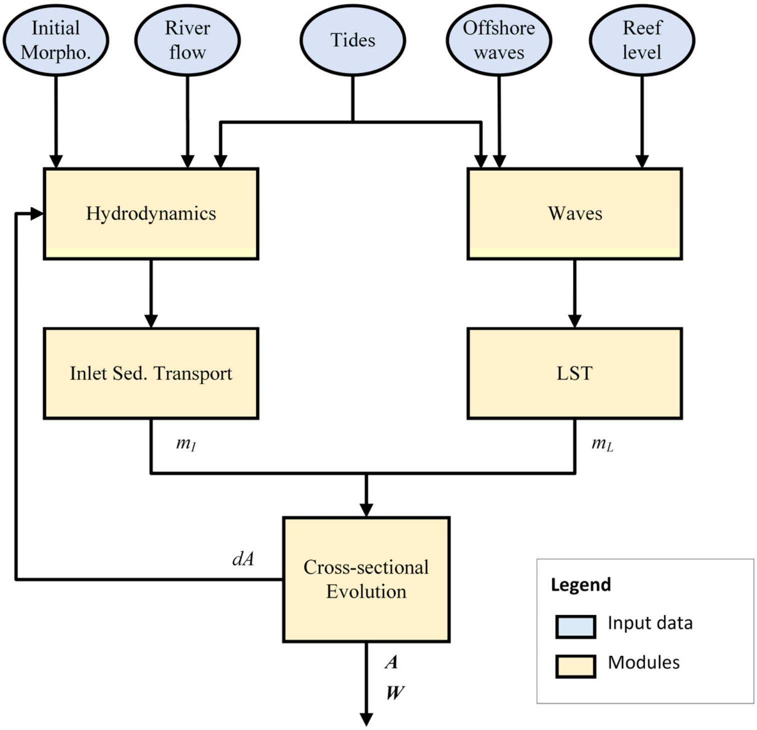

Figure 3.2
Diagram of the connection among the modeled processes for inlet flow and morphological evolution.

In Figure 3.2 it is shown that the two sediment transport processes (m_I and m_L) are combined in the final module to calculate a new inlet area through the numerical solution of the sediment balance equation for the inlet channel volume, as proposed by Kraus (1998). For this modeling approach, the inlet cross-sectional geometry was schematized through a geometric similarity description (Stive *et al*, 2009). This idealization allowed for estimation of the inlet width that was used in the calibration and validation process for the morphological model.

From Figure 3.2 it is shown that the calculated new inlet area is returned to the hydraulics computations to reproduce the feedback processes, as is typical in morphological models. This area is assumed constant during the hydraulics calculations during one tidal cycle and, during the new cross-sectional area estimate, the maximum velocity remains constant, corresponding to a quasi-steady approach.

This model setup was tested against a real choked inlet (presented in the following chapter – Study Area). Certain adaptations were made when applied to Mundaú Inlet, some already mentioned, such as the use of a depth variation in the hydraulic model; considering the river runoff effects on the inlet flow; and wave energy reduction caused by sandstone reefs alongshore the coast. Regarding the inlet cross-sectional area, it was idealized by assuming that the cross-section could be schematized into two parts: a triangular channel adjacent to a rectangular plateau.

The model simulation was carried out for a total period corresponding to 11 years. The time step applied for the hydrodynamic model was 1 hour, while for the morphological model a 12-hour time step was used. The initial value of the water level was set to the mean sea level, and initial morphology was used according to the observed value at the start of the simulations, equal to an inlet width of 170 m.

The performance of the model was assessed following two scenarios: first for schematized cases in which the forcing was constant and the expected equilibrium or closure behavior were assessed; and later through calibration and validation against observations of lagoon water levels and inlet widths.

3.2 Impacts on Coastal Lagoons

Different processes occurring in coastal lagoons due to inlet hydraulics were also modeled in this thesis. A hydrodynamics and water exchange study (**Paper I**) was the first step in this thesis research and allowed for an understanding of the most important processes of the water flow. The last part of this thesis investigated how the inlet hydraulics acts on important processes controlling coastal lagoon water quality and ecosystems related to the salinity dynamics (**Paper IV**).

3.2.1 Water Exchange

Following the recommendation to precisely define the water exchange time scale concepts used (Bolin and Rodhe, 1973), both the integrated and spatially distributed concepts of water exchange are described in detail in this section. Subsequently, this section describes how these concepts were applied to the study region.

The integrated time scales used, here called the flushing times, follow the definition suggested by Monsen *et al*. (2002). The most basic expression of the flushing time (T_f) is the ratio between the lagoon volume (V) at mean sea level and the exchange flow rate (Q) (Eq. 3.3). This description assumes steady-state flow in a well-mixed lagoon and exchange dominated by advection (Sanford *et al*., 1992).

$$T_f = \frac{V}{Q} \qquad 3.3$$

Furthermore, this concept may be modified to include the fraction of flow that returns to the lagoon during the flood cycle by splitting the exchange flow rate into two terms: the tidal flow (Q_T) and the river runoff (Q_R) and introducing a return flow factor (b). This factor has a value equal to 0, if the entire tidal prism is composed of new seawater, and value equal to 1 if the tidal flow does not contribute to the water renewal. This modified flushing time is expressed as:

$$T_f = \frac{V}{(1-b)Q_T + Q_R} \qquad 3.4$$

For the study system, were this concept was applied, the return flow factor was equal to 0.7, based on salinity measurements by Oliveira and Kjerfve (1993). This study determined that during the flood tide only 30% of the prism consist of new water from the sea.

Another useful version of the flushing time, that was also applied in this thesis, is the e-folding flushing time. This concept is an analogy to a continuously stirred tank reactor (CSTR) (Monsen *et al.*, 2002; Ridderinkhof *et al.*, 1990) and estimates the average amount of time spent by a water parcel in the studied system. This concept is expressed by the decay of the concentration (C) or the number of water parcels inside the lagoon:

$$C(t) = C_0 e^{\frac{-t}{T_f}} \qquad 3.5$$

where C_0 is equal to the initial value of concentration or number of parcels. For some lagoons, this is a more realistic estimate of the water exchange time as some systems are never totally renewed and the e-folding flushing time is defined as the time for the tracer to reach an e^{-1} (37%) concentration. This concept assumes that: (1) at t = 0, the tracer is introduced to the system and is instantaneously and completely mixed; (2) no further tracer is added; and (3) constant volume and flow of the system.

Besides the integrated time scales presented above, the current study applied two spatially distributed water renewal time scales: the once-through residence time and the reentrant residence time, as defined by Oliveira and Baptista (1997). The once-through residence time is defined as the time spent by a water parcel in the system from its position at t = 0. The reentrant residence time allows the water parcel to leave the system and eventually return and the total time scale is the cumulative time spent in the system (Figure 3.3). This concept is useful in tidal systems, where the same water often reenters the lagoon or bay.

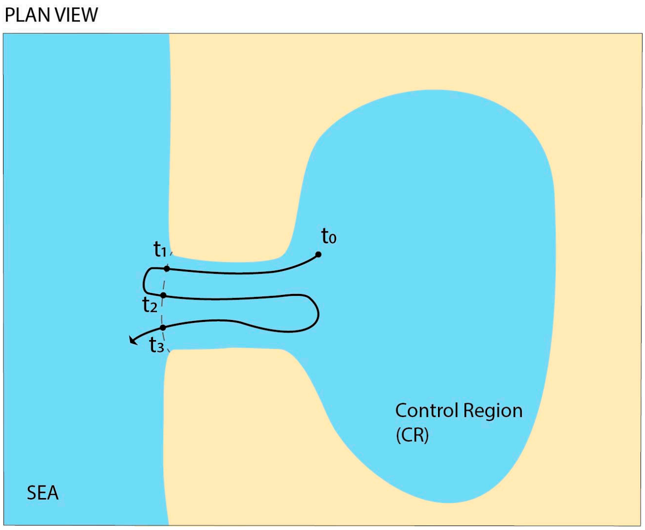

Figure 3.3
Scheme of the spatially distributed water exchange concepts applied for tracking the particle movement: once-through ($t_1 - t_0$) and reentrant time ($t_3 - t_2 + t_1 - t_0$) residence times.

In the present study, the water parcels of the spatially distributed time scales as well as of the e-flushing time were represented by neutrally buoyant particles. The particle tracking used the flow fields generated in the study area by a 2D hydrodynamic model called IPH-ECO (Cavalcanti *et al*., 2015; Fragoso *et al*., 2009; Pereira *et al*., 2013). Based on the flow velocities, a fourth-order Runge–Kutta method (Press *et al*., 1992) was applied to estimate the particle trajectories. A random-walk algorithm was also implemented to add dispersion to the movement of the particles (Dimou and Adams, 1993), using as coefficients the results of the Smagorinsky formulation for the turbulence (Smagorinsky, 1963). A total of 10073 particles were positioned at t = 0 in the center of the regular grid cells used by the hydrodynamic model in a region of interest, named the control region (CR). The position of the particles and the number of remaining particles inside the CR were registered every 30 minutes of simulation.

As mentioned before, the estimated water renewal times are strictly dependent on the environmental conditions in which the system was defined. Based on this, several scenarios were explored (Table 1) to investigate the effects of tides and wind on the water exchange. The main process investigated was the effect of the spring/neap tidal cycle. For this, 12 simulations were executed with particles released during varying the tidal cycles: combining spring and neap tides and ebb and flood cycles. These simulations were executed with no wind and constant river flow of 4.25 m^3/s, the flow exceeded 95% of the time (Q_{95}). The effect of the wind was investigated through a simulation using wind measurements coinciding with the studied period.

Table 1. Executed simulations and corresponding tidal cycle in which the particles were released, the value of the constant river flow and wind conditions imposed.

Number of Simulations	Tide on particles release	River flow	Wind
3	Spring/flood	Q_{95}	No wind
3	Spring/ebb	Q_{95}	No wind
3	Neap/flood	Q_{95}	No wind
3	Neap/ebb	Q_{95}	No wind
1	Spring/ebb	Q_{95}	Historical data

A novel semi-analytical expression for the water exchange in coastal lagoons was also developed in **Paper II**, although this approach was not applied in Mundaú Lagoon, but more general cases were investigated.

3.2.2 Salinity and Ecological Modeling

The salinity and the effect of its dynamics on coastal lagoons were investigated in this thesis through a simple modeling approach based on the conservation equation for salt. The salinity was described with a box model approach considering as main salt transport drivers the river runoff and the tidal flows, enhanced to consider the salinity distribution profile along the lagoon. The salinity modeling was then coupled to a heuristic model of the evolution of the mussel population to develop a useful management tool for the impacts of the hydraulics and the salinity dynamics on the mussel population. The approach is further described below, starting with the salinity modeling and followed by the model of mussel population.

The salinity box model was implemented considering two time scales: monthly variations and changes within the tidal cycles. The latter approach was implemented to assess the effect of high river runoff events on the salinity and its decrease in the lagoon. The former approach, involving monthly averaged salinity levels, is more convenient for estimating the effects of the seasonality in the river flow. The box model at the monthly time scale led to the following expression:

$$\frac{d\bar{s}}{dt} = \frac{Q_T s_O - (Q_T + Q_R)\bar{s}}{V} \qquad 3.6$$

where $\bar{s}$ and s_o are the mean lagoon and sea salinity concentrations, respectively.

The salinity model for the short time scales was obtained in a similar way to Eq. 3.6; however, here the model was divided into two expressions, one for transport during flood and one during ebb tides. The expression corresponding to the flood tide is:

$$\frac{d\bar{s}}{dt} = \frac{(1-b)Q_I s_o + bQ_I \bar{s}}{V} \qquad 3.7$$

where a return factor (b) was introduced as already discussed in the Water Exchange section. The expression for the ebb tide is:

$$\frac{d\bar{s}}{dt} = \frac{Q_I \bar{s}}{V} \qquad 3.8$$

Eqs. 3.6, 3.7 and 3.8 were solved numerically through a finite differences scheme. The inlet hydraulics was obtained using the calibrated model by Hill (1994), as described in the section regarding the numerical approaches for inlet hydraulics and morphological changes.

As the transport can vary spatially along the lagoon (as was demonstrated by the 2D hydrodynamic simulations in **Paper I**), a representation of the salinity variation along the lagoon was developed in this study based on the average salinity concentration in the lagoon and a specific profile function expressed by:

$$s(x) = s_o \left(\frac{x}{L}\right)^m \qquad 3.9$$

where x is a position along the lagoon originating from the most upstream location; L the total distance from the farthest upstream location to the inlet; and m a parameter defining the salinity profile shape (≥ 0), and describing the rate which salinity increase from zero to s_o. This equation expresses the salinity variation from zero at $x = 0$ to sea salinity (s_o) at $x = L$. By calculating the mean salinity of the salinity profile equation (Eq. 3.9) and using the mean value estimated by the box model, it is possible to estimate the value of the shape parameter m as:

$$m = \frac{s_O}{\bar{s}} - 1 \qquad 3.10$$

Based on an analytic solution to the salinity box model, employed in Eq. 3.9, it is possible to investigate the behavior of the salinity levels in time and along the lagoon (**Paper IV**). Displayed in Figure 3.4 is the salinity dynamics at different positions in the lagoon, and Figure 3.5 shows the salinity profile estimated at different times.

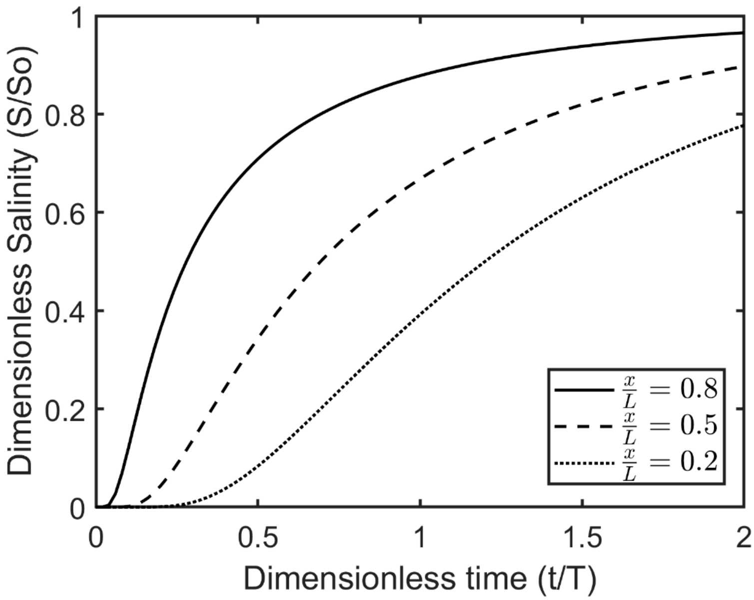

Figure 3.4
Evolution of the lagoon salinity in time at fixed locations for the case in which the lagoon, initially presenting only freshwater, is exposed to a seawater exchange flow.

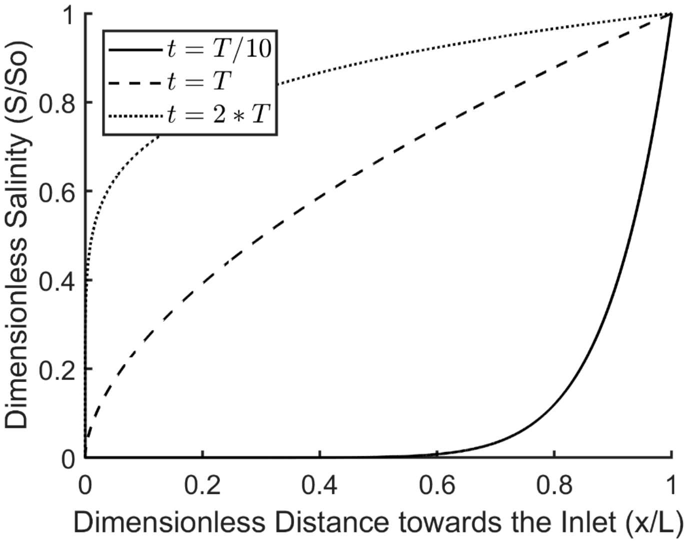

Figure 3.5
Salinity profile along the lagoon at selected times for the case in which the lagoon, initially presenting only freshwater, is exposed to a seawater exchange flow.

After developing a model of the salinity dynamics in coastal lagoons, this study used the salinity model as input to a mussel population model. Here the Sururu mussel (*Mytella Falcata*) was chosen, as it is an important and abundant species in the studied coastal lagoon (more details presented in the next chapter).

The present population dynamics approach is based on the idea that the mussel population (N) approaches an equilibrium state (N_E) at constant environmental conditions. Thus, the population grows or decays in proportion to the difference between the present value and the equilibrium state (N_E-N). In order to introduce the effect of the salinity on the mussel population, a second term is added in the evolution equation. With this term lower salinity levels result in a decrease in the mussel population and for a critical salinity level, few or no mussels remain. The population dynamics equation is finally expressed as:

$$\frac{dN}{dt} = \alpha(N_E - N) - \beta\left(\frac{s_o}{s} - 1\right)^n N \qquad 3.11$$

where α and β are growth and decay rate coefficients, respectively; and n is a coefficient describing the decay based on the salinity influence. By setting $\frac{dN}{dt} = 0$

is possible to achieve an expression of a new population equilibrium state ($\widehat{N}_E$) based on the salinity:

$$\widehat{N}_E = \frac{N_E}{1+\frac{\beta}{\alpha}\left(\frac{s_o}{s}-1\right)^n} \quad 3.12$$

By using $\widehat{N}_E$ in Eq. 3.11 it is possible to achieve a more convenient formulation for solving the equation, given by:

$$\frac{dN}{dt} = \alpha(N_E - \delta N) \quad 3.13$$

where $\delta = 1 + \frac{\beta}{\alpha}\left(\frac{s_o}{s} - 1\right)^n$, implying $\widehat{N}_E = N_E/\delta$. The non-dimensional expression of this formulation was solved in this study both analytically and numerically.

4 Study Area: Mundaú Lagoon

*This chapter describes Mundaú Lagoon, a choked coastal lagoon in Brazil, and its tidal inlet in which most of the methods developed in the present thesis work were applied in **Papers I, III, and IV**. This chapter also briefly presents the dataset used.*

"After so many versions of its work, the sea can't rest content.
It's the forever unsatisfied artist."

Octávio Brandão (1896 – 1980)
(about the Mundaú Lagoon Inlet)

4.1 General Information

The coastal lagoon and inlet that most of this thesis work used as study area is the Mundaú Lagoon and its inlet (Figure 4.1), located in northeastern Brazil at a highly developed coast, characterized by an abundance of coastal lagoons with different sizes (Kjerfve *et al*., 1990). Mundaú Lagoon (positioned between the coordinates 9°35' and 9°46' south and 35°44' and 35°58' west) is a part of an estuarine-lagoon system called Mundaú-Manguaba (MMELS), additionally composed by Manguaba Lagoon to the west and a network of channels connecting both lagoons to the sea and, with poor efficiency, between each other. Although Mundaú Lagoon is part of the MMELS, this thesis work focuses exclusively on Mundaú, for its importance due to the proximity to a large urban center (Maceió city) and its high productivity, especially for a bivalve mussel called Sururu (*Mytella Falcata*).

Mundaú is a shallow lagoon with an average depth of about 1.5 m and a surface area of 24 km^2. This lagoon is connected to the sea through a long channel (10 km). The geomorphological classification of this lagoon is a choked coastal lagoon (Kjerfve, 1994; Kjerfve and Magill, 1989) due to the observed dynamic filter effect that the long channel imposes on the tide level, markedly reducing the lagoon water level range. In Mundaú lagoon this reduction reaches 88% according to observations and is more pronounced during the dry season (Oliveira and Kjerfve, 1993). Another effect of the Mundaú channel geomorphology on its hydraulics is a fortnightly set-up of the average water level in the lagoon.

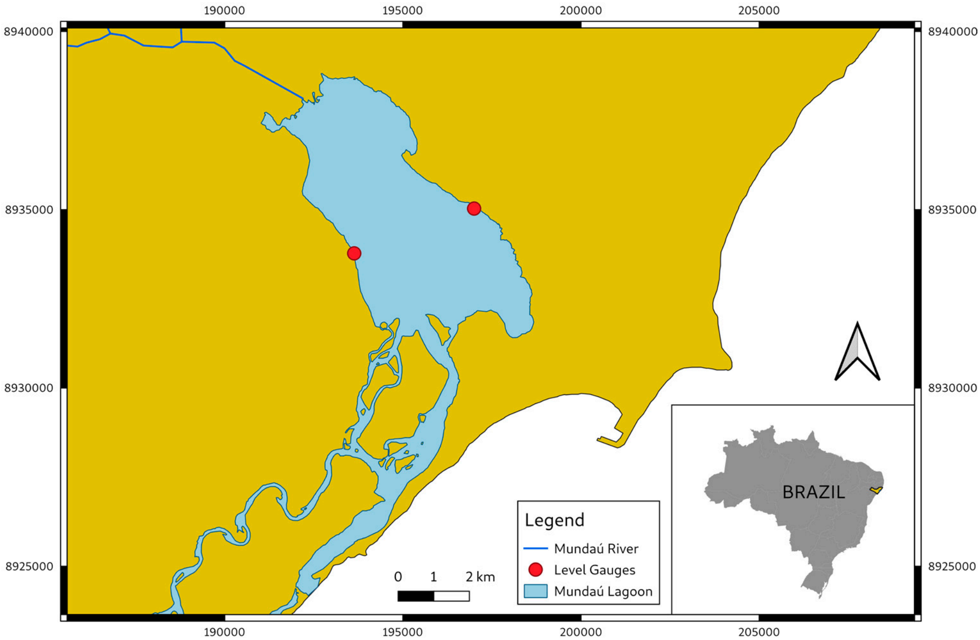

Figure 4.1
Mundaú Lagoon location and gauge positions.

4.2 Hydrology

Mundaú Lagoon has as main freshwater input the Mundaú river, located at the northern end of the lagoon. This river has a basin area of approximately 4126 km^2 (Costa *et al.*, 2016) and a flow regime that varies markedly between the rainy season (from May to August) and the dry season (December to March) (Figure 4.2). This river has an average flow of approximately 26 m^3/s and minimum flow lower than 10 m^3/s, values that differ significantly with observed highs of 1000 m^3/s during extreme events (COTEC Consultoria Técnica, 1999). Following this marked seasonality, the precipitation in the region varies from the minimum monthly average of 32 mm in November to the maximum in May with a monthly average value of 382 mm (INMET, 1992).

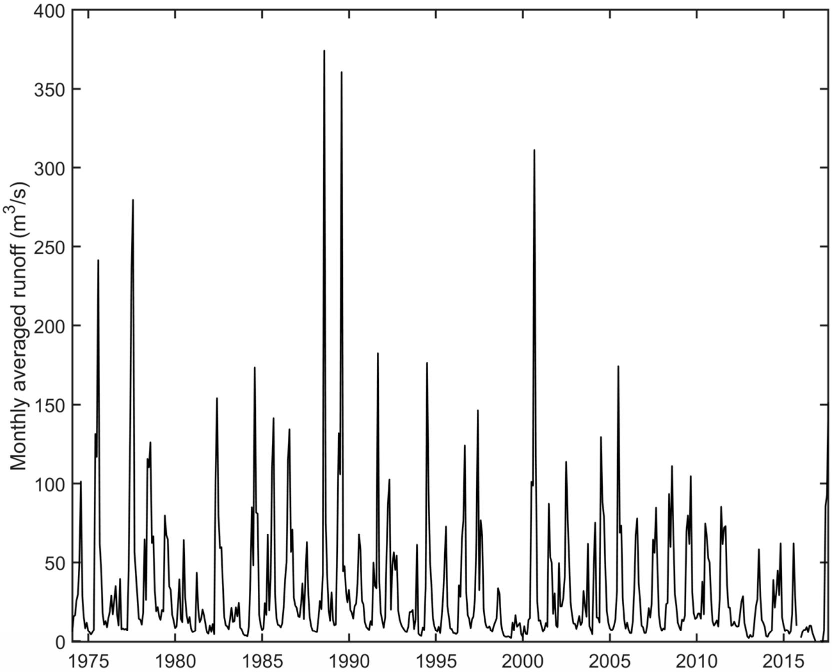

Figure 4.2
Monthly averaged Mundaú River flow illustrating its seasonality.

The Mundaú river runoff data used in this thesis work were provided by the Brazilian National Agency of Waters (ANA) and correspond to daily measurements at a gauge 24 km upstream of the outlet to Mundaú Lagoon; historical data is available for a period from 1975 to present. An analysis of this data set to determine a low flow indicator (Q_{95}) to be used in **Paper I**, resulted in a value of 4.25 m^3/s. This value corresponds to the runoff surpassed 95% of the time in a flow duration curve.

4.3 Tides and Lagoon Levels

Tidal levels fluctuations at the Mundaú Lagoon coast is characterized as semi-diurnal with a mesotidal range of approximately 1.44 m (average). The fortnightly variation of the tidal levels is varying considerably from 0.5 m during neap tides to 2.3 m during spring tides.

As there has not been any continuous measurement campaigns for tidal levels on the Mundaú lagoon coast, the tidal level data used in this thesis work was generated from a set of harmonic constituents that are displayed in Table 2. These constituents were obtained from the harmonic analysis done for level measurements 9 km away from the Mundaú inlet, at Maceió Harbour (9º 40.968S, 35º 43.424W). These measurements were done by the Brazilian Navy Oceanographic (CHM) for a total period of one year, from April 2006 to April 2007.

Table 2. List of harmonic constituents considered in the generation of the tidal levels.

Constituent (Period)	Amplitude (cm)	Phase (º)
M2 (12.42 h)	69	107
S2 (12 h)	30.7	125
N2 (12.9 h)	13.2	89
Q1 (26.87 h)	1.8	101
O1 (25.82 h)	6	126
K1 (23.93 h)	1.9	191

The data on water levels in Mundaú Lagoon were measured at two different locations during varying periods, using In-Situ Aqua Troll 200 gauges and operating with a sampling interval of 15 minutes. Gauge A positioned at the eastern margin of the lagoon in Maceió city was operated in 2014 from February 15 to March 14. Gauge B located at the western margin in Coqueiro Seco city is a station that has been operating continuously since 2016 and is run by the Environmental Agency of the State of Alagoas (IMA-AL).

4.4 Waves

The wave climate at the coast of the Mundaú Lagoon coast has seasonality of quiescent and intensive wave activity for months, similar to the rainy and dry seasons of the river runoff. This wave climate is mostly controlled by trade winds that generate waves from east-southeast presenting periods from 6 to 8 s and wave heights between 1 and 2 m on the coast (Pianca *et al.*, 2010).

Although the Brazilian coast involves a length of around 9000 km, few permanent wave measurement buoys exist along it. This is the case for the coast where Mundaú Inlet is located; thus, the offshore wave data used in this thesis work were generated by the NOAA Wavewatch III model (Tolman, 2009; Tolman *et al.*, 2002). The Wavewatch III model uses as input the wind fields resulting from the weather model known as the Global Forecast System (GFS) (Chawla *et al.*, 2008). The results from a global simulation using Wavewatch III are provided by NOAA with a 3-hr temporal resolution and a 0.5-degree spatial resolution, for the period from 1997 to the present.

The output from Wavewatch III was previously validated through measurements in southern Brazil by Pianca et. al, 2010. Furthermore, several other studies have already applied this wave model on the Brazilian coast (da Silva *et al*., 2016; Gomes and Silva, 2014; Guimarães *et al*., 2014; Innocentini *et al*., 2005).

The closest location to the study area with Wavewatch III hindcast data available is at a 45-km distance from the inlet (10ºS and 35.5ºW). The modeled offshore wave climate exhibited the predominant directions of ESE (~51.5%) and S (~15.5%). The highest and average wave heights were 4.47 m and 1.76 m, respectively.

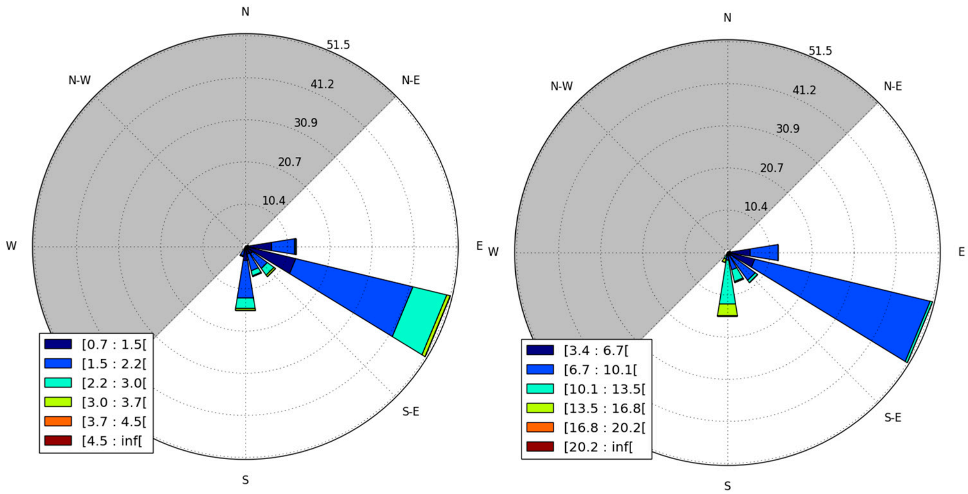

Figure 4.3
Study region offshore wave height (left) and period (right) obtained from the Wavewatch III hindcast.

The offshore wave data were used to derive the nearshore wave characteristics used in **Paper III** following the methodology presented in the previous chapter.

4.5 Inlet and Lagoon Morphology

Mundaú Lagoon is connected to the sea through a single inlet and a long channel. There are also narrow channels connecting Mundaú Lagoon to Manguaba Lagoon, the adjacent lagoon that forms MMELS; however, this connection is poor. Mundaú inlet (Figure 4.4) is a highly dynamic tidal inlet with an evolution that has already been described by Lima (1998) through historical records from over 400 years ago together with recent aerial images.

Since 1910, Mundaú inlet maintains approximately the same position, although it is known that in the past this inlet used to migrate towards the southwest. Another inlet morphological process, that has not been observed for a long time in Mundaú inlet, is closure. These processes are believed to have happened in part due to available stocks of sand present in dunes fields near the inlet that were exploited or replaced by built areas. Breaches due to river runoff events are common in the barrier island of this system, with the most recent event occurring in 2017. Overwash caused by storms can also be observed in this barrier island Oliveira and Kjerfve (1993).

The coast adjacent to Mundaú inlet is composed of sandy beaches with a median grain size of around 0.25 mm. Along this stretch of the coast the wave action is reduced by a sandstone reef line parallel to the lagoon entrance (Dominguez *et al.*, 2016).

The data describing morphological changes in Mundaú Inlet are derived from satellite images (Landsat and Google Earth). From these images, it was possible to measure the inlet width on different dates during the simulation period of the morphological modeling. The cross-sectional geometry of the inlet was obtained through a bathymetric survey campaign in the whole of Mundaú Lagoon and the inlet. This survey was conducted by ANA in 2012, taking as reference level the Maceió Harbour datum for tidal fluctuations.

Figure 4.4
Satellite images of Mundaú inlet for the years: (a) 2002; (b) 2005; (c) 2009; (d) 2013; (e) 2015; and (f) 2016

4.6 Water Quality and Salinity

Mundaú lagoon presents several water quality problems due to different sources of pollution combined with its choked conditions that make efficient flushing of these pollutants difficult.

One major source of pollutants is the agricultural areas present in the Mundaú River watershed. These pollutants are transported to the lagoon during flood events during the rainy season, often raising the concentration of suspended matter to more than 100 mg/l (Oliveira and Kjerfve, 1993). On the other hand, during the dry season sugar cane plantations present in this watershed are in the process of leaf burning before harvesting, and the ashes are then washed, generating discharges of organic pollutants to the river and then to the lagoon. According to Maioli *et al*. (2010), this burning process has caused higher concentrations of polycyclic aromatic hydrocarbons (PAH) in the Sururu mussel of Mundaú lagoon.

Events of algal blooms are also observed in MMELS and have been associated with the hydrodynamics and residence times of the lagoon system (Cotovicz Junior *et al*., 2013). As a consequence, these algal blooms events incite ecological imbalance that causes changes in fish composition and production (Melo-Magalhães *et al*., 2009).

Several studies have pointed out the crucial role of the salinity dynamics for the Mundaú lagoon aquatic ecosystems; thus, this abiotic factor was explored more in-depth in this thesis work. The salinity dynamics of Mundaú Lagoon has been identified as the most important regulator of the distribution and abundance of its macrocustraceans (Teixeira and Sa, 1998). Salinity was also pointed out as an important controlling factor for different fish species in MMELS (Melo and Teixeira, 1992; Teixeira, 1997, 1994). Furthermore, many studies have defined the crucial dependence of the Sururu mussel on the salinity dynamics: die-off events and prolonged disappearance of Sururu were related to low salinity levels (Asbury, 1979). This can be explained by the experiments done by Pereira-Barros and Macedo (1967) that concluded after exposing Sururu during 7 days to salinities lower than 2 psu and greater than 35 psu that these are fatal levels to these organisms. These results corroborate other studies that concluded that low salinity levels cause high mortality rates on *Mytella Falcata* bivalves (Onodera, 2012). Thus, the rainy season and associated extreme flood events, when the salt water is flushed out by runoff events, are periods and events presenting a risk for the Sururu mussels.

Few studies have been conducted about the Sururu population dynamics and distribution in Mundaú Lagoon. Regarding the density of mussel individuals (ind) in MMELS, Silva (1994) estimated that around 1770 ind/m^2 occupy approximately 15% of the total area of the lagoon system. Although it can vary markedly between years, the annual harvest, which in Mundaú lagoon is artisanal, was estimated to be between 3000 and 5000 metric tons in the ’80s (Pádua *et al*., 1985; Pereira-Barros, 1987).

The salinity dataset used in this thesis work corresponds to several measurement campaigns executed using different approaches during different periods from the ’70s to the most recent in 2017. Salinity concentrations from 1972 to 1978 were recovered from Asbury's (1979) study. These monthly average concentrations were measured at 5 different locations in the Mundaú lagoon through sampling and analysis with the Knudsen method. This dataset was important to investigate the prolonged period of mussel disappearance reported in the original study.

A time series of salinity measurements using a CTD installed in a fixed location (9º 28' 1.92" S, 35º 51' 34.92" W) in the lagoon was also obtained, corresponding to the period from April to May of 2017 with a sampling interval of 15 min. Finally, a set of spatial measurements from the inlet to the farthest upstream point of the lagoon was carried out by the IMA-AL on February 29th of 2016 and were used to investigate the salinity distribution along the lagoon.

5 Results and Discussion

This chapter describes and discusses the main results obtained in the appended papers, as well as how the results of these individual studies are connected to achieve the main goal of this thesis.

5.1 Lagoon and Inlet Hydraulics

As described in the Methods chapter, the present research explored two different approaches for estimating the inlet hydraulics: Semi-analytic and numerical modeling. Although differing in form, these approaches advanced in obtaining estimates of the key elements of inlet hydraulics requiring minimum information about the study regions.

5.1.1 Semi-Analytic Approach

This approach was developed in **Paper II** of the appended papers. The main results obtained from the development of the semi-analytic solution of the Keulegan equations were a set of expressions describing the key elements of the inlet flow. A summary of these equations is presented in this section.

The first expression developed, that served as the starting point to derive other quantities, was the non-dimensional bay level amplitude obtained after solving Eq. 3.1, based on the two criteria presented. The obtained solution is:

$$\hat{a}_B = \left(1 - \frac{(C_M K)^4}{4}\left(\sqrt{1 + \frac{4}{(C_M K)^4}} - 1\right)^2\right)^{1/2} \qquad 5.1$$

where C_M is a coefficient differing the obtained solution for criteria 1 and 2. The value of C_M is equal 1 for the first criterion and equal $2/\sqrt{\pi}$ for the second criterion. To optimize the predictive skill of this equation, a least-square fit to the numerical solution of the bay amplitude was applied over the interval $0.05 < K < 2.0$, resulting in $C_M = 1.23$. Figure 5.1 displays the results for the different values of C_M.

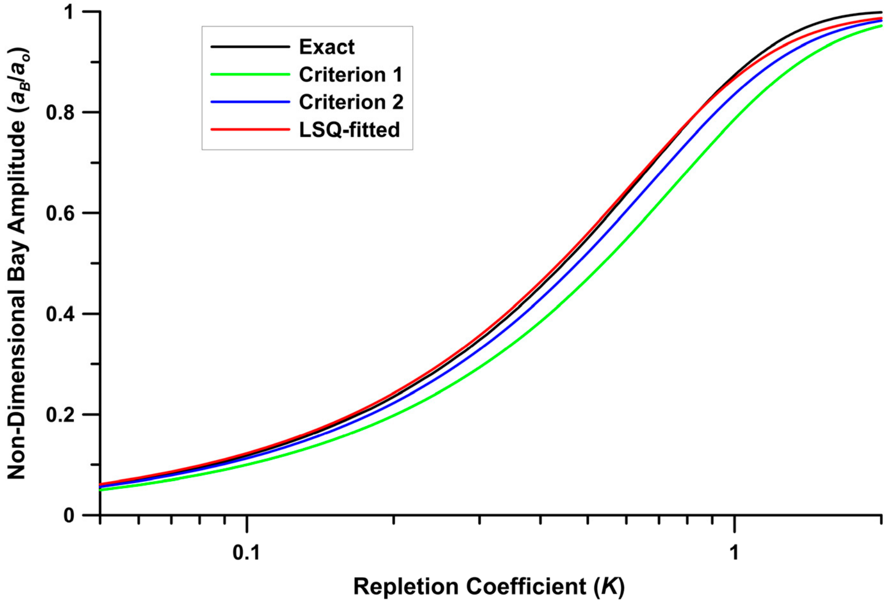

Figure 5.1
Estimated non-dimensional bay amplitude for different solutions to the inlet flow equation.

As can be seen in Figure 5.1, an excellent agreement was obtained by the optimized solution. A larger error is obtained for higher K-values, but the difference is still small, around 1% of difference compared to the exact solution. The solution for higher values on the repletion coefficient could be improved by extending the interval of the optimization; however, the error on lower values of K would increase.

As already mentioned, this solution for the bay amplitude served as a base for obtaining different inlet flow properties expressions in non-dimensional form. In this study, this essential expression, that represents both the non-dimensional tidal prism and bay amplitude, is denoted $\Psi(K)$. Some of the key expressions are summarized in Table 3.

Table 3. Summary of expressions developed through the semi-analytic development of the inlet flow.

Flow property	Expression
Tidal prism	$\hat{P} = \left(1 - \frac{(C_M K)^4}{4}\left(\sqrt{1 + \frac{4}{(C_M K)^4}} - 1\right)^2\right)^{1/2} = \Psi(K)$
Tidal prism (Taylor series expansion of full solution; valid for K < 0.6)	$\hat{P} = C_M K \left(1 - \frac{1}{2}(C_M K)^2\right)^{1/2}$
Inlet maximum velocity	$\hat{u}_I^{max} = \frac{\Psi(K)}{C_M K}$
Inlet mean velocity	$\hat{u}_I^{m} = \frac{2}{\pi}\frac{\Psi(K)}{K}$

5.1.2 Numerical Approach

The numerical approach to simulate the inlet hydraulics was developed and applied in **Paper III** and applied again in **Paper IV**. This approach had as a goal to develop a simple solution method that could be applied in a complex setting of a real-world lagoon-inlet system. It allows for more flexible input information about the forcing, such as the complete cycles of tidal variation and the important freshwater input seasonality, in contrast to the simplified input conditions in the approach developed in **Paper II.**

The performance of the numerical solution of the inlet flow applied to Mundaú lagoon was satisfactory as indicated by the validation against observed levels in the lagoon displayed in Figure 5.2. The statistical analysis of this validation presented low values for the error indicators applied. The mean absolute error calculated was 0.041 m for the comparison during the dry season and 0.052 m for the rainy season. The root-mean-square error yielded values of 0.046 m and 0.066 m, respectively. The coefficient of determination applied (R^2) also resulted in satisfactory values: 0.89 (dry season) and 0.95 (rainy season).

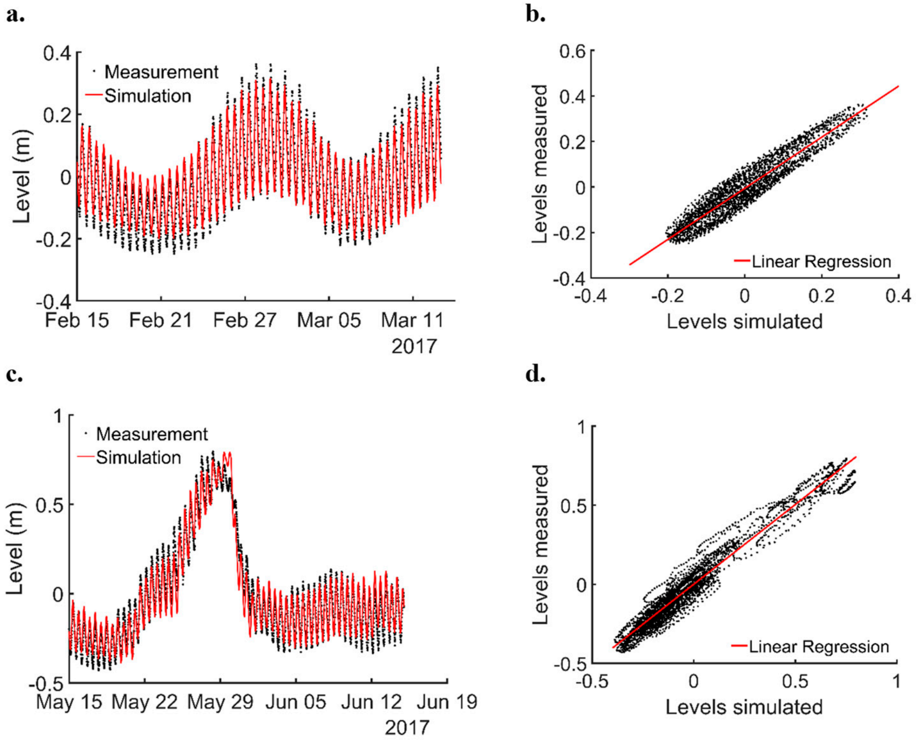

Figure 5.2
Comparison between modeled and observed lagoon levels during the dry (a) and the wet (c) seasons, and also the respective linear regressions for the dry (b) and the wet seasons (d).

Two important phenomena common in choked coastal lagoons were well represented by this approach: the fortnightly set-up of the average lagoon levels (Figure 5.2a), and the river flooding event (Figure 5.2c). These are crucial to be described due to their importance to sediment transport (**Paper III**) and the transport of dissolved material (**Paper IV**), as became evident in the simulation results of **Paper I**, presented later in this Chapter. The phase of the lagoon level variation was also well represented by this numerical approach.

The numerical solution with the Hill (1994) formulation for inlet hydraulics is not particularly new. The performance of the model obtained in the current study is in accordance with previous studies by MacMahan *et al.* (2014), involving an application in the New River Inlet (USA). However, the approach developed in this thesis advanced, in comparison with previous studies, applications to include more accentuated friction asymmetry caused by the long channel; it was also tested against a considerable river runoff event.

Comparing the numerical inlet hydraulics model presented here against a more detailed representation of the flow by a complex modeling approach, the current model presented some advantages. The results of the Mundaú Lagoon water level variation obtained by the 2D hydrodynamic model of **Paper I** were similar to the solutions presented here. However, the presented model obtained these satisfactory results using larger time steps for solving the numerical scheme resulting in much lower computational costs compared to the 2D model. On the other hand, regarding the flow velocities estimates, the present approach produces only a cross-sectional average value. Thus, the sediment transport in the inlet disregards the variations along the cross-section, which for Mundaú lagoon, with a curved inlet channel, are significant.

Regarding the spatial variation of the lagoon levels, the developed model assumes it to be uniform over the whole lagoon. This assumption is considered valid for Mundaú Lagoon, supported by the agreement with observations at different gauge locations and by the results of the 2D model applied in **Paper I.**

5.2 Inlet Morphological Modeling

5.2.1 Semi-Analytic Approach

Based on the semi-analytic solution of the inlet flow, it was possible to explore inlet morphological processes such as tidal prism-inlet area relationship, inlet evolution, and inlet equilibrium conditions. The derived expressions associated with these processes and the analysis derived from the solutions are presented in this section.

The relationship between the inlet cross-sectional area and the tidal prism is a classic empirical relationship of inlets explored in many studies, as mentioned in the Introduction chapter. A common assumption made in these studies is that the inlet is in dynamic equilibrium regarding sediment transport. Here, the repletion coefficient was used together with the tidal prism to produce a semi-analytic expression for the *P*-*A* relationship. The present approach assumes that the changes in morphology are slower than the response of the inlet hydrodynamics; this approach is also valid when the inlet is not in equilibrium. Comparisons between the exact solution and approximate solutions based on a Taylor-series expansion with different number of terms retained are presented in Figure 5.3, with tidal prism normalized by the maximum tidal prism ($P_{max} = 2a_o A_b$) and inlet cross-sectional area normalized by $A_o = \frac{\pi P_{max}}{T u_{max}}$, where $u_{max} = \sqrt{\frac{2 g a_o}{K_I}}$ (*cf*, Stive *et al.*, 2009).

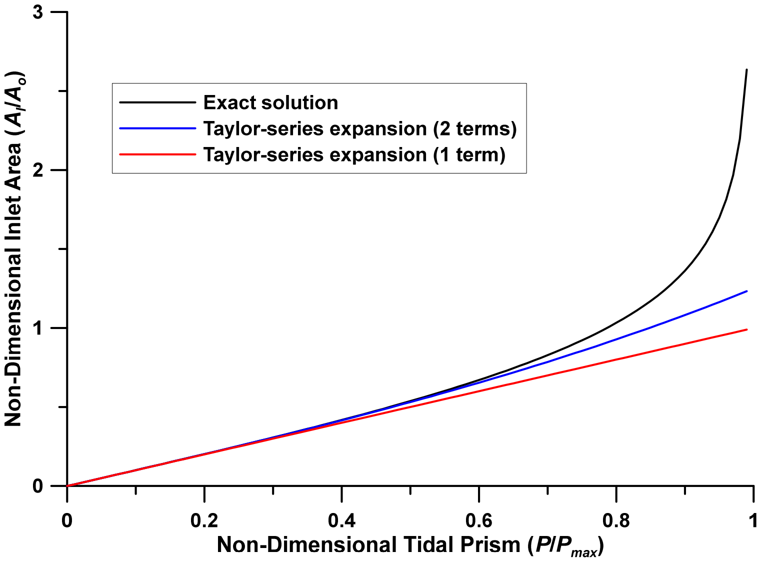

Figure 5.3
Comparison between the exact and approximate solutions for the non-dimensional cross-sectional inlet as a function of the non-dimensional tidal prism.

A non-dimensional equation of inlet evolution was derived using the expression for the mean inlet velocity derived through the semi-analytic approach as the representative inlet velocity in a non-dimensional version of Eq. 2.6. The resulting expression is:

$$\frac{dK}{d\hat{t}} = \left(\left(\frac{2}{\pi}\right)^2 \left(\frac{\Psi(K)}{K}\right)^2 - \hat{u}_{cr}^2\right)\frac{2}{\pi}\frac{\Psi(K)}{K}K^n - \widehat{m}_L \qquad 5.2$$

where n is a power coefficient related to the inlet geometry assumption. The value of n varies according to the assumed geometric schematization: $n = 0$ for an inlet with constant width; $n = 1$ for constant depth; and $n = 1/2$ for geometrically similar inlets.

The inlet dynamic equilibrium considering the longshore sediment transport is given by $\frac{dK}{d\hat{t}} = 0$ and the following equation should be solved using the appropriate value of n to determine this condition:

$$\left(\left(\frac{2}{\pi}\right)^2\left(\frac{\Psi(K_E)}{K_E}\right)^2 - \hat{u}_{cr}^2\right)\frac{2}{\pi}\frac{\Psi(K_E)}{K_E}K_E^n = \widehat{m}_L \qquad 5.3$$

The results of exploring Eq. 5.3 are displayed in Figure 5.4, for the geometrically similar schematization, Figure 5.5, for the constant depth, and Figure 5.6, for the fixed inlet width assumption. The first two cases presented similar curves of equilibrium repletion coefficient (K_E). These curves, plotted for different normalized critical velocities, presented two solutions for a specific normalized longshore transport, one of them representing a stable dynamic equilibrium and the other a solution subject to closure for small perturbations. Another observed behavior for the solution in these two cases is that the curves present a maximum longshore transport rate for which a transport higher than these values the inlet will infill and close. This behavior described above is similar to the one represented by the Escoffier curve using the inlet velocity instead of the transport rates (*cf.*, Escoffier, 1940).

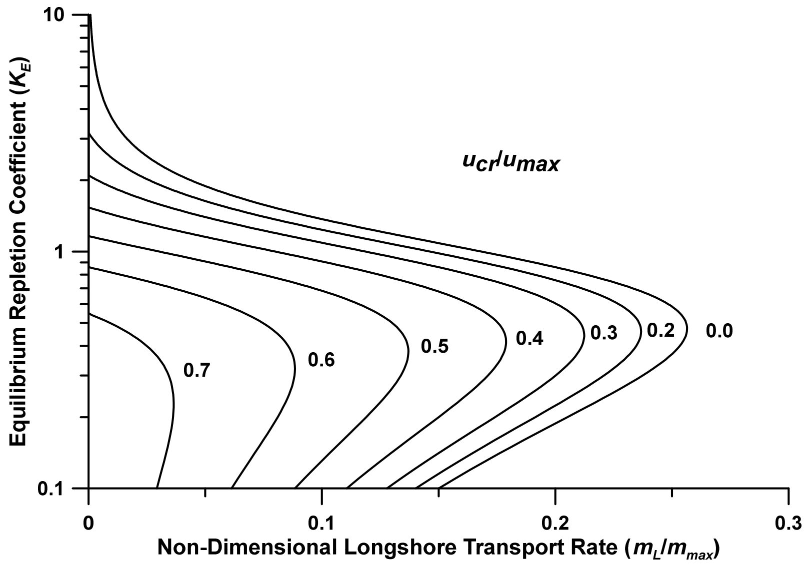

Figure 5.4
Equilibrium repletion coefficient for different non-dimensional critical velocities as a function of the longshore sediment transport for the case of geometrically similar inlet cross-sections.

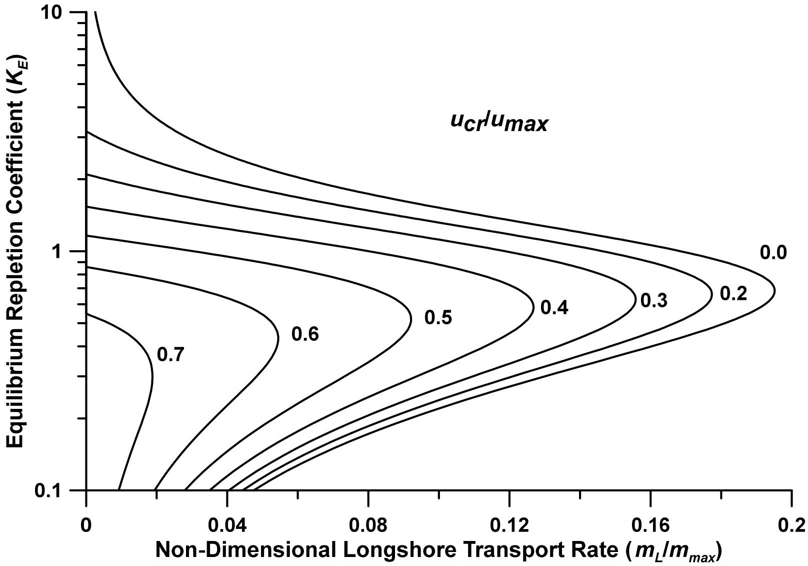

Figure 5.5
Equilibrium repletion coefficient for different non-dimensional critical velocities as a function of the longshore sediment transport for the case of fixed inlet water depth.

Differing from the two cases presented above, the dynamic equilibrium for the constant inlet width displays only one solution that is always stable. However, this solution may in some cases with the transport being close to its maximum value result in an unrealistic inlet geometry; the width is constant whereas the depth becomes very small. This would, in reality, affect the velocity and the transport capacity due to the high frictional losses occurring.

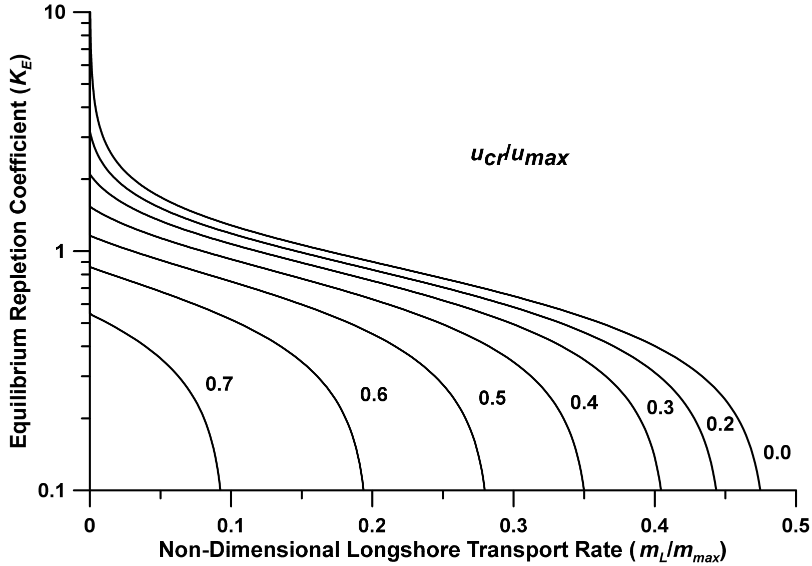

Figure 5.6
Equilibrium repletion coefficient for different non-dimensional critical velocities as a function of the longshore sediment transport for the case of fixed inlet width.

5.2.2 Numerical Approach

The results for the numerical model employed to describe the inlet evolution are presented here according to the two scenarios for which it was validated. First, the model was applied for schematized scenarios, with quasi-steady tidal flow and constant longshore sediment transport rate. These results were compared with the expected behavior of equilibrium or closure as described in **Paper II** for the inlet evolution. Later, the numerical model approach was validated for a more realistic setting, applied to simulate the evolution of the Mundaú lagoon inlet morphology and considering as forcing the river runoff, the tidal level, and the longshore transport due to breaking waves, all input variables varying in time based on input measurements.

Figure 5.7 displays the results of the schematized simulations. Two different initial conditions of inlet width and 3 different longshore transport rates (m_L) were applied. A constant m_L with a value equal to 1711 m^3/cycle resulted in the same equilibrium inlet width (500 m) for both initial width conditions (170 and 1200 m). For a smaller transport rate, equal to 1300 m^3/cycle, the equilibrium width was 2500 m. Finally, a very high rate of longshore transport (4000 m^3/cycle) resulted in the closure of the inlet. These results demonstrated a considerable sensitivity to the resultant equilibrium width for changes in longshore transport. This may be explained by the adopted schematization of the inlet geometry.

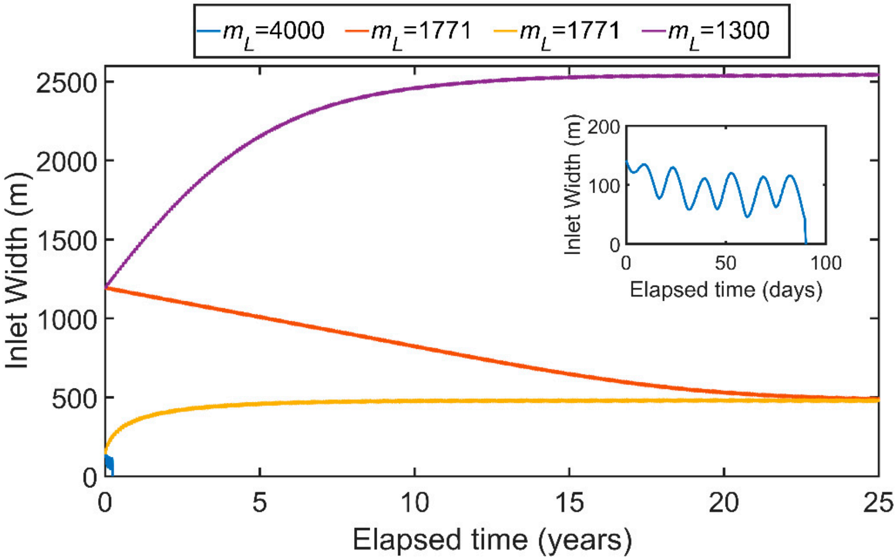

Figure 5.7
Simulations of the schematic inlet for constant m_L showing as results the inlet width either reaching equilibrium or closure.

A qualitative assessment of the results for the schematic simulations with the numerical model is possible by observing that the behavior presented in Figure 5.7 is in agreement with the expected behavior as described in **Paper II**. For the semi-analytical formulations developed for inlet evolution, equilibrium or closure were achieved as a proportional response to the magnitude of the constant longshore transport applied; thus, the numerical model results were considered qualitatively validated and satisfactory.

Figure 5.8 presents the results of the numerical morphological model to simulate the Mundaú Inlet evolution. The computational cost to run this 11-year simulation was considerably low, taking 2.5 minutes on a 3.4 GHz processor. These results correspond to the validation period using parameters already calibrated. The main results, the comparison between modeled and observed inlet width in time, are displayed in the upper panel of Figure 5.8. It is possible to observe that the model reproduces the overall dynamics of the inlet width, despite marked differences being present during specific periods. The long-term inlet widening during the period from 2012 is well represented by the current model. However, the model results display a seasonality in the inlet evolution that corresponds with the river runoff seasonality, which is not obvious in the observed inlet width.

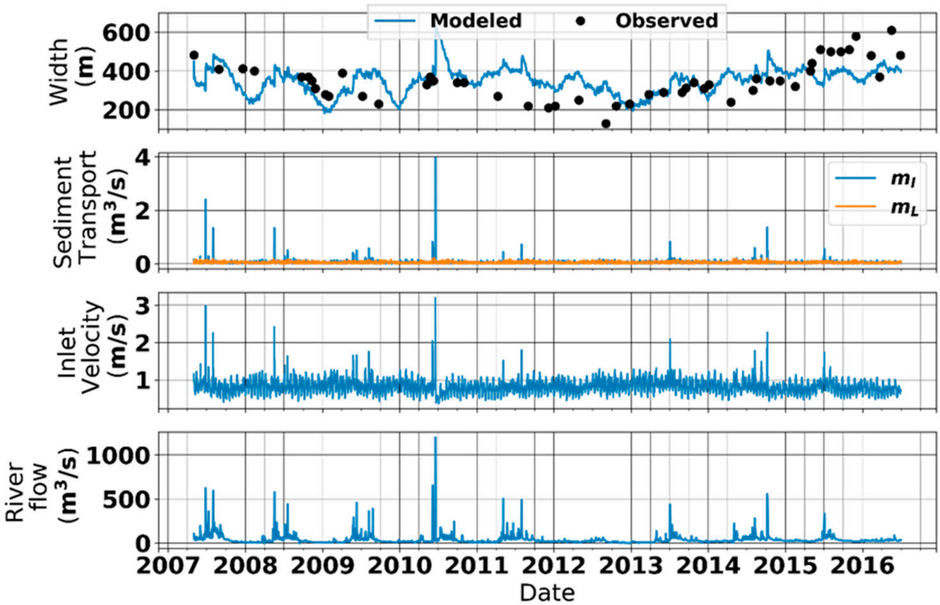

Figure 5.8
The numerical morphological model results. From top to bottom: modeled inlet width compared to observations, sediment transport rates (m_I and m_L), maximum inlet velocity for each tidal cycle simulated, and observed river discharges.

The representation by the model of the long-term trends of widening and narrowing of a natural inlet in a complex setting was satisfactory. This suggests that the present numerical model can be a useful tool for the quantitative assessment of tidal inlets evolution. In comparison with a similar approach by Tanaka and Ito (1996), applied to Nanakita River entrance (Japan), the approach developed in the present thesis advances the ability to describe long-term inlet evolution and to consider more dynamic input conditions. These advantages were achieved through the numerical implementation of the transport processes in contrast to the use of analytical approaches in previous similar studies (Larson *et al*., 2011; Tanaka *et al*., 1996; Tanaka and Ito, 1996).

The use of a simplified model approach to represent one of the most complex features on the coast, presented some limitations and sources of errors that resulted in some differences between simulated and observed inlet width. These discrepancies can be caused by the existence of morphological processes that have been neglected, being of importance during parts of the simulated period, for example, overwash of the barrier island. Errors in the input information may also be a source of the differences in the modeled results, for example, the wave information been based on modeling both in the offshore and the nearshore. Finally, the observations used to assess the performance of the model relied only on the inlet width, derived from satellite images. These measurements were made manually, and significant imprecisions are involved, although the use of satellite images is a great advantage, especially in regions with a lack of regular measurement campaigns.

5.3 Impacts on the Coastal Lagoon

5.3.1 Water Renewal Estimations

Different methods to estimate the water renewal were applied in **Paper I** to investigate the tidal exchange through the lagoon tidal inlet. The results of the integrated and spatially distributed renewal time scales applied are presented in this section.

The first integrated method applied (the flushing time) was estimated using Eq. 3.4. The tidal prisms obtained from the 2D hydrodynamic model employed were $4.4 \cdot 10^6$ m^3 and $9.9 \cdot 10^6$ m^3, for the neap and spring tides, respectively. The value of the spring tide prism is in accordance with the observations in Mundaú Lagoon done by Cavalcante (1988).

Thus, for a tide period of 12.42 h, the tidal flows (Q_T) used were 98 and 221 m^3/s. The flushing times estimated considering these Q_T values and a Q_R equal to 4.25 m^3/s (Q_{95}) was 12.6 days and 5.7 days (for neap and spring constant flows, respectively).

The second integrated method used, the e-flushing time, is based on the exponential fit to the number of particles leaving the lagoon. Figure 5.9 displays the fraction of particles in the CR in time for different release time conditions and both once-trough and re-entrant particles. An average e-folding flushing time of 54 days was estimated for the once-through particles, while 64 days was the time estimated for the re-entrant case. Figure 5.9b and Figure 5.9d, regarding the reentrant particles, show how the fortnightly tidal cycles affect the water exchange. It is possible to observe that the spring tides present a considerable number of particles exiting the CR, in comparison with during the neap tides.

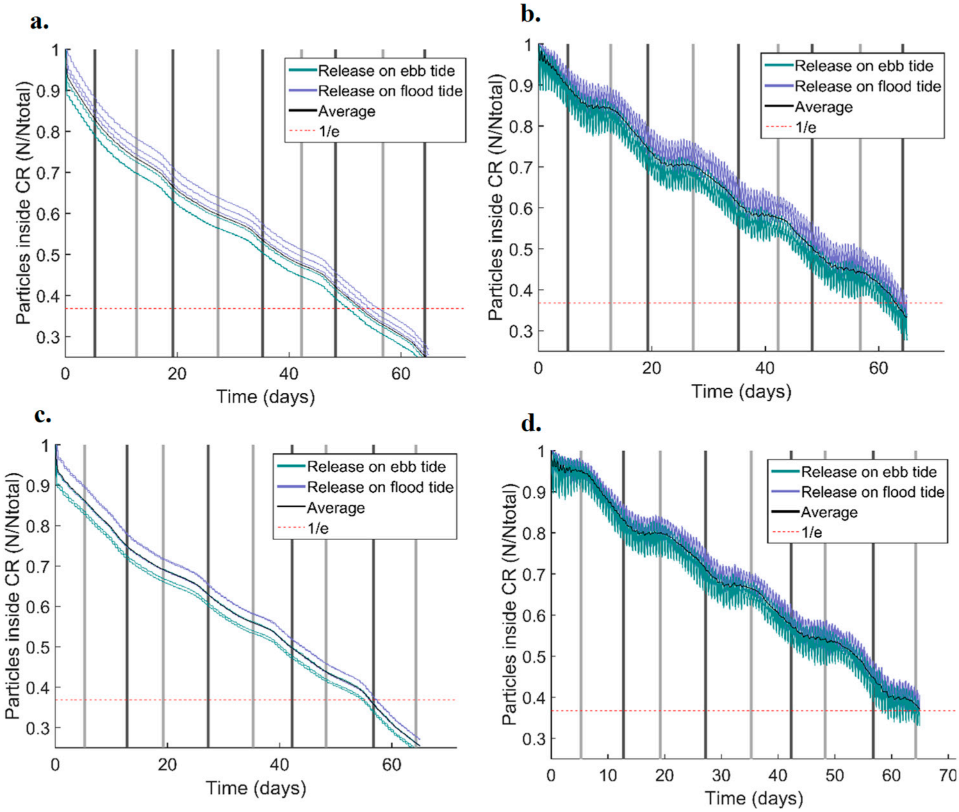

Figure 5.9
The fraction of remaining particles in the CR in time. (a) once-trough particles released during spring; (b) reentrant particles released during spring; (c) once-through particles released during neap; (d) reentrant particles released during neap; The vertical shade areas correspond to spring tides (dark grey) and neap tides (light grey).

The effect of the wind, with E and SE being the prevailing directions, on the water exchange of Mundaú Lagoon, was also investigated through the e-folding flushing time method with a particle release during the spring/ebb tide. For this case, the time calculated was 77 days for once-through and 81 days for reentrant particles. This is a considerable delay in the water renewal compared to the scenarios without wind imposed. Thus, this is an important forcing to be considered in the water exchange of Mundaú Lagoon, at least during the dry season.

The results for the spatially distributed water renewal time, the residence time, can be seen in Figure 5.10 for a total simulated period of 65 days. This duration of the simulations was chosen based on the results of the e-folding flushing time. From Figure 5.10a and Figure 5.10c, corresponding to the scenarios without wind, it is possible to observe that the residence time values increased gradually from south to north of the CR, with residence times varying from less than a day to no significant exchange.

The effect of the wind on the residence time distribution is presented in Figure 5.10b and Figure 5.10d. This forcing acted to redistribute the zones of equal water renewal changing the pattern of gradual increase from south to north. It is possible to observe that the central to eastern parts of the lagoon presented more limited renewal due to eddies promoted by winds in these regions. An opposite effect was also observed; the wind acting to promote higher renewal rates in the northern part of the lagoon, a region that does not present significant exchange when the wind is not considered.

The spatial projection of the residence times allowed for a zoning of the water exchange potential in the lagoon. Three zones were identified based on the scenarios considering wind: (1) the southern zone with the lowest residence times due to the proximity to the inlet (from 6 hours to 15 days); (2) the northern and western zones with intermediate values (from 20 to 40 days); and (3) central to eastern parts with residence times longer than the total duration of the simulations (> 65 days).

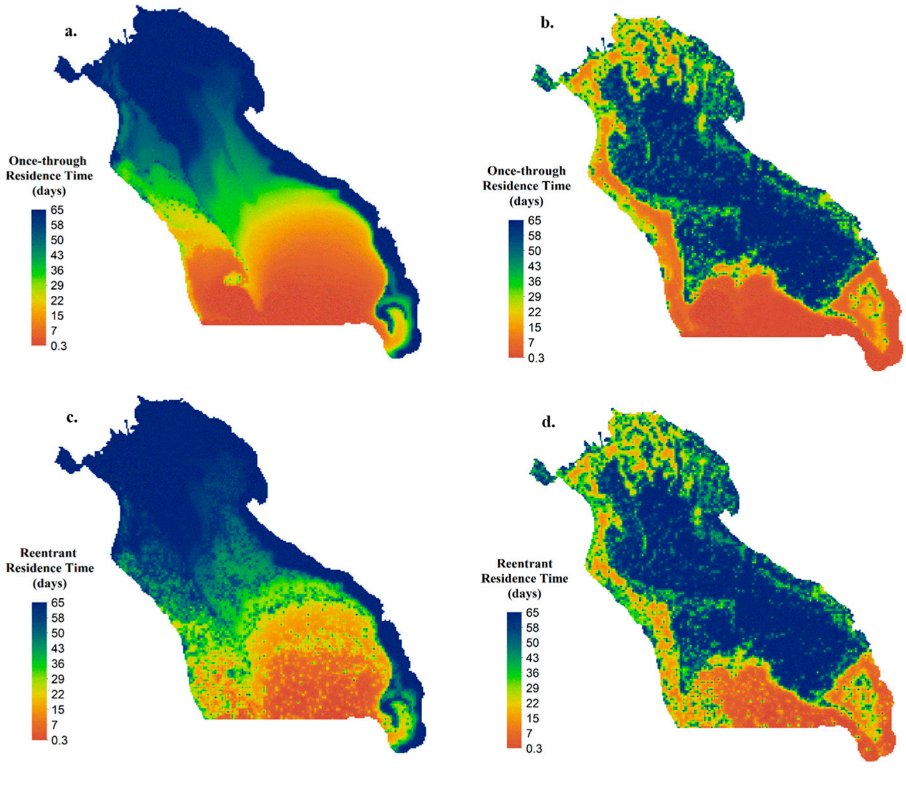

Figure 5.10
Spatial distribution of residence time: Top figures correspond to once-through and bottom to reentrant residence times. Left figures correspond to no wind and right ones considering wind scenarios.

The once-trough residence time resulted in well-defined zones of equal residence time in contrast to the reentrant cases. However, no significant differences from the once-trough and reentrant particles can be observed in the spatial distribution of the residence times.

5.3.2 Salinity Levels and Ecosystems Response

The modeling results for the salinity dynamics and impacts on the Sururu population are presented in this section. Firstly, the salinity results for both the monthly averaged simulations and for intertidal salinity model. The results of the monthly averaged salinity simulations are presented in Figure 5.11. This simulation encompassed a period of 5 years from 1974 to 1979 with a time step adopted of 1 day and results averaged monthly. The model simulations resulted in an R^2 (coefficient of determination) of 0.71.

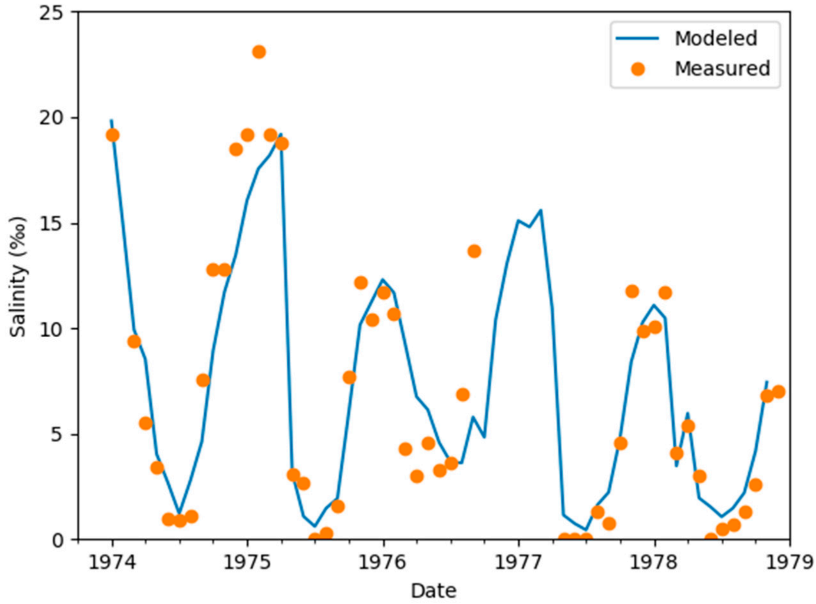

Figure 5.11
Results of the simulation corresponding to the monthly salinity model and comparison with observations.

Regarding the intertidal salinity modeling approach, a time step of 10 minutes was applied for a simulation period from May 15th to May 28th, 2017, this period corresponding with the available measurements. The return flow factor (*b*) was 0.7, the same value adopted in **Paper I** for the flushing time estimate. The results for this modeling approach are presented in Figure 5.12, these estimates consider the spatial distribution approach described in the Methods chapter and correspond to the same position as the measurements, with a coordinate *x* of 5.3 km, producing a ratio of 0.33. The coefficient of determination (R^2) obtained is 0.74. Still in Figure 5.12, the results of the applied inlet hydraulics model (developed in **Paper III**) are presented in the upper panel, where the simulated and measured lagoon water levels during the river runoff event can be seen. The model simulation resulted in an R^2 value of 0.95.

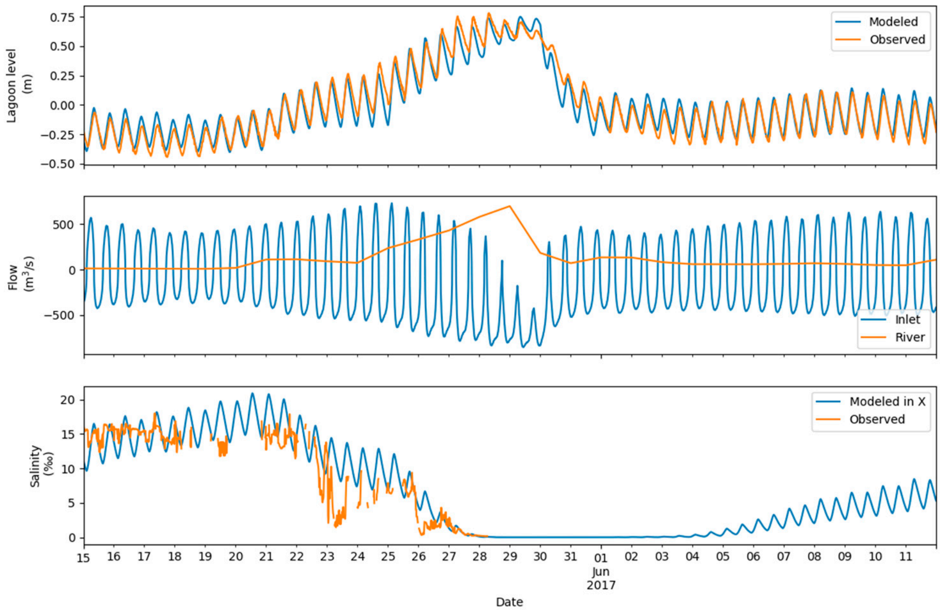

Figure 5.12
Results of the model simulations and comparison with observations capturing an event of salinity drop due to river discharge. The results of the intertidal salinity models correspond to the same coordinate along the lagoon as the measurements buoy (5.3 km distant from the river mouth).

Both modeling approaches presented a satisfactory representation of the salinity dynamics in comparison with measurements. The salinity levels variation due to the marked seasonality of the river discharge was reproduced by the monthly averaged simulation results. However, punctual deviations were observed in comparison with data. A considerable source of error may be due to imprecision in the measurements' exact dates, which were obtained once a month and generalized. Neglected water inputs in the system as the urban waters drainage from the surrounding cities, can also be a source of errors in this modeling approach.

Regarding the intertidal salinity model, the marked drop caused by the river runoff event was well captured, both intensity and time in which the system reaches the minimum salinity value were both well estimated. However, the estimated range of variability in the salinity due to the semidiurnal tidal cycle was considerably higher than observed in the measurements. The time estimated for the recovery of the salinity to levels pre-runoff event was of around 19 days. This kind of result can be useful for the management of the lagoons.

Another modeling approach, useful for the management of coastal lagoons, is the coupling of the salinity dynamics with the mussel population dynamics. The population model was first tested against a schematic salinity variation, sinusoidal and non-dimensional signal. This model's coefficients (α, β and n) were determined through a qualitative assessment of the growth and survival salinity level of the Sururu. Thus, the critical salinity levels for the mussel survival were found to be in the interval > 35‰ and < 2‰, and the optimum salinity range were from 5‰ to 15‰ (Pereira-Barros and Macedo, 1967). From this analysis, the coefficients were determined, resulting in 2 days^{-1}, 0.5 days^{-1} and 2 for α, β and n, respectively. Figure 5.13 present the result for the schematic simulation. It is possible to observe that the maximum non-dimensional population is around 0.7, this is due to the slower response of the population dynamics compared to the salinity changes.

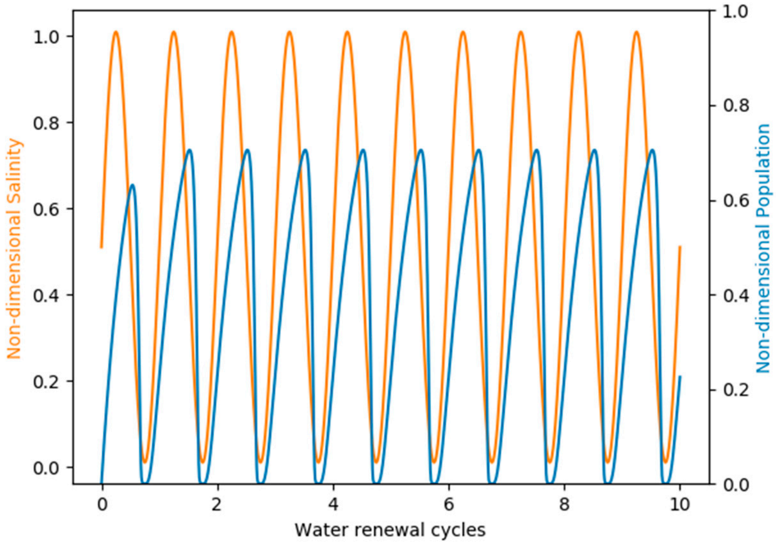

Figure 5.13
Results of the simulated non-dimensional mussel population dynamics having as input a sinusoidal, non-dimensional salinity variation.

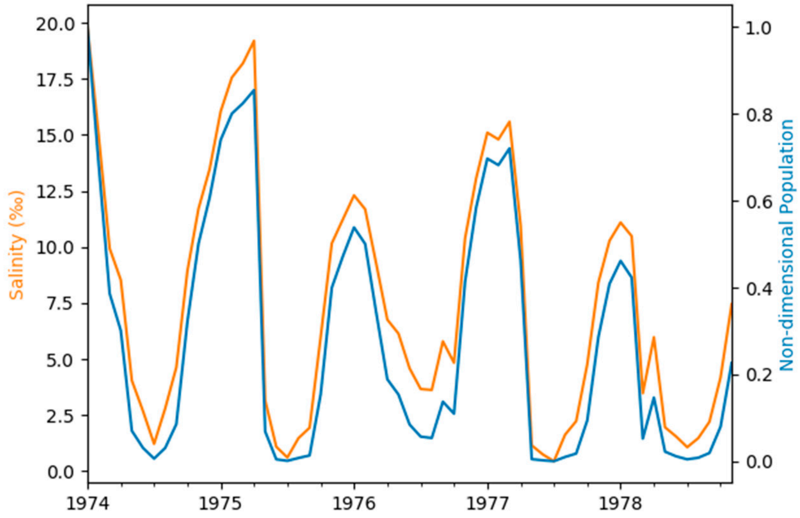

Figure 5.14
Results of the non-dimensional mussel population for a salinity input corresponding to the simulated monthly values.

Furthermore, the selected coefficients were applied to a simulation using as input the simulated salinity from 1974 to 1979. The results of this simulation are displayed in Figure 5.14. It is possible to observe that the mussel population reaches very low values during the rainy season of the lagoon and recovers during the dry season proportionally to the salinity levels reached during that season. It is possible to observe that the years after 1975 presented lower population peaks during the dry season, in particular during the year of 1978 when the peak was lower than 0.5. This is an indication of a critical period for the Sururu stocks, which is in accordance with the reported situation by Asbury (1979). However, the lack of precise data about the Sururu abundance at the time does not allow more conclusions about the model performance.

6 Conclusions and Future Steps

"No man ever steps in the same river twice, for it's not the same river and he's not the same man."

Heraclitus (c. 535–c. 475 B.C.)

The present research developed a set of modeling approaches for the understanding of tidal inlet hydraulics and morphological changes as well as the implications of these inlet processes for the environmental conditions in coastal lagoons. During the process of developing these models, the main characteristics desired were the applicability in regions with limited inlet data to support more detailed approaches, yet producing reliable and robust estimates about the key elements of the inlet flow and evolution. Such models are of great use in the management of coastal inlets and lagoons.

Two different approaches for the description of the inlet hydraulics and evolution were developed, resulting in analytic and numerical models. The former approach resulted in useful expressions for quick analysis and preliminary studies of key elements of the inlet flow, such as the bay amplitude, tidal prism, and maximum and average inlet velocities. These expressions, in particular the description of the lagoon levels response, were used to develop an inlet sediment balance equation to be applied in qualitative studies of the morphology of tidal inlets, allowing the assessment of the equilibrium conditions of the inlet and also inlet evolution. This morphology assessment was centered on the repletion coefficient, producing Escoffier-like diagrams for the equilibrium conditions, but advancing the method by considering also longshore transport conditions and the threshold of the sediment movement in the inlet. However, this approach is based on simplified input conditions for tides and sediment transport.

The numerical approach for simulating the inlet hydraulics and morphological changes allowed more flexibility when considering the input conditions. Regarding the tidal levels, for example, this flexibility allowed satisfactory representation of the nonlinearity in the lagoon level response observed in the case of choked lagoons, such as Mundaú Lagoon. Besides being a choked lagoon, this study area presented other challenges including the existence of a sandstone line parallel to the inlet, the lack of measured wave information, and only a few measured inlet cross-sections.

Despite these challenges, common in many inlet-lagoon systems around the world, the numerical model presented satisfactory results in an 11-years simulation of the inlet evolution.

As further improvements to the numerical model, some processes should be added to attend the particularities of other inlets, for example, cross-shore processes and inlet migration. The lack of cross-shore processes can explain deviations in the width observed during certain periods. As a next step, the methodologies presented here should be applied to other inlet-lagoon systems.

As the numerical approach resulted in short execution times, this model demonstrated the potential to be used in a probabilistic way with a high number of simulations involving different future scenarios. This can be explored in the future to assess the effects of forecasted sea-level rise on the inlet morphology and consequences for the inlet water quality and ecosystems.

The present research also provided insights into the Mundaú Lagoon water exchange and quality. A better understanding of the hydraulics of this choked lagoon was obtained and the very limited water exchange during the critical conditions of very low river discharge during the dry season. Also, zones of similar water exchange were identified and it was possible to determine regions of the lagoon with higher risk of eutrophication or substance accumulation. The developed inlet hydraulic model was applied and resulted in satisfactory agreement with data, comparable to a more detailed 2D hydrodynamic model. The relationship between the water exchange, salinity dynamics, and the mussel population was also explored. The success of the simple methodologies developed here indicated the potential for these approaches to be used to answer other questions about the internal ecological processes of coastal lagoons related to its connectivity with the sea.

Finally, the developed models applied to Mundaú lagoon and its inlet demonstrated their potential to contribute to coastal and lagoon management, as they provided important insights into the impacts on the inlet-lagoon system from the main processes involved.

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