UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

Water quality assessment and modelling in a eutrophic coastal lagoon: A case study in the Óbidos Lagoon, Portugal

Maria Madalena dos Santos Malhadas

Supervisor: Doctor Ramiro Joaquim de Jesus Neves

Thesis approved in public session to obtain the PhD Degree in Environmental Engineering

Jury final classification: Pass with merit

Jury

Chairperson: Chairman of the IST scientific board

Members of the committee:

Doctor Ramiro Joaquim de Jesus Neves
Doctor João Miguel Sequeira Silva Dias
Doctor António Alberto Pires Silva
Doctor Aires José Pinto dos Santos
Doctor Luís Ivens Ferraz Saavedra Portela
Doctor Paulo Chambel Leitão

2015

UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

Water quality assessment and modelling in a eutrophic coastal lagoon: A case study in the Óbidos Lagoon, Portugal

Maria Madalena dos Santos Malhadas

Supervisor: Doctor Ramiro Joaquim de Jesus Neves

Thesis approved in public session to obtain the PhD Degree in Environmental Engineering

Jury final classification: Pass with merit

Jury

Chairperson: Chairman of the IST scientific board

Members of the committee:

Doctor Ramiro Joaquim de Jesus Neves, Professor associado, Instituto Superior Técnico da Universidade de Lisboa
Doctor João Miguel Sequeira Silva Dias, Professor Auxiliar (com Agregação), Universidade de Aveiro
Doctor António Alberto Pires Silva, Professor Auxiliar, Instituto Superior Técnico da Universidade de Lisboa
Doctor Aires José Pinto dos Santos, Professor Auxiliar, Instituto Superior Técnico da Universidade de Lisboa
Doctor Luís Ivens Ferraz Saavedra Portela, Investigador Auxiliar, Laboratório Nacional de Engenharia Civil
Doctor Paulo Chambel Leitão, Consultor Ambiental, HIDROMOD Porto-Salvo, individualidade reconhecida na área científica em que se insere a tese

2015

Preface

This study is integrated on the Environmental Monitoring Program (EMP) implemented for the Óbidos Lagoon and Foz do Arelho coastal area. The EMP was carried out with the financial support of Águas do Oeste S.A (AdO), as part of the project "Monitoring and modelling the Óbidos Lagoon and Foz do Arelho submarine outfall". In July 2004, AdO initiated a monitoring program in the Óbidos Lagoon and adjacent coastal area, with the participation of Instituto Superior Técnico (MARETEC/IST) from the Universidade Técnica de Lisboa and Instituto de Investigação das Pescas e do Mar [1](IPIMAR). The main goal of the project is to understand the influence of the urban loads in the lagoon trophic state and the impact of the submarine outfall in Foz do Arelho in bathing waters.

In addition to this thesis the project also promoted one master degree (Malhadas, 2008) and a doctor degree (Kolowski, 2009). The project also allowed the possibility to participate in various conferences at national and international level, and publish scientific articles in Óbidos Lagoon case study.

The author wants to thank to Sandra Carvalho from AdO for being the driving force in the financial support along five years of monitoring program.

A warmly thanked to Ramiro Neves and MARETEC staff for their efforts, knowledge, skills and friendship. The team spirit and gratitude made MARETEC as my second home in the moments away from family and hometown.

[1] IPIMAR is now part of Instituto Português do Mar e da Atmosfera (IPMA)

Resumo

As lagoas costeiras correspondem a massas de água que, em função das suas características intrínsecas e cargas de poluentes a que estão sujeitas, podem apresentar flutuações na qualidade da água e alterações do estado ecológico.

A Lagoa de Óbidos, como qualquer outro ecossistema sujeito a pressões antrópicas, desenvolveu problemas nas cabeceiras, onde se destacam elevadas concentrações de nutrientes e Clorofila *a*, em particular no Braço da Barrosa. Por conseguinte, a laguna foi classificada como um sistema sensível em relação aos critérios de eutrofização relativamente ao tratamento de águas residuais urbanas. Para diminuir as pressões antrópicas nas cabeceiras, foram adotadas medidas de gestão ao nível da bacia hidrográfica, focadas na redução das cargas de origem urbana. No entanto, as melhorias foram pouco significativas continuando a observar-se os mesmos sintomas de eutrofização. Foi dentro deste âmbito, que a laguna constitui o interesse científico e trabalho de investigação desta tese, que pretende ser um contributo para a gestão e modelação de ecossistemas eutrofizados.

O estudo teve como principal objetivo, modelar e avaliar a qualidade da água da Lagoa de Óbidos, para explicar o seu estado de eutrofização. Para dar cumprimento ao objetivo proposto, recorreu-se uma estratégia que integrou observações e modelação numérica. As observações serviram para, numa primeira fase, adquirir conhecimento científico sobre a laguna e numa segunda fase para, alimentar os modelos implementados e validar o sistema de modelação. O sistema de modelação implementado integrou três classes de modelos, nomeadamente: MOHID (modelo hidro-ecológico), STWAVE (modelo de ondas) e SWAT (modelo de bacias).

As principais conclusões são apresentadas sob pontos de vista distintos, nomeadamente modelação, qualidade da água da laguna e do estudo em si. Os modelos aplicados neste trabalho, embora com todas as limitações encontradas, conseguiram reproduzir a variabilidade observada nas medidas podendo ser utilizados para análises causa-efeito. As tendências de eutrofização nas cabeceiras da lagoa persistem após remoção da carga de origem urbana, porque os processos internos de regeneração de nutrientes em particular no Braço da Barrosa perpetuam o seu estado de eutrofização e as cargas geradas pelas suiniculturas são mais importantes do que as de origem urbana. Este estudo mostrou a importância de utilizar abordagens integradas e inovadoras pois permitirá melhorar a implementação das medidas de gestão na área da qualidade da água. O conhecimento científico adquirido neste ecossistema pode ser de importância em casos de estudo semelhantes quer a nível nacional quer a nível internacional.

Palavras-chave: MOHID, SWAT, tempos de renovação, cargas urbanas, suiniculturas, estado trófico, Diretiva Quadro da Água, Lagoa de Óbidos.

Abstract

Coastal lagoons correspond to water bodies which, according to their intrinsic characteristics and loads of pollutants that are subject, may have fluctuations in water quality and changes in ecological status.

The Óbidos Lagoon, like any ecosystem under pressure, developed problems in the upper areas, such as high concentrations of nutrients and chlorophyll *a*, particularly in Barrosa arm. Therefore, the lagoon was classified as a sensitive system in relation to eutrophication criteria for the treatment of urban waste water. To reduce the anthropogenic pressures management measures were adopted within the river basin, focused on reducing the loads from urban origin. However, after these measures, improvements were negligible continuing to be observed the same symptoms of eutrophication. Within this context, the lagoon represent the scientific interest and research work of this thesis, contributing to management and modelling of eutrophic ecosystems.

The study aimed to, model and assess the water quality in the Óbidos Lagoon, to explain his state of eutrophication. To comply with the proposed objective, we used a strategy that integrates observations and numerical modelling. The observations serve to initially acquire scientific knowledge of the lagoon and a second stage for, feed implemented models and validate the modelling system. The implemented modelling system integrated three classes of models, namely: MOHID (hydro-ecological model), STWAVE (model waves) and SWAT (model basins).

The main conclusions in this study are presented in different views, including modelling, lagoon water quality and the study itself. The models used in this work, although with all the limitations found, have reproduced the observed variability in the measurements and can be used for analysis of cause and effect. The trends of eutrophication in upper areas persist after removal of urban loads, because the internal processes particular nutrient regeneration in the Barrosa arm perpetuate his state of eutrophication and charges generated by pig farms are more important than the urban origin. This study showed the importance of using integrated and innovative approaches improving the implementation of management measures in the area of water quality. Scientific knowledge acquired in this ecosystem may be of importance in similar case studies both nationally and internationally.

Keywords: MOHID, SWAT, water renewal, urban loads, pig farms, trophic state, Water Framework Directive, Óbidos Lagoon.

Publications from the candidate in the aim of the project

Malhadas, M.S., Vaz, N., Marques, C.A.F., Nunes, S., Dias, J.M. Mateus, M., Neves, R.., 2015. Summer-winter diel variability in a mesotidal coastal lagoon: a focus on biogeochemical and metals cycle in reference and eutrophic sites. *Hydrobiologia* (accepted, under review).

Malhadas, M.S., Mateus, M., Brito, D., Neves, R., 2014. Trophic state evaluation after urban loads diversion in a eutrophic coastal lagoon (Óbidos Lagoon): A modeling approach. *Hydrobiologia*, **740**:231-251.

Malhadas, M.S., Neves, R., Leitão, P.C., Silva, A., 2010. Influence of tide and waves on water renewal in Óbidos Lagoon, Portugal. *Ocean Dynamics* **60**, pp. 41-55.

Malhadas, M.S., Leitão, P.C., Silva, A., Neves, R., 2009. Effect of coastal waves on sea level in Óbidos Lagoon. *Continental Shelf Research*, *Continental Shelf Research* **29 (9)**, pp. 1240-1250.

Malhadas, M.S., Leitão, P.C., Silva, A., Neves, R., 2009. Effect of the bathymetric changes on the hydrodynamic and residence time in Óbidos Lagoon (Portugal). *Journal of Coastal Research* **SI56**, pp. 549-553.

Malhadas, M.S., Nunes, S., Neves, R., Carvalho, S., Couto, C., Zenha, H.S., 2009. Impact of Casalito waste water treatment plant discharge on Óbidos Lagoon water quality. *Global NEST Journal* **Vol. A**, pp. 796-803.

Malhadas, M.S., Nunes, S., Neves, R., Carvalho, S., 2009. Avaliação do impacte da descarga da ETAR do Casalito na qualidade da água da Lagoa de Óbidos. *Encontro Nacional de Entidades Gestoras de Água e Saneamento, ENEG*, 22-26 Novembro, Lisboa, Portugal.

Santos, M., Leitão, P.C., Neves, R., Carvalho, S., Alves, C., 2008. Hydrodynamics downscaling for predicting the dynamics of Foz do Arelho submarine outfall plume. *In Proceedings of MWWD 2008-5th International Conference on Marine Waste Water Discharges and Coastal Environmental*, 27-31 Outubro, Cavtat/Dubrovnik, Croatia.

Pereira, P., **Santos, M.,** Pablo, H., Carvalho, S.M., Alves, C.P, Vale, C., Neves, R., 2008. Avaliação da qualidade da água da Lagoa de Óbidos em ciclos de 24 horas. *In Proceedings of 13º Encontro Nacional de Saneamento Básico, ENaSB*, 14-17 Outubro, Covilhã, Portugal.

Alves, C., Carvalho, S., **Santos, M.**, Zenha, J.H.S. & Neves, R. 2006. Monitoring and Modelling Foz do Arelho submarine outfall plume. *In Proceedings of 7th International Conference on Hydroinformatics* HIC 2006, 3-7 September, Nice, France.

Santos, M., Neves, R., Leitão, P.C., Pereira, P., Pablo, H., Fernandes, L. D., Carvalho, S., Alves, C., 2006. Qualidade da Água da Lagoa de Óbidos: Que Futuro? *In Proceedings of 12º Encontro nacional de Saneamento Básico, ENaSB*, 24-27 Outubro, Cascais. ISBN: 978-972-95302-8-9.

Carvalho, S.M., Alves, C.P., **Santos, M.,** Neves, R., 2006. Protecção e Prevenção da Lagoa de Óbidos. *In Proceedings of 2º Seminário sobre sistemas lagunares costeiros*, 2-4 Junho, Vila Nova de Santo André, Portugal.

Santos, M., Carvalho, S.M., Alves, C.P., Neves, R., 2005. Programa de Monitorização do Emissário Submarino da Foz do Arelho. *Encontro Nacional de Entidades Gestoras de Água e Saneamento, ENEG*, 22-24 Novembro, Lisboa, Portugal.

Silva, A., **Santos, M.,** Leitão, P., Coelho, H. & Neves, R. 2004. Aplicação de um modelo hidrodinâmico (MOHID) como ferramenta na avaliação da qualidade da Lagoa de Óbidos. *In Proceedings of 1º Seminário sobre sistemas lagunares costeiros*, 30 Setembro-2 Outubro, Vila Nova de Santo André, Portugal.

Publications included in this thesis

Publication	Contributor	Statement of contribution
Malhadas, M.S., Leitão, P.C., Silva, A., Neves, R., Effect of coastal waves on sea level in Óbidos Lagoon. *Continental Shelf Reasearch*	Madalena Malhadas (candidate)	Undertook model simulations and data analysis (100%) Wrote the Article (100%) Reviewed the article after submitted to journal and before publication (100%)
	Paulo C. Leitão	Schematic Óbidos Lagoon model expressions (100%)
	Adélio Silva	Reviewed the article before submitted to journal (5%)
	Ramiro Neves	Reviewed the article before submitted to journal (5%)
Malhadas, M.S., Leitão, P.C., Silva, A., Neves, R., 2009. Effect of the bathymetric changes on the hydrodynamic and residence time in Óbidos Lagoon (Portugal). *Journal of Coastal Research*	Madalena Malhadas (candidate)	Undertook model simulations and data analysis (100%) Wrote the article (100%) Reviewed the article after accepted and before publication (100%)
	Paulo C. Leitão	Reviewed the article before submitted to journal (5%)
	Adélio Silva	Reviewed the article before submitted to journal (5%)
	Ramiro Neves	Reviewed the article before submitted to journal (5%)
Malhadas, M.S., Neves, R., Leitão, P.C., Silva, A., 2010. Influence of tide and waves on water renewal in Óbidos Lagoon, Portugal. *Ocean Dynamics*	Madalena Malhadas (candidate)	Undertook model simulations and data analysis (100%) Wrote the article (100%) Reviewed the article after accepted and before publication (100%)
	Ramiro Neves	Reviewed the article before submitted to journal (50%)
	Paulo C. Leitão	Reviewed the article before submitted to journal (5%)
	Adélio Silva	Reviewed the article before submitted to journal (5%)
Malhadas, M.S., Mateus, M., Brito, D., Neves, R., 2014. Trophic state evaluation after urban loads diversion in a eutrophic coastal lagoon (Óbidos Lagoon): A modeling approach. *Hydrobiologia*	Madalena Malhadas (candidate)	Undertook model simulations and data analysis (100%) Wrote the article (100%) Reviewed the article after accepted and before publication (50%)
	Marcos Mateus	Restructure the article (50%) Reviewed the article after accepted and before publication (50%)
	David Brito	Guidance in SWAT simulations (50%)
	Ramiro Neves	Reviewed the article before submitted to journal (5%)
Malhadas, M.S., Vaz, N., Marques, C.A.F., Nunes, S., Dias, J.M. Mateus, M., Neves, R.., 2015. Summer-winter diel variability in a mesotidal coastal lagoon: a focus on biogeochemical and metals cycle in reference and eutrophic sites. *Hydrobiologia* (accepted, under review)	Madalena Malhadas (candidate)	Undertook model simulations and data analysis (100%) Wrote the article (100%) Reviewed the article (100%)
	Nuno Vaz	Reviewed the article before submitted to journal (40%)
	Carlos Marques	PCAs guidance analysis (100%)
	Susana Nunes	Reviewed the article before submitted to journal (5%)
	João Dias	Reviewed the article before submitted to journal (15%)
	Marcos Mateus	Reviewed the article before submitted to journal (40%)
	Ramiro Neves	Reviewed the article before submitted to journal (20%)

Agradecimentos

O desfecho desta aventura apenas foi possível graças a pessoas e instituições cuja dedicação e apoio jamais se esvanecerá da minha memória e do meu afeto. Para além de todo o apoio por diversas pessoas e instituições, esta tese traduziu-se num enorme esforço a todos os níveis, uma vez que foi feita a título pessoal.

Ao Professor Ramiro Neves, orientador científico da tese, agradeço a confiança que depositou em mim ao longo deste trabalho. A minha imensa gratidão ao Marcos Mateus (IST/MARETEC) por ser a força impulsionadora para fechar este documento e por conseguinte a publicação de um dos artigos mais importantes desta tese. Ao meu colega Paulo Chambel (HIDROMOD) pela ajuda no arranque deste trabalho. A ambos agradeço o saber que me transmitiram, contribuindo para o meu enriquecimento e amadurecimento, não apenas científico mas também como pessoa.

A cada um dos amigos e colegas de trabalho do MARETEC e HIDROMOD que contribuíram com algo especial. Agradeço em especial aos colegas da HIDROMOD a amizade e força nas alturas em que foi difícil conjugar o trabalho com a investigação desta tese.

À Susana Nunes e Tânia Cota pela amizade mostrada e constante força e apoio. Obrigada por me ouvirem nos dias mais difíceis desta longa caminhada. Obrigada por me darem força e acreditarem que conseguia.

À minha família pela alegria e força transmitida.

Finalmente, ao Lando, pelo apoio incondicional paz e força transmitida, mas sobretudo por acreditar que chegaria ao fim.

A cada um muito obrigada.

TABLE OF CONTENTS

1. Introduction

1.1. Overview

A workable definition of a coastal lagoon is: "**a shallow water body separated from the ocean by a barrier, connected at least intermittently to the ocean by one or more restricted inlets, and usually oriented shore parallel**" (Kjerfve, 1994). Coastal lagoons formed as a result of sea level rising mostly during the Holocene period and the building of coastal barriers by marine processes (Kjerfve, 1994).

As transitional land-sea systems they are characterized by significant changes in their environmental conditions. Therefore the ecosystem metabolism is shaped between connection of physical and biogeochemical factors.

Coastal lagoons favor the formation of phytoplankton blooms by the combined effect of the high residence time of water, constant supply of nutrients and light availability (shallow waters). They are frequently exposed to anthropogenic stress (Gaertner-Mazouni and De Wit 2012; Newton *et al*. 2014; Newton and Weichselgartner, 2014) and the restricted exchange of water with the coastal area enhance their vulnerability to eutrophication (Cloern, 2001; Scanes *et al*. 2007) mostly related to human activities (e.g., use of fertilizers in the watershed, aquaculture production, etc.). As such, coastal lagoons are highly productive systems, but also highly impacted by nutrient excess from catchment basin.

Given their natural conditions, coastal lagoons tend to naturally change from a state of lack of nutrients (oligotrophic) to nutrient enrichment (eutrophic). A simple definition of "**Eutrophication**" is an overabundance of nutrients in waters, especially compounds of nitrogen and phosphorus. Common symptoms resulting in increased growth, primary production and biomass of algae, high turbidity and increasing anoxia in waters from the decay of dissolved and particulate organic matter and overall water quality degradation.

The emphasis on controlling eutrophication has been focused heavily on decreasing phosphorus and nitrogen inputs. Phosphorus has received priority traditionally in upstream freshwater regions, while controlling nitrogen inputs has been the focus of management strategies in estuarine and coastal waters (Paerl *et al.*, 2014). The general paradigm of these strategies assumes a fine line of simplification: "**controlling nutrients, specifically nitrogen from point sources, solve eutrophication problems**"(Smith *et al*., 1999, Taylor *et al.*, 2005; Smith, 2009).

Although the general agreement in the literature that "increasing nutrients develop eutrophic symptoms" this have implications in water management plans (Hilton *et al.*, 2006). The companies of water management tend to easily adopt strategies that are focused on the improvement of the sewage treatment; and/or diverging the sewage to a pipe into the ocean. This is troubling because, sometimes, protective measures are planned without any scientific knowledge and are not the most suitable to solve the problem. A classic example of that, are the ecosystems that experimented perpetually external loads over decades and undergo an enrichment of organic matter in sediments. Internal loads can have significant influence on the water quality of a system that has experienced excessive external nutrient loads (Fisher *et al*., 2005).

The models can be used in all the phases of the implementation of management plans, especially in the evaluation of the pollution effects on water status, analysis of future actions on the trophic level, and in defining cost-effective monitoring programs. They are also the tools that help to conceptualize, integrate, and generalize knowledge to interpret the conceptual model of the system and to simulate hypothetical management scenarios.

In fact, strategies defended by Water Framework Directive (WFD, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000) and Marine Strategy Framework Directive (MSFD, 2008/56/CE) to achieved the good ecological status of marine waters and prevent significant environmental degradation included three main steps (Figure 1.1): 1) Monitoring, 2) Modelling and 3) Management. The output of this methodology is the development and implementation of monitoring networks and local management plans. Integrated methodologies, such as monitoring and modeling, can be used for planning the necessary measures to protect and preserve water bodies.

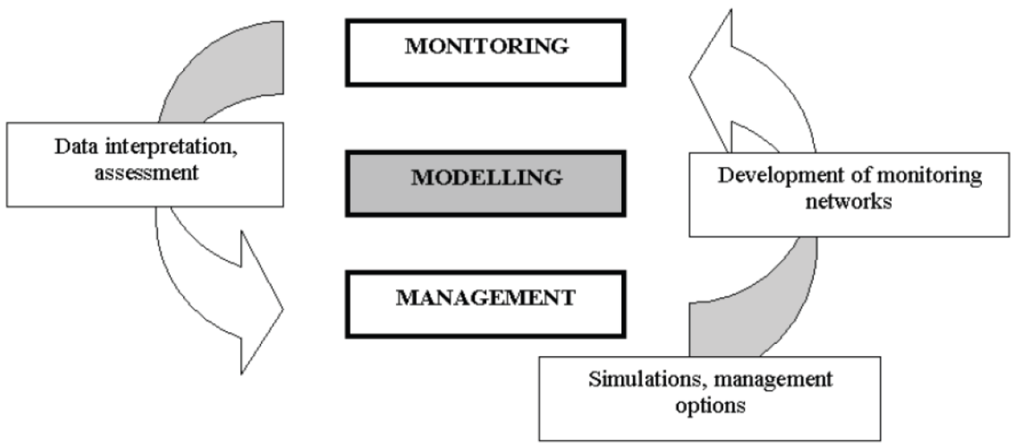


Figure 1.1. Integrated strategies for a better design of monitoring and management plans (CLMP, 2012, 2014).

Traditionally, water is managed by different geographical compartments (e.g. rivers, reservoirs, lakes, estuaries, ground) using specific tools for each compartment (Giupponi *et al*., 2012). An integrated methodology assists in the definition of a program to restore and/or conserve ecosystems.

During the past decades the integration of multidisciplinary models (watershed, river, lagoon, ocean etc.) and innovate monitoring programs have been under dynamic development representing an important decision toll in water quality management (Gikas *et al*. 2006; Duarte *et al*. 2008; Stybel *et al*. 2009; Konstantinou *et al*. 2012; Azzellino *et al*. 2013). The ability to understand and predict the distribution, transport and fate of contaminants has become an indispensable requirement to support environmental monitoring and mitigate coastal and estuarine pollution effects.

The development of integrated tools and its application to coastal lagoons, by coupling hydro-ecological processes with reliable data, results on a multidisciplinary study of these ecosystems. However, lagoon models, even hydro-ecological cannot be by itself the best modelling strategy because the land pressures are not included. The more complete modelling approach is one that is able to make a water quality management issues of the watershed and its lagoon (Giupponi *et al*., 2012). Management for sustained use of water and coastal lagoons resources requires a watershed-lagoon modelling based approach (Gönenç *et al*., 2008). These methods are accepted by European Union and defended in the policies of the WFD/MSFD as a tool for national legislations and council governments.

A thorough assessment on data, models and other tools must be employed by local authorities, improving the implementation phases of a watershed-lagoon management system. Taken together, this set of tools provides options for representing the effect of human activities in a range of aquatic systems and for qualifying benefits of mitigation actions within watershed (Giupponi *et al.*, 2012).

Understanding processes controlling these water bodies is a key aspect to perceive the variability of the ecosystem and to do a better management. It is also important from an economic perspective considering social benefits in coastal systems prevention (Stemplewski *et al*. 2008)

1.2. Motivation

Óbidos Lagoon, the case study of this dissertation, is a small coastal lagoon connected to the Atlantic Ocean by a mobile inlet in the west coast of Portugal (Óbidos council).

The lagoon is an area of great importance and capacity of economic, social, and finally, scientific interest. Fishermen, touristic development, diversified sports (sailing, windsurf or rowing, kitesurf, catamaran, optimist, canoeing, wakeboard, water ski lessons) and leisure activities benefit from the Óbidos Lagoon wellbeing (Figure 1.2) and its natural resources. The wetland area also provides nursery for fishes and shellfishes and shelter for birds. Numerous migratory waterfowl can be seen, but it is mainly at the level of mollusk that is the importance of the fauna of the area.

Figure 1.2. Community activities beyond the Óbidos Lagoon ecosystem.

Beyond progressive accretion, common to these coastal systems, some regions in the lagoon suffer from severe water quality problems typical of eutrophic water bodies.

Within the context of vulnerable system according to eutrophication criteria and the socio-economic values of the lagoon, environmental protection is therefore an issue for the local community. The implementation of the Urban Water Treatment Directive in the region has contributed to improve the trophic status of the lagoon but did not solve the problem completely.

This study models hydrodynamic and biogeochemical in the lagoon and contributes to explain the eutrophic conditions of the coastal lagoon. The development of a numerical tool and its application to coastal lagoon, by coupling hydro-ecological processes, results on a multidisciplinary study. Moreover the approach rely in a coupled watershed-lagoon model representing the integration of different processes and an innovate tool.

The methods developed here are defended in the policies of the WFD/MSFD and could be applied in other eutrophic coastal lagoons. Additionally, this strategy could be adopted by local authorities to improve the management of water quality in coastal areas.

1.3. Hypothesis

The null hypothesis of this thesis is that **"removing the urban loads in the watershed improves water quality and reduces trophic state of the Óbidos Lagoon."**

1.4. Objectives and research questions

The general objective of this thesis is modelling and evaluating the water quality to explain the eutrophication state in Óbidos Lagoon. To accomplish the main goal the specific research questions will be answered:

Question 1. Is Tide the only dominant process in the lagoon circulation and water renewal?

The physical processes affecting the lagoon circulation are analyzed in Chapter II through hydrodynamic modelling. To better understand mechanisms the influence of individual factors in lagoon circulation was examined. The water renewal is evaluated coupling Lagrangian to hydrodynamic model (Chapter III).

Question 2. Will promoting the stability of the inlet improve tidal prism and consequently water renewal in the lagoon?

The effect of bathymetric changes on the hydrodynamic and water renewal is presented and discussed in Chapter IV.

Question 3. Why trophic state did not change after the implementation of protective measures?

In Chapter V the application of the water quality model is detailed. Load reduction scenarios are performed after model validation. Chapter VI analyzes diel observations in the lagoon complementing the conclusions achieved in Chapter V.

1.5. Study area

1.5.1. Óbidos Lagoon characteristics

The Óbidos Lagoon (39º24´N, 9º17'W) is a shallow and well-mixed coastal lagoon located between Cape Carvoeiro and São Martinho do Porto Bay, in western Portuguese coast (Figure 1.3). The lagoon occupies a NW-SE oriented shallow depression and is separated from the ocean by a sand barrier with 1.5 km length (Ferreira *et al*., 2009). The lagoon is impounded by Foz do Arelho beach formed at the coastline. This is a good example of a coastal lagoon formed as a result of sea level rising mostly during the Holocene period and the building of coastal barriers by marine processes (Dinis *et al*., 2006).

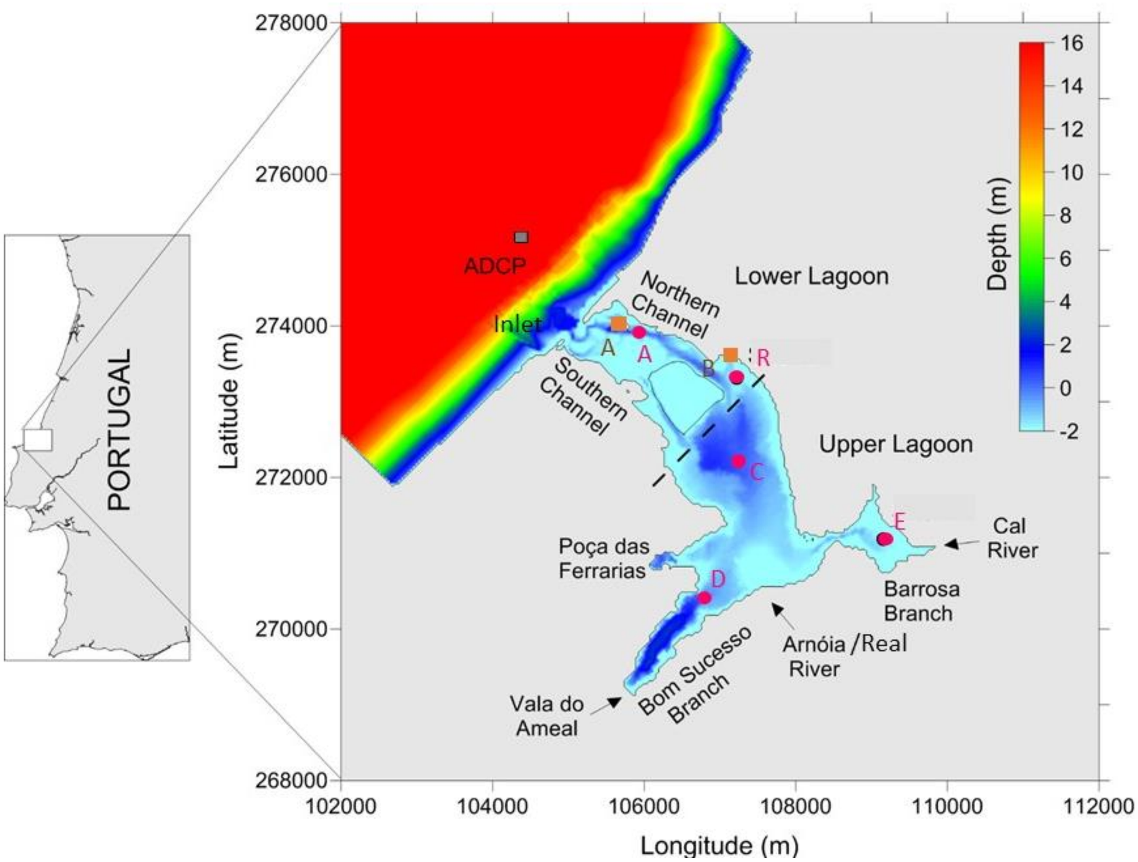


Figure 1.3. Geographical location of the Óbidos Lagoon. Main channels and freshwater river discharges are marked. The orange squares (station A and B) refers to currents data and pink dots to sea level (station A, D and E) and water quality (A, D, C, E and R) data. The local station of the ADCP is marked with a grey square.

The lagoon is connected to the Atlantic Ocean through a shallow, narrow and mobile inlet (100 m wide). Inlet position and small channels have changed naturally during the last decades due to erosion-deposition processes (Oliveira *et al*. 2005). The position of the inlet has changed naturally during the last decades; it moves from north to south being currently positioned at north (Oliveira *et al*. 2006). As a consequence, every time the inlet position approaches to the north or south shoreline, the associated erosion threatens local houses and some emergency interventions to protect the northern shoreline were needed.

It occupies a surface area of 4.4 km^2 at mean sea level and 8.0 km^2 at high spring tide (Oliveira *et al.*, 2006). Maximum length and width is about 4.5 km and 1800 m, respectively; and average depth 2 m (Oliveira *et al*. 2006; Ferreira *et al*., 2009).

The shape of the lagoon is complex and similar to an inverted triangle, with a central oval area which extends two elongated arms and one bay (Figure 1.3): Barrosa arm, Bom sucesso arm and Poça das Ferrarias embayment (Ferreira *et al*., 2009).

The main freshwater inputs come from two small streams (Arnóia/Real and Cal rivers) and one drainage creek (Vala do Ameal). Arnóia/Real Rivers (3 m^3s^{-1} annual average flow, Vão, 1991) enters near the oval area and accounts for 90% of the freshwater input into the lagoon. Cal River and Vala do Ameal enters via Barrosa arm and Bom Sucesso arm, respectively; with annual average flows of 0.14 m^3s^{-1} and 0.08 m^3s^{-1} (Vão, 1991).

The tides are semi-diurnal with a tidal range varying between 0.5 and 4.0 m. The influence of the tide extends throughout the entire lagoon without pronounced longitudinal variation in salinity or stratification (Carvalho *et al.*, 2005).

The oceanic influence from the Atlantic Ocean combined with perpetually industrial loads leads to significant differences in terms of hydrodynamic, water quality and sediment characteristics. This clearly divides two geographical areas in the lagoon (Figure 1.3): lower lagoon and upper lagoon.

The lower lagoon, is the most dynamic part, is directly influenced by the oceanic waters and composed by sand banks and narrow channels (northern and south channels).

The upper lagoon, particularly influenced by land inputs, has inefficient water circulation. High chlorophyll *a* concentrations associated to enriched nutrient waters were observed this part of the lagoon

(Pereira *et al*. 2009a, 2009b, 2010, 2011, 2012a, 2012b). In addition, high affinities for metals in muddy bottom sediments are also common in the upper lagoon (Carvalho *et al*., 2006; Pereira *et al*., 2009b).

Barrosa arm is considered the most impacted area of the upper lagoon due to particular characteristics. The arm is like an enclosed embayment with lower velocities and relatively high residence times where phytoplankton growth is favoured. Symptoms of eutrophication with extremely high primary production and large fluctuations in dissolved oxygen are observed in the arm (Kowalski, 2009). Opportunistic macroinvertebrate species found in Barrosa corroborates the eutrophic condition in the arm (Carvalho *et al*. 2005, 2006).

1.5.1. Óbidos Lagoon watershed

The Óbidos Lagoon watershed has a surface area of about 432 km^2 (Figure 1.4a) and is constituted by five basins: Arnóia and Real Rivers, Cal River, Vala do Amela, Poça das Ferrarias and Foz do Arelho. The most representative basin is the Arnóia and Real Riversoccupying 90% of the total area and Cal River about 4%. The rest of them (Vala do Ameal, Poça das Ferrarias and Foz do Arelho) drains a small area sparsely populated.

The predominant land/use soil in the watershed is the vineyard (80%), followed by agricultural activities especially around lagoon, and eucalyptus near the headwaters (Figure 1.4b, main uses basing in Corine 1986).

Despite agriculture practice with use of fertilizers, the watershed is dominated by industry activities. From the several industrial activities intensive farming systems (Table 1.1) and wastewater treatment plant discharges (WWTP, Table 1.2) are the most important

The phosphorus and nitrogen loads generated by the animal farms in the lagoon watershed come from the poultries (1378 tonN/year and 300 tonP/year) and swine’s (454 tonN/year and 95 tonP/year). The pig farms are very representative for the lagoon water quality since are connected to the septic tanks.

Until September 2005, the WWTP represents a total of urban loads into the lagoon of 337 tonN/year and 80 tonP/year, being 280 tonN/year and 64 tonP/year originated by the Cal River basin.

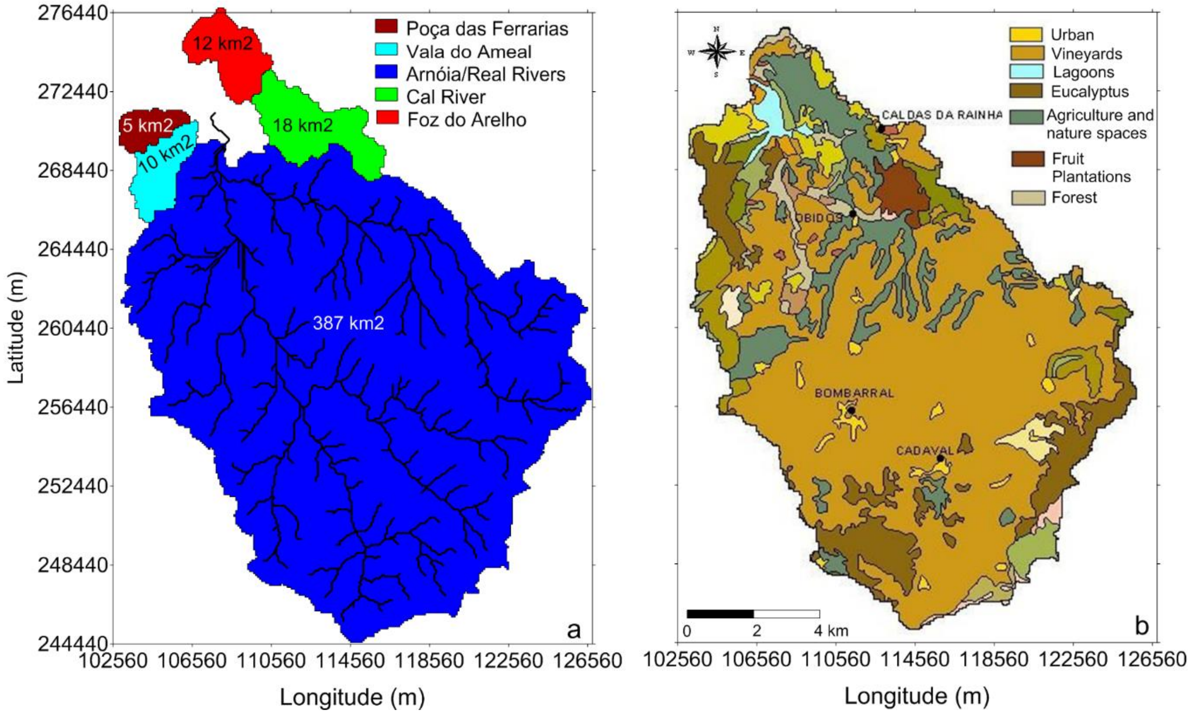


Figure 1.4. Óbidos Lagoon watershed main basins area in km^2 (a). Identification of the main land uses in basin according to Corine, 1986 (b).

Table 1.1. Nutrient loads in terms of phosphorus and nitrogen generated by the animal farms in the lagoon watershed. The loads were calculated with the data from agricultural census 1999.

Animal Farms	Number of animals	Nitrogen (ton/year)	Phosphorus (ton/year)	Inhabitants equivalent
Goat meats	3270	63	11	13587
Rabbits	37286	212	58	56639
Equines	250	6	1	1447
Bovines	4287	258	38	51201
Swine’s	38126	454	95	123708
Poultries	2386776	1378	300	378996
Ovine	4906	83	12	16529
Total	**-**	**2454**	**515**	**642107**

Table 1.2. Nutrient loads in terms of phosphorus and nitrogen generated by WWTP in the Óbidos Lagoon watershed until September 2005. The loads were calculated with the data from AdO.

River Basin	Nitrogen (ton/year)	Phosphorus (ton/year)
Arnóia/Real	57	16
Cal	280	64
Total	**337**	**80**

1.5.2. Conceptual model for the lagoon

A conceptual model of the Òbidos Lagoon has been derived from natural characteristics of lagoon and watershed, data and numerical modelling (Figure 1.5 and Figure 1.6).

The main governing processes in hydrodynamic are the tides and waves. The seasonal variation of the climate regime lead to an alternation of tide forcing alone and tide plus waves forcing. Wave forcing is activated as physical forcing in the episodes of storm waves causing a substantial variability in lagoon sea level. The consequence of the storm waves is a set-up at the inlet entrance that causes a sea level rise in the lagoon with a timescale of a few days. Winds causing vertical mixing in the water column. Freshwater runoff are absent altogether.

Baroclinic pressure gradients will drive longitudinal circulation within lagoon generating an acceleration of the currents towards the lagoon promoting a tidal asymmetry with flood dominance (blue arrows, Figure 1.6). Within this type of asymmetry, the ebb phase lasts longer than the flood phase, resulting in stronger currents during the flood phase.

The alongshore drift (white arrows, Figure 1.5) and local sediments supply subsequently maintained the sand barrier. The inlet functions as a constrainer for water flow in and out the lagoon, promoting the incoming of sediments during tidal exchanges. The sediments that pass through the inlet are transported by the strong residual currents along North Channel favouring accretion in the lagoon.

The timing of water exchange with ocean drives the timing of hydrology and therefore a weak longitudinal salinity gradient is observed. Due to the lack of freshwater and low depths the lagoon is well-mixed in vertical all the year.

The saltier water that enters in the lagoon is transported by the residual currents and mixed with water masses in oval central. The mixing in this area is promoted by the large clockwise gyre (blue gyre, Figure 1.5) developed by tidal residual circulation.

The water renewal time varies between few days to one month from the lower to the upper lagoon. This parameter is a primarily key for explaining the conceptual model of biochemical in the lower lagoon, exposed to high tidal flushing and low pressures loads (Figure 1.6). Nutrient storage in this part of the lagoon is highly dependent on water residence time. Likewise, no appreciable primary production occurs in lower lagoon which typically reveals oligotrophic symptoms. The balance of primary productivity is not surprising since nutrients (nitrogen and phosphate) uptake strongly depends of the time that water resides in this part of the lagoon. Dissolved oxygen levels respond to primary production balance remaining relatively constant all the year and close to the standards of oligotrophic waters (~90%).

The lack of forcing by tides combined with shallow and unstratified waters makes hydro-ecology in the upper lagoon particularly in Barrossa arm, at times, similar to lakes rather than estuaries. The interaction with the ocean in the upper lagoon is negligible and tidal flushing partially eliminated. High primary productivity is the result of the residence time, large nutrient and organic matter inputs and sediment-water column interactions (Figure 1.6). The lack of mixing in this part of the lagoon results in stagnation of waters. When water circulation stagnates, the atmospheric flux of dissolved oxygen is reduced and anoxic crises occurred. Dissolved oxygen concentrations varied considerably – from super-saturated to virtually anoxic– on diurnal and seasonal time scales. The hypoxia can persist for much longer in summer compared to winter. Hence, the annual cycle of phytoplankton is explained due to the balance between nutrient loads, phytoplankton uptake and exchange of nutrients between the sediments. These factors combined with hydrodynamic conditions inhibit the flushing of nutrients out of the lagoon and contribute to excessive phytoplankton biomass.

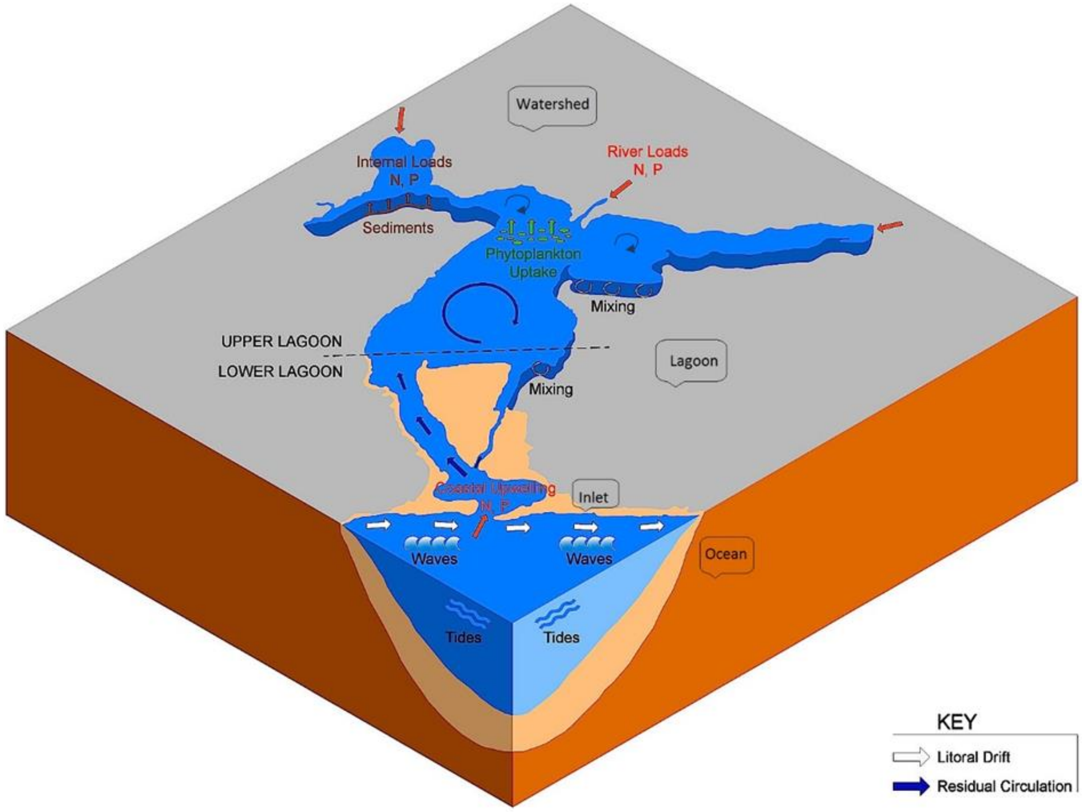


Figure 1.5. Conceptual model of the Óbidos Lagoon with the four compartments in horizontal: watershed, lagoon, inlet and ocean.

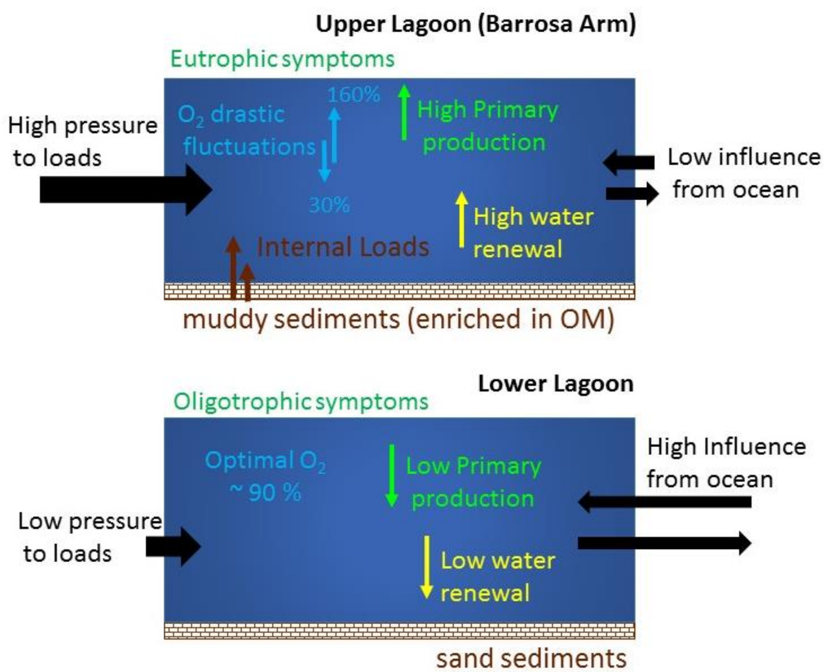


Figure 1.6. Conceptual model of the lower and upper lagoon for the vertical changes between water column and sediments.

1.5.1. The problem and solutions

The Óbidos Lagoon has been under significant nutrient load pressure originated in the drainage basin both in the form of point sources (e.g., WWTP and pig farm effluents) or diffusive sources (e.g., runoff from agriculture fields). Like any other coastal system under pressure the lagoon reveals high nutrients and chlorophyll *a* levels in the headwaters and then eutrophication symptoms. In fact the problematic area is Barrosa arm showing high biomass of phytoplankton (chlorophyll *a* concentrations >15 $\mu g\ l^{-1}$) combined with hypoxia in the upper sediment layers and anoxia in the bottom layers (Pereira *et al*. 2012b; Pereira *et al*. 2009a; Pereira *et al*. 2009b).

In 2004 the Óbidos Lagoon was classified as vulnerable system according to eutrophication criteria in the Portuguese Decree-Law n. º 149/2004, June 22 which transposes the standards of Urban Waste Water Treatment Directive- UWWTD (Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment). The UWWTD aims to protect the environment from the adverse effects of urban waste water discharges from certain industrial sectors requiring the collection and treatment of waste water in agglomerations with a population equivalent (p.e) over 2000, and more advanced treatment in agglomerations with a p.e. greater than 10000 in sensitive areas.

In a tentative of diminishing the anthropogenic pressures and improve the lagoon trophic state, Águas do Oeste, S.A (AdO), the entity responsible for water management in the west region of Portugal, implemented the UWWTD in the important ones basins (Arnóia/Real Rivers and Cal River). After September 2005 five WWTP (dots orange in Figure 1.7) were removed to a submarine outfall (Foz do Arelho submarine outfall). To achieve a better improvement in water quality the sewage treatment in the WTTP that were not connected to the sewage collector was improved.

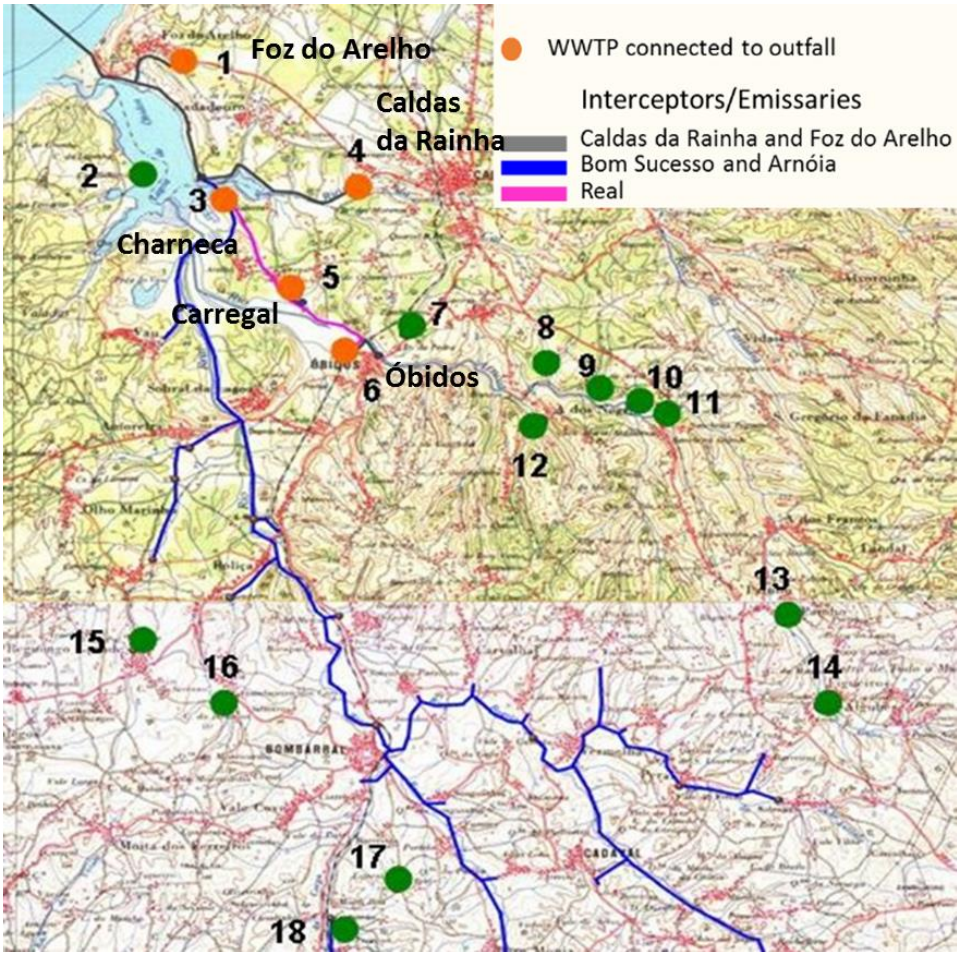


Figure 1.7. Spatial map of the wastewater treatment plants is also presented. In orange are marked the wastewater treatment plants connected to the outfall.

From the total of WWTP removed to the outfall three (Óbidos, Carregal and Charneca) are in the Arnóia/Real Rivers basin and two (Caldas da Rainha and Foz do Arelho) in Cal River basin. The removal of urban loads (Table 1.3) in major basin (Arnóia/Real) corresponded to 25% in terms of nitrogen and 18% of phosphorus. In the small basin, Cal River (4% of the total watershed area), the removal is drastic representing 97% of nitrogen and phosphorus. This reduction is mainly due to Caldas da Rainha WWTP since loads generated by Foz do Arelho WWTP are less 0.001% tons per year in terms of nitrogen/phosphorus.

Table 1.3. Nutrient loads in terms of phosphorus and nitrogen generated by WWTP in the Óbidos Lagoon watershed before and after September 2005. In Cal River basin the loads are mainly due to Caldas da Rainha WWTP since loads generated by Foz do Arelho WWTP are less 0.1 ton/year of nitrogen/phosphorus. The loads were calculated with the data from AdO.

River Basin	Before September 2005		After September 2005	
	Nitrogen (ton/year)	**Phosphorus (ton/year)**	**Nitrogen (ton/year)**	**Phosphorus (ton/year)**
Arnóia/Real	57	16	43	13
Cal	280	64	6	7
Total	**337**	**80**	**49**	**20**

To follow the evolution of water quality in lagoon before and after implementation of UWWTD an Environmental Monitoring Program- EMP (IST/IPIMAR, 2010) for the lagoon and Foz do Arelho coastal area was set-up. The EMP aims to: 1) evaluate the evolution of the water quality state within lagoon, 2) monitor the effects and of the marine outfall in adjacent coastal waters, and 3) access the adequacy of the implemented protective measures.

EMP of the Óbidos Lagoon was conducted from October 2004 till December 2009 with the financial support of AdO. The first year of monitoring aims to characterize the reference state of the lagoon and coastal area, before the loads deviation into the ocean. Continued monitoring of the lagoon intended to verify that protective measures have proved to be effective for the water management in the lagoon and eutrophic symptoms retrogress. At the same time, adjacent coastal areas were observed to assess the impact affecter shifting the outfall discharges in the ocean.

Environmental decision-making by the Portuguese water industry is therefore critical to the success of the adopted management strategies in the Óbidos Lagoon.

1.6. Methodology

The research approach combines field measurements (oceanographic and water quality data) with multidisciplinary numerical modelling (watershed and hydro-ecological). A detailed description of the models and data is described from Chapter II to VI, being provided here a brief summary to assist the reader.

1.6.1. Observational data

The observational data used in this study could be divided in oceanographic and water quality measurements.

The oceanographic data was collected during the ‘‘Monitorização Ambiental da Lagoa de Óbidos’’ Project (MAMBO), a contribution from the Portuguese Hydrographic Institute - IHPT (IHPT; 2001a,b; 2002a,b). The project commenced on October 24th, 2000 and lasted four months acquiring bathymetric surveys and measured oceanographic data (sea-level, currents, winds and waves). Sea level was measured between December 2000 and December 2002 at three stations (Figure 1.3 pink dots), one near the inlet (A) and two in the arms (D and E). Currents were measured near the inlet (A, Figure 1.3 orange squares) and along the northern channel (B, Figure 1.3 orange squares) during a tidal cycle on November 26th and 29th, 2000 and July 3rd and 6th, 2001. In the coastal area, the Acoustic Doppler Current Profiler-ADCP (Figure 1.3) measured the winds and waves from November to December 2000 and during May 2001.

The water quality data comes from EMP (IST/IPIMAR, 2010) of the Óbidos Lagoonactive from October 2004 to December 2009 (5-years period). The program combines two types of monitoring ensured that the data captured seasonal variability and diel cycles. Measured parameters in water column relevant for these research are nutrients (nitrate-NO3-, nitrite-NO2-, ammonia-NH4+ and phosphate-PO43-) and chlorophyll a. Surface sediments were collected to further determine physicochemical characteristics and metals (Aluminium-Al, Iron-Fe, Manganese-Mn and Lead-Pb)

Seasonal campaigns were performed in 4 stations within lagoon (A, C, D and E, Figure 1.3 pink dots): Station A is near the inlet and is representative of ocean conditions, Station B is located in central body in a zone with mixing of sea and freshwater, Station D in Barrosa arm and D in Bom Sucesso (problematic area). First year of monitoring is representative of the system before the removal of WWTP inputs to the lagoon. Samplings were performed on the surface (<0.4 m depth) and centered in low-tide (e.g., optimal conditions of riverine influence).

Diel cycles were carried out in summer (high temperatures and low flows) and winter (low temperatures and high flows) at two sites (R and E, Figure 1.3 pink dots) covering a complete 24-hours cycle. Site E is representative of eutrophic conditions and was surveyed on 19th and 20th September 2008 (summer) and 3rd and 4th December 2008 (winter). Site R is the reference station being surveyed in summer (winter campaign was not performed because significant variances were not expected). Water and sediment samples were collected at both sites.

1.6.2. Modelling system

An integrated modelling approach has been applied in the Óbidos Lagoon with a system centred in three main models (Figure 1.8): SWAT (Soil and Water Assessment Tool http://swat.tamu.edu/), MOHID (3D Water modelling system www.mohid.com) and STWAVE (STeady State spectral WAVE http://www.usace.army.mil/).

The final application of model system corresponded to an integration between land and lagoon, or in other words, a watershed model (SWAT) coupled to lagoon hydro-ecological (MOHID plus STWAVE) model. Basically, the hydrodynamic model simulates the mixing of waters in the lagoon; and the ecological model calculates the lagoon´s biogeochemical and physical dynamics considering the effect of pollution loads generated by the watershed model.

The first effort commenced with the application of the MOHID hydrodynamic module to the lagoon. The module was used to predict water level changes and currents variability by driving the hydrodynamics with a combination of tide, wind stress and atmospheric pressure; wave radiation stresses and rivers discharge. The predictive values of wave radiation stresses were simulated with STWAVE model.

A particle tracking Lagrangian module was coupled to a hydrodynamic module. Particle module allows the analysis of water masses dispersion, represented as passive particles, and therefore water renewal time's estimation.

Water properties evolution in the water column such as turbidity, cohesive sediments, nutrient levels, oxygen and phytoplankton are calculated with the transport information and biogeochemical cycles. The transport information is provided by hydrodynamic to water quality module. The processes modelled in water quality model result in the calculation of water properties assuming sources and sinks for each property; and biogeochemical cycles of carbon, nitrogen, phosphorus, silicon and oxygen. Meanwhile, the loads (nutrient and sediments) reaching the lagoon are provided with watershed model (SWAT), assuming as input data the soil, Corine Land Maps, NASA DEM (Digital Elevation Model) and weather. The rates of nutrient exchange between sediment and the overlying water column are handled in the benthic layer.

The models are feed and validated with the Observational data gathered for this work. Outcoming results were quantified with statistical metrics such as root mean square error (RMSE), correlation coefficient (R), Analysis of Variance (ANOVA) and Principal Component Analysis (PCAs). The major findings are published as scientific articles in Science Citation Index (SCI) journals (see Thesis outline).

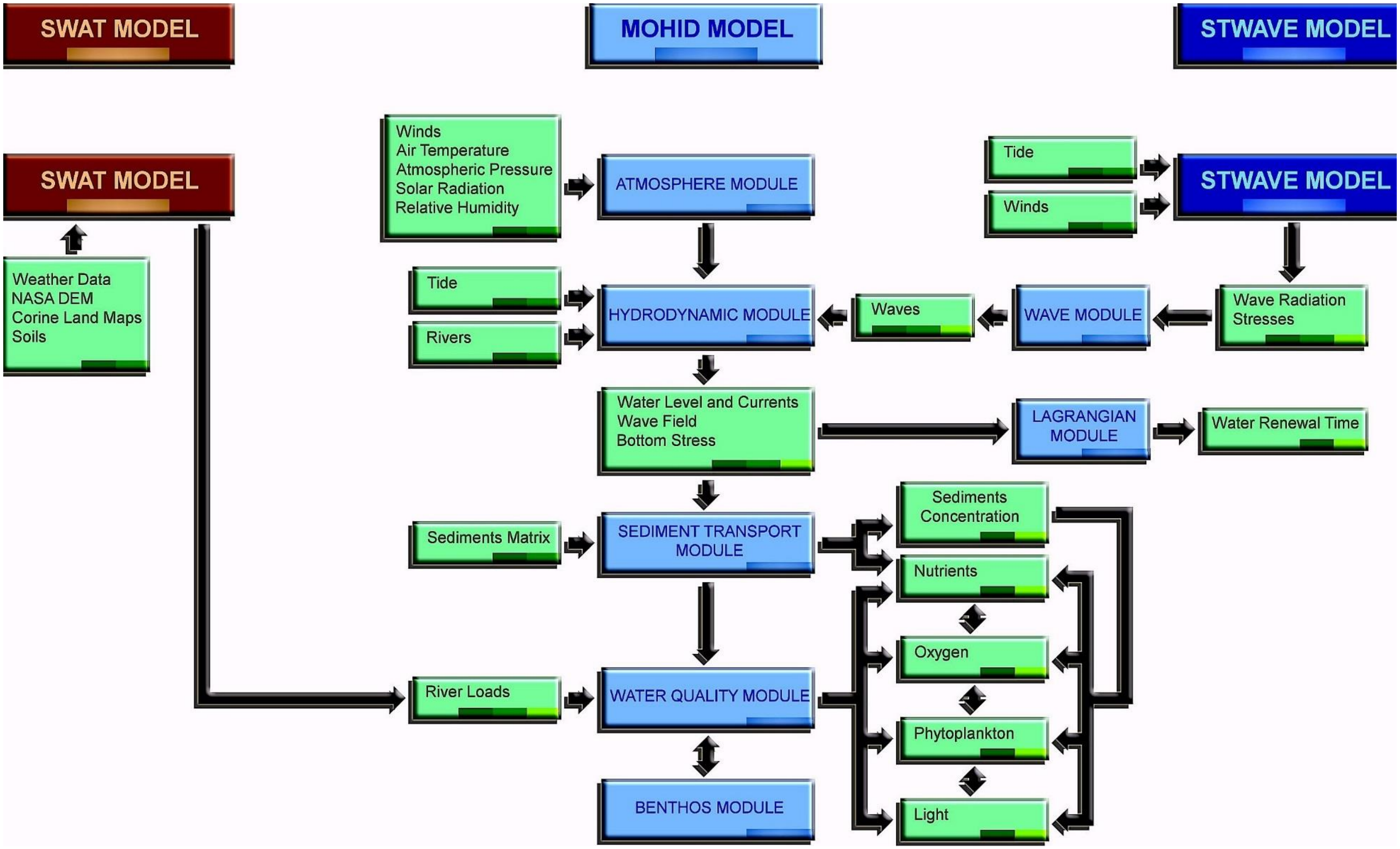


Figure 1.8. Scheme of the models used in the work.

1.6.1. Model configuration for the Óbidos Lagoon

The model configuration used in this study consists in a methodology of downscaling with two nesting levels (one domain for level) on-line coupled (Figure 1.9). A 2D depth-integrated model was used, because it was assumed that the study area presents a homogeneous water column, due to the shallow depth and minor fresh water inputs.

The first level includes the coast between Nazaré to Peniche (Figure 1.9a) and the second, the Óbidos coastal lagoon (Figure 1.9b). Bathymetry domains were rotated ~45º (see the North indicator, in Figure 1.9) in order to reduce the number of land points in the model area.

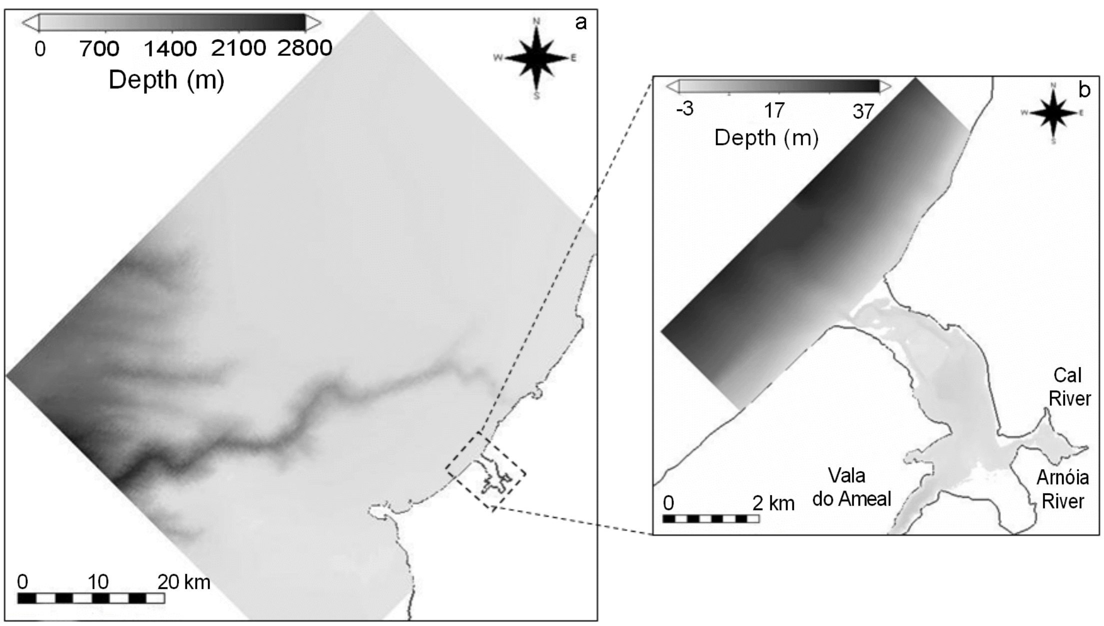


Figure 1.9. Domain bathymetry for the two-nested model implemented: (a) Nazaré-Peniche coast; and (b) Óbidos Lagoon. The freshwater fluxes are marked in the Óbidos Lagoon domain.

The first level has higher resolution nearshore (100 m) and approximately 200 m offshore. The total number of grid points is 346 by 250 cells. The model was forced through prescribed surface elevations from FES95.2 global tidal solution (Le Provost *et al.*, 1998) at the open boundaries in the Northeast, Northwest and Southwest (Figure 3.3a). This model domain solves the tide and propagates the boundary conditions to the second level.

The second level has a total number of grid points of 300 by 340 cells and horizontal resolution of 25 m to solve hydrodynamic and 75 m for ecological processes. The open boundary conditions were prescribed from the level one assuming the issues for the downscaling process described in Leitão *et al.* (2005).

Prescribed boundary conditions are open ocean boundary (tide, waves and sea-water biochemical concentrations), land boundary (river and WWTP discharges) and bottom boundary (grid/matrix of nutrients and sediments).

A wave model was coupled to the hydrodynamic model to account for the effect of waves on bottom shear stress. Wave conditions such as significant height (Hs), mean period (Tp) and wave direction were prescribed with the data gathered ADCP.

Reliable meteorological forcing variables such as wind, air temperature, solar radiation and precipitation from Óbidos meteorological station (http://www.inag.pt) were prescribed. Representative concentrations for nutrients, chlorophyll *a* and oxygen were also imposed at the ocean boundary (IST/IPIMAR, 2010). Rivers forcing (Arnóia/Real, Cal and Vala do Ameal) were done with SWAT model providing daily river flow and concentrations. Casalito WWTP discharge was defined using monthly flow and nutrient concentrations measured by AdO. Initial conditions were defined using a method of boxes and imposing annual average values from the monitoring programme (IST/IPIMAR, 2010). A grid/matrix of non-cohesive sediments and nutrients concentrations was generated also using data from monitoring programme and prescribed as bottom boundary condition.

1.7. Thesis outline

This study is comprised of seven chapters.

Chapter II discusses the numerical modelling framework developed to understand lagoon circulation including relevant physical forcing. This chapter is an article published in Continental Shelf Research;

Chapter III estimate the water renewal time in the lagoon including the integration of the hydrodynamic and Lagrangian model results. This chapter is an article published in Ocean Dynamics;

Chapter IV analyses the effect of promoting the inlet stability and dredging the channel in the lagoon circulation and water renewal time. This chapter is an article published in Journal of Coastal Research;

Chapter V examines the impact of protective actions in Lagoon water quality. Potential management scenarios are also analyzed with the lagoon model. This chapter is an article published in Hydrobiologia;

Chapter VI discusses supplementary analyses diel cycles in the eutrophic area of the lagoon both at summer and winter. This chapter is an article under review in Hydrobiologia; and

Chapter VII provides a general discussion of the findings, final conclusions and recommendations for further research.

1.8. References

Azzellino, A., M. Carpani, S. Çevirgen, C. Giupponi, P. Parati, F. Ragusa & R. Salvetti, 2013. Managing the nutrient loads of the Venice Lagoon Watershed: are the loads external to the watershed relevant under the WFD River Basin District framework? *Journal of Coastal Research* SI65: 25-30.

Carvalho, S., Moura, A., Gaspar, M. B., Pereira, P., Fonseca; L. C., Falcão, M., Drago, T., Leitão, F., Regala, J., 2005. Spatial and inter-annual variability of the macrobenthic communities within a coastal lagoon (Óbidos Lagoon) and its relationship with environmental parameters. *Acta Oecologica*, 27, pp. 143–159.

Carvalho, S., Gaspar, M. B., Moura, A., Vale, C., Antunes, P., Gil, O., Fonseca; L. C., Falcão, M., 2006. The use of the marine biotic index AMBI in the assessment ofthe ecological status of the Óbidos Lagoon (Portugal). *Marine Pollution Bulletin* 52, 1414–1424.

CLMP, 2012. Coastal Lagoons Management Plans. http://www.gosford.nsw.gov.au/

CLMP, 2014. Coastal Lagoons Management Plans. http://www.gosford.nsw.gov.au/

Cloern J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. *Mar Ecol. Prog. Series* 210: 235-265.

Dinis, J.L, Henriques, V., Freitas, M.C., Andrade, C., 2006. Natural to anthropogenic forcing in the Holocene evolution of three coastal lagoons (Caldas da Rainha valley, western Portugal). *Quaternary International*, 150: 41-51.

Duarte, P., B. Azevedo, M. Guerreiro, C. Ribeiro, R. Bandeira, A. Pereira, M. Falcao, D. Serpa & J. Reia, 2008. Biogeochemical modelling of Ria Formosa (South Portugal). *Hydrobiologia* 611:115-132 doi:DOI 10.1007/s10750-008-9464-3.

Ferreira, T., Ramos, R., Freitas, M.C. and Andrade C., 2009. Morphological evolution of the Óbidos lagoon (western coast of Portugal) since Holocene transgressive maximum. Journal of Coastal research, SI 56. Proceedings on the 10th International Coastal Symposium, 612-616. Lisbon, ISSN 0749-0258.

Fisher, M.M., Reddy, K.R. and James R.T., 2005. Internal Nutrient loads from Sediments in a Shallow, Subtropical Lake. *Lake and Reservoirs Management*, 21(3):338-349.

Gaertner-Mazouni N, De Wit R., 2012. Exploring new issues for coastal lagoons monitoring and management Estuarine, *Coastal and Shelf Science* 114:1-6.

Gikas, G. D., T. Yiannakopoulou & V. A. Tsihrintzis, 2006. Water quality trends in a coastal lagoon impacted by non-point source pollution after implementation of protective measures. *Hydrobiologia* 563:385-406 doi:DOI 10.1007/s10750-006-0034-2.

Giupponi, C., Azzelino, A., Salvetti, R., Parati, P., Carpani, M., 2012.Water Quality Assessment in the Venice Lagoon Watershed with Multiple Modelling Approaches. International Environmental Modelling and Software Society (iEMSs), International Congress on Environmental Modelling and Software, Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany, R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.) http://www.iemss.org/society/index.php/iemss-2012-proceedings.

Gönenç, I.E., Vadineanu, A., Wolflin, J.P., Russo, R.C., 2008. Sustainable Use and Development of Watersheds. Gönenç, I.E., Vadineanu, A., Wolflin, J.P., Russo (eds.). Springer Netherlands Publisher. Pp. 532. Doi: 10.1007/978-1-4020-8558-1.

IHPT, 2001a. *Monitorização Ambiental da Lagoa de Óbidos NOV 2000 – JUN 2001*. Relatório Técnico Final, Report TF. 08/ 2001 (in Portuguese).

IHPT, 2001b. *Monitorização Ambiental da Lagoa de Óbidos JUL 2001 – DEZ 2001*. Relatório Técnico Final, Report PT. OC. 06/2001 (in Portuguese).

IHPT, 2002a. *Monitorização Ambiental da Lagoa de Óbidos DEZ 2001 – ABR 2002*. Relatório Técnico Final, Report PT. OC. 02/2002 (in Portuguese).

IHPT, 2002b. *Monitorização Ambiental da Lagoa de Óbidos MAI 2002 – AGO 2002*. Relatório Técnico Final, Report PT. OC. 05/2002 (in Portuguese).

IST/IPIMAR, 2010. Variação sazonal e inter-annual da qualidade da água na Lagoa de Óbidos, seus afluentes e emissário submarino da Foz do Arelho. Relatório Final: Outubro 2004-Janeiro 2008 (in Portuguese). IST / IPIMAR, Lisboa.

Hilton J., O´Hare, M., Bowes, M.J., Jones, J.I., 2006. How green is my river? A new paradigm of eutrophication in rivers. *Sci Total Environ*., 365(1-3):66-83.

Leitão, P., Coelho; H., Santos, A., Neves, R., 2005. Modelling the main features of the Algarve coastal circulation during July 2004: A downscaling approach. *Journal of Atmospheric and Ocean Science*,10 (4), pp. 1-42.

Le Provost, C., Lyard, F., Molines, J. M., Genco, M. L., Rabilloud, F., 1998. A hydrodynamic ocean tide model improved by assimilating a satellite altimeter derived data set. *Journal of Geophysical Research-Oceans,* 103, pp. 5513-5529.

Kjerfve, B., 1994. Coastal Lagoons, chapter 1. In: Kjerfve, B. (ed.) Coastal lagoon processes. pp 1-8. Elsevier Oceanography Series, Amsterdam.

Kowalski, P.P., 2009. Combined use of chemical data and biomarkers in aquatic key species: an eco-toxicological study in Óbidos lagoon. Thesis in Biology for obtaining the degree of doctor of philosophy. Aveiro University, 284p., http://ria.ua.pt/bitstream/10773/957/1/2009001266.pdf.

Konstantinou, Z. I., Y. N. Krestenitis, D. Latinopoulos, K. Pagou, S. Galinou-Mitsoudi & Y. Savvidis, 2012. Aspects of Mussel-Farming Activity in Chalastra, Thermaikos Gulf, Greece: An Effort to Untie a Management Gordian Knot. Ecol Soc 17(1) doi:Doi 10.5751/Es-04455-170101.

Newton A et al., 2014. An overview of ecological status, vulnerability and future perspectives of European large shallow, semi-enclosed coastal systems, lagoons and transitional waters. *Estuarine, Coastal and Shelf Science* 140:95-122.

Newton A and Weichselgartner J., 2014. Hotspots of coastal vulnerability: A DPSIR analysis to find societal pathways and responses. *Estuarine, Coastal and Shelf Science* 140:123-133.

Oliveira, A., A. B. Fortunato & F. E. P. Sancho, 2005. Morphodynamic modeling of the Obidos lagoon. *Coastal Engineerin*g, Vols 1-4:2506-2518.

Oliveira, A., Fortunato, A.B. and Rego, J.R.L., 2006. Effect of morphological changes on the hydrodynamics and flushing properties of the Óbidos Lagoon (Portugal). *Continental Shelf Research*, 26, pp. 917-942.

Paerl, H.W., Nathan, S.H, Benjamin, L.P., Rossignol, L.K., 2014. Envolving Paradigms and Challenges in Estuarine and Coastal Eutrophication Dynamics in a Culturally and Climatically Stressed World. *Estuaries and Coasts*, 37:243–258 DOI 10.1007/s12237-014-9773-x.

Pereira, P., M. J. Botelho, M. T. Cabrita, C. Vale, M. T. Moita & C. Goncalves, 2012a. Winter-summer nutrient composition linkage to algae-produced toxins in shellfish at a eutrophic coastal lagoon (Obidos lagoon, Portugal). *Estuar Coast Shelf S* 112:61-72 doi:DOI 10.1016/j.ecss.2011.07.016.

Pereira, P., S. Carvalho, F. Pereira, H. de Pablo, M. B. Gaspar, M. Pacheco & C. Vale, 2012b. Environmental quality assessment combining sediment metal levels, biomarkers and macrobenthic communities: application to the Obidos coastal lagoon (Portugal). *Environ Monit Assess* 184(12):7141-51 doi:10.1007/s10661-011-2486-8.

Pereira, P., H. de Pablo, S. Carvalho, C. Vale & M. Pacheco, 2010. Daily availability of nutrients and metals in a eutrophic meso-tidal coastal lagoon (Obidos lagoon, Portugal). *Marine Pollution Bulletin* 60(10):1868-1872 doi:DOI 10.1016/j.marpolbul.2010.07.021.

Pereira, P., H. de Pablo, M. D. Subida, C. Vale & M. Pacheco, 2011. Bioaccumulation and biochemical markers in feral crab (Carcinus maenas) exposed to moderate environmental contamination--the impact of non-contamination-related variables. *Environmental toxicology* 26(5):524-40 doi:10.1002/tox.20641.

Pereira, P., H. de Pablo, C. Vale, V. Franco & M. Nogueira, 2009a. Spatial and seasonal variation of water quality in an impacted coastal lagoon (Óbidos Lagoon, Portugal). *Environ Monit Assess* 153(1-4):281-292 doi:DOI 10.1007/s10661-008-0355-x.

Pereira, P., H. de Pablo, C. Vale, F. Rosa-Santos & R. Cesario, 2009b. Metal and nutrient dynamics in a eutrophic coastal lagoon (Óbidos, Portugal): the importance of observations at different time scales. *Environ Monit Assess* 158(1-4):405-418 doi:DOI 10.1007/s10661-008-0593-y.

Scanes P, Coade G, Doherty M, Hill R., 2007. Evaluation of the utility of water quality based indicators of estuarine lagoon condition in NSW, Australia. *Estuarine Coastal and Shelf Science* 74:306-319.

Smith, L.G., 2009. Missisquoi Bay sediment phosphorus cycling: the role of organic phosphorus and seasonal redox fluctuations. MSc. Thesis, University of Vermont.

Smith, V.H., Tilman, G.D., and Nekola, J.C., 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, 100: 179-196.

Stemplewski J, Krull D, Wermter P, Nafo II, Palm N, Lange C., 2008. Integrative socio-economic planning of measures in the context of the Water Framework Directive. *Water Environ. J*. 22: 250 257.

Stybel, N., C. Fenske & G. Schernewski, 2009. Mussel Cultivation to Improve Water Quality in the Szczecin Lagoon. *Journal of Coastal Research*, 1459-1463.

Taylor, D., Nixon, S., Granger, S., Buckley, B., 2005. Nutrient limitation and the eutrophication of coastal lagoons. *Marine Ecology Progress Series*, 127:235-244.

Vão–Arquitectos Associados, 1991. *Estudo de Recuperação e Ordenamento da Lagoa de Óbidos, Concha de São Martinho do Porto e Orla Litoral Intermédia*. Vols. I, II and V (in Portugese).

2. Effect of coastal waves on sea level in Óbidos Lagoon, Portugal

Madalena S. Malhadas[a], Paulo C. Leitão[b], Adélio Silva[b], Ramiro Neves[a]

[a] *Instituto Superior Técnico, Depto. de Mecânica, Av. Rovisco Pais, 1049-001 Lisboa, Portugal*
[b] *Hidromod, Modelação em Engenharia, Lda., Av. Manuel da Maia, nº 36, 3º Esq., 1000-201 Lisboa, Portugal*

Published in: Continental Shelf Research 29 (2009) 1240–1250, **Impact Factor:** 2.183

Abstract

This study reports the role of waves, tide, wind and freshwater discharges over the sea level in Óbidos Lagoon, a coastal system connected to the sea through a narrow and shallow mobile inlet. To address the hydrodynamic features of this coastal system, the relative importance of different physical forcings were evaluated. For this purpose, observations together with realistic and idealized numerical modeling were used. Both model and measurements show that the lagoon sea level remains above offshore sea level during storm wave periods. Hence, a simplified inlet-lagoon idealized model was described through mathematical expressions, to understand and highlight the physical processes responsible for sea-level elevation.

In general, it can be concluded that multiple forcing conditions, specifically tide and waves, are important in defining the dynamics of the Óbidos Lagoon. The variability of the lagoon sea level is 80% due to tide and 20% due to waves. A correlation was found with wave height and sea-level elevation during high wave activity periods; no correlation was found for low wave activity. A significant super- elevation on lagoon sea level occurs during storm wave periods. Such super-elevation is explained, not only by wave set-up or radiation stresses due to waves, but also by tidal inlet morphology (mainly depth and length).

Keywords: MOHID, Hydrodynamic, Wave radiation stresses, Wave set-up, Tidal inlet morphology, Óbidos Lagoon

2.1. Introduction

Direct (wind) and indirect atmospheric (rain, through river flow) and marine (tide and waves) forces cause large differences and rapid changes in the physical and the chemical characteristics of coastal lagoons (Troussellier and Gattuso, 2007). These systems are typically shallow, fresher than near-ocean conditions and are separated by sand spits or barrier islands (Fortunato and Oliveira, 2007). The hydrodynamic behavior in these coastal systems is driven mainly by tide and waves. The presence of waves can cause large differences in terms of sea-level variations (Nielsen and Apelt, 2003); their relative importance depends upon the morphology of the lagoon entrance, as well as the local wave regime. In shallow and narrow entrances, the sea-level elevation caused by wave motion, such as wave breaking, is an important mechanism. This rise in sea level, or set-up, induced by waves is commonly termed as ‘‘wave set-up’’ (Angwenyi and Rydberg, 2005). The theoretical background of wave set-up was introduced by Longuet-Higgins and Stewart (1960, 1962, 1964), who related the effect to the concept of radiation stresses, due to the presence of waves. Basically, the radiation stress is defined as the excess of flow of momentum due to the presence of waves (Longuet- Higgins and Stewart, 1973). This original analysis established a relationship between the gradient of the radiation stresses for waves approaching the beach at an oblique angle, and the resulting of alongshore current (Nielsen and Apelt, 2003).

Factors governing the relative magnitude of wave set-up at tidal inlets and river entrances have been addressed by Guza and Thorton (1981), Hanslow and Nielsen (1992), Hanslow *et al*. (1996), Dunn *et al.* (2000), Dunn (2001), Oshiyama *et al.* (2001), Tanaka *et al.* (2000, 2003) and Nguyen *et al*. (2007). In the past Dunn (2001) explained a part of the ‘‘missing’’ or ‘‘lack’’ of set-up in the Brunswick River, Australia. The explanation was based upon the mechanism of wave height decay. Recently, Nguyen *et al*. (2007) showed that set-up, or sea-level elevation, depends not only upon offshore wave height but also on the different morphological river entrances or tidal inlets. These authors found a correlation between wave set-up height and water depth of the entrance, based upon data collected in seven different morphological river entrances and one inlet.

They showed that the wave set-up height is inversely proportional to the average water depth, at a river or inlet entrance.

In most cases, the estimation of wave set-up at entrances was based upon only observations. Numerical models, on the other hand, provide an approach to the study of the importance of simulating effect of waves or other external forces (e.g., winds) upon the hydrodynamic behaviour. In addition, hydrodynamic model applications are useful in understanding the main physical processes, since the complete field data sets is, however, hard to obtain.

The main purpose of this study is to evaluate the dominating driving forces on sea-level rise (SLR) in the Óbidos Lagoon, a coastal system located on the western Portuguese coast (Figure 2.1), connected to the sea through a narrow, shallow and mobile inlet. Fluctuations in lagoon sea level (LSL), under distinct physical forcing, are analysed: (i) tide; (ii) tide and wind; (iii) tide and freshwater river discharges; and (iv) tide and waves. To achieve the main objective, field measurements and numerical modelling were used, in addition to an idealized inlet-lagoon model. Field data are useful to develop an understanding of the hydrodynamic features of the coastal system and numerical model validation. The results show a rise in the LSL, during storm wave periods. This SLR can be attributed not only to wave-induced effects but also to the inlet morphology (depth and length). This contribution is arranged as follows. Section 2 describes the study area, field sites and measurements obtained in the coastal area and in the lagoon; it introduces also the numerical model. Section 3 presents an analysis of the observations and numerical simulations, together with the inlet-lagoon idealized model. Finally, the major findings are summarized in Section 4.

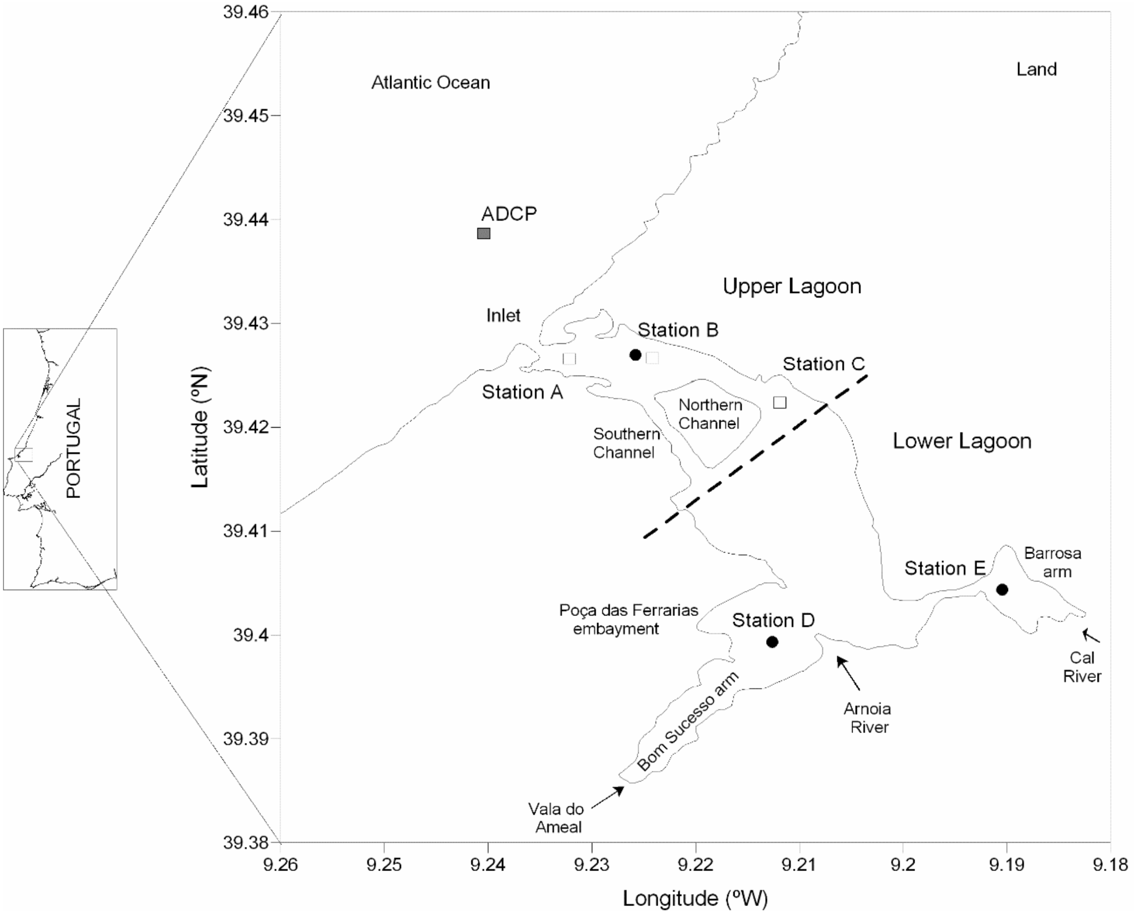


Figure 2.1. Geographical location of the Óbidos Lagoon. Tidal gauges (•), current measurement stations (□); and river discharges are represented also in the Figure, as well the main basins.

2.2. Material and methods

This analysis combines field data and numerical model predictions. Initially, bathymetric and sea-level data were used as a preliminary assessment, of the morphological and the hydrodynamic characteristics of the lagoon. These data were used then to validate the hydrodynamic numerical model. Subsequently, the hydrodynamic model was used to simulate the LSL, under several physical forcings. The following sub-sections describe the study area and summarize the characteristics of the field data and the model set-up.

2.2.1. Description of the system

The Óbidos Lagoon is a small and shallow coastal lagoon with a surface area of 7 km^2 and 2 m average depth (Vão, 1991). The Óbidos Lagoon consists of two regions, with distinct morphological hydrodynamic characteristics (Figure 2.1): the lower and the upper lagoon. The lower lagoon, connected to the Atlantic Ocean, is composed of several channels (Carvalho *et al.*, 2006). The water velocities in this region often exceed $1ms^{-1}$ along the northern channel and about $1.6ms^{-1}$ in the inlet (Malhadas, 2008). The upper lagoon consists of a shallow basin, elongated arms (Barrosa and Bom Sucesso) and a small embayment in the south (Poça das Ferrarias, Oliveira *et al.*, 2006). Because the velocities are weaker (0.4 ms^{-1} in the arms, Malhadas, 2008), sediments originating from various tributaries tend to settle out in this part of the lagoon (Fortunato and Oliveira, 2007). Freshwater inflow enters the lagoon at both arms: the Cal River at the Barrosa arm and Vala do Ameal at the Bom Sucesso arm. The Arnóia River discharge, between the lagoon arms, contributes about 90% of freshwater fluxes into the lagoon. The river is the major source of sediments, whose deposition has created an extensive sand bank.

This shallow lagoon is characterized by semi-diurnal tides (tidal range 0.5-4.0 m depending upon location and tidal phase) enabling important water exchanges to take place with the coastal waters. These are estimated at $6x10^6m^3$ for an average neap tide and 10^7m^3 for a spring tide (Santos *et al.*, 2006). Overall, freshwater input plays a minor role, with average flow rates of the order of $3m^3s^{-1}$; this is less than 5% of the average tidal prism, scaled by the M2 period (Rego, 2004). The influence of the tide extends throughout the entire lagoon, without pronounced longitudinal variation in salinity or stratification (Carvalho *et al.*, 2005). Salinity from the upper to the lower lagoon varies from 34 to36 (Santos *et al*., 2006).

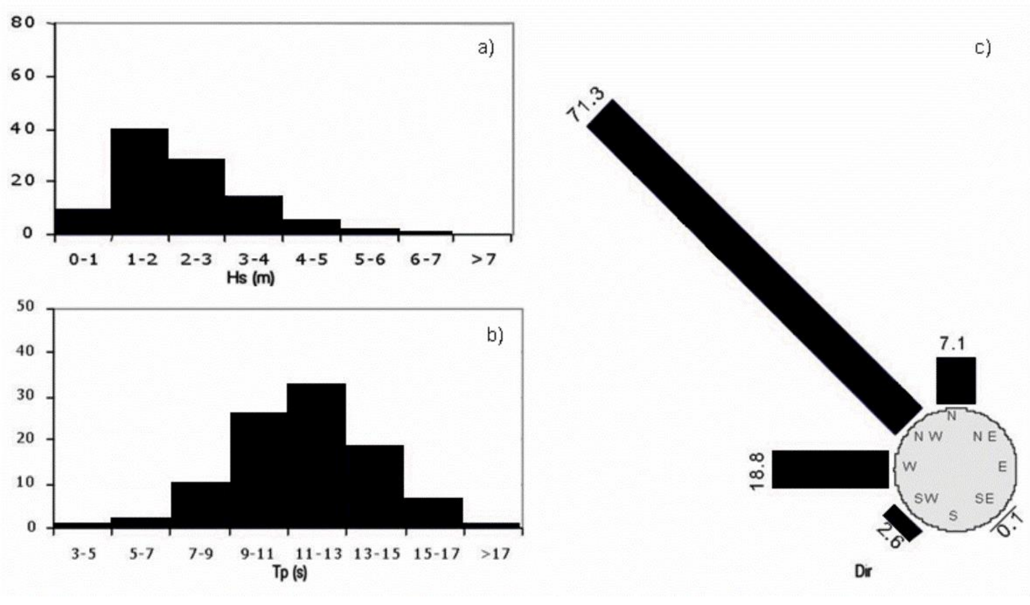


Figure 2.2. Typical wave climate in the western Portuguese coast: (a) wave height (Hs, m); (b) wave period (Tp, s); and (c) wave direction (Dr, degrees from North - clockwise) (adapted from Costa *et al*., 2001).

As within many other shallow coastal systems, friction play an important role in the dynamics of the lagoon; thus, in turn, leads to the establishment of flood dominance. Within this type of asymmetry, the ebb phase lasts longer than the flood phase, resulting in stronger currents during the flood phase (Stanev *et al*., 2007).

The offshore wave climate along the western Portuguese coast (Costa *et al.*, 2001) is characterized commonly by wave heights (Hs) within the range 1–2 m (40% of the records), whilst 22% of the observed values exceed 3 m (Figure 2.2). In terms of wave peak periods (Tp), it was observed that 60% of the values were between 9 and 13 s. Wave direction observations showed that 90% of the incoming waves were originating from the West (W) and Norwest (NW) sectors. Waves generate an alongshore southward current (e.g., littoral drift), which promotes the inflow of marine sands into the inlet and suspend sediments; this affects significantly the hydrodynamic within the lagoon.

2.2.2. Bathymetric and oceanographic data

The oceanographic data available for this particular study were collected during the‘‘Monitorização Ambiental da Lagoa de Óbidos’’ Project (MAMBO), a contribution from the Portuguese Hydrographic Institute - IHPT (IHPT; 2001a,b; 2002a,b). The data available included bathymetric surveys, sea-level time-series, currents, wind and wave data.

The project commenced on October 24th, 2000 and lasted for months. The monitoring program incorporated: automatic tidal gauges and current measurements obtained with an Acoustic Doppler Current Profiler (ADCP,RDIWORKHORSE1200kHz) inside the Óbidos Lagoon; an ADCP, with module WAVES in the coastal area (RDIWORKHORSE600kHz); meteorological automatic station (ANDERAAAWS2700) and set to collect the bathymetric data with an acoustic sensor. Sea level was measured, between December 2000 and December 2002, at three stations within the lagoon: one located near the inlet (Station B); and two located within the arms (D and E, station locations in Figure 2.1). Currents were measured near the inlet (Station A) and along the northern channel (Station B and C) during a tidal cycle on November 26th and

29th, 2000 and July 3rd and 6th, 2001. In the coastal area, the ADCP (within 20m water depth) measured the waves from November to December, 2000 and during May 2001.

All of the data were sampled at 10 min intervals, except for the wave height and wind, which were recorded every hour.

2.2.3. Hydrodynamic model

The numerical model used in this study was MOHID (Martins *et al.*, 2001), a three-dimensional finite volume model. The MOHID hydrodynamic model was used to achieve an accurate characterization of the flow regime in the study area, because it has the ability to simulate flow over complex bathymetry in shallow coastal systems (Vaz *et al*., 2007). The hydrodynamic equations of MOHID model and the down-scaling methodology have been described by Leitão *et al*. (2005). Here, we present only the implementation of the Óbidos Lagoon predictive model.

The configuration applied to the Óbidos coastal lagoon included two levels of nested models, with one-way coupling (Figure 2.3). To reduce the number of land points in the model area, we rotated the region ~45º (see the North indicator, in Figure 2.3).

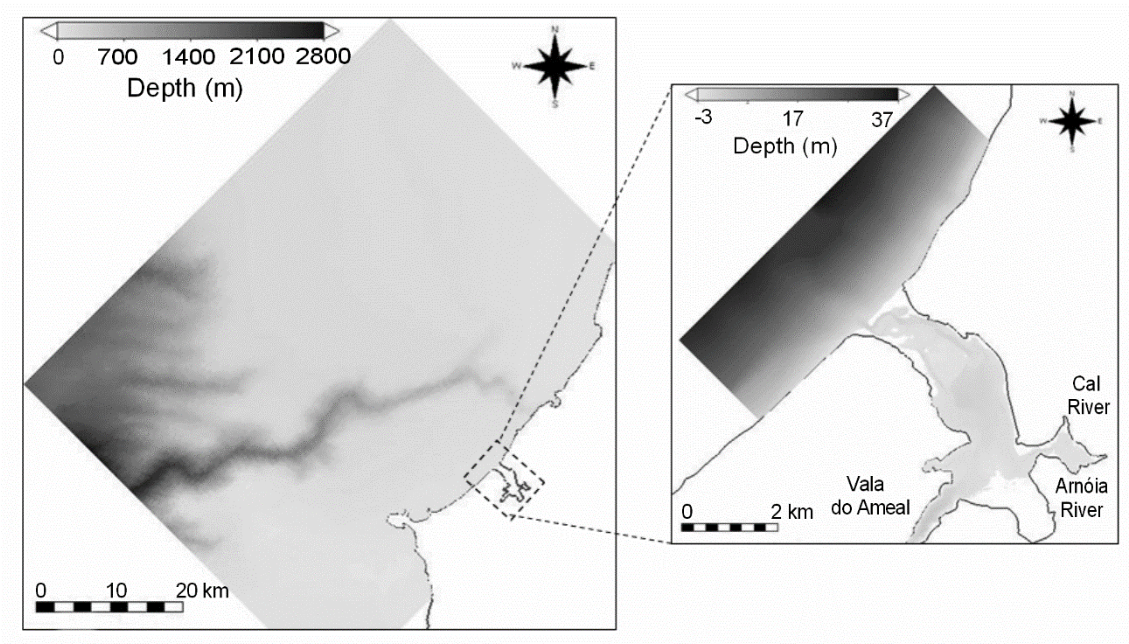


Figure 2.3. Domain bathymetry for the two-nested model implemented: (a) Nazaré - Peniche coast and (b) Óbidos Lagoon. The fresh water fluxes are marked in the Óbidos Lagoon domain.

The first level covers the coast between Nazaré and Peniche (between 39.1ºN and 39.8ºN). The grid spacing is less than 100 m near shore and approximately 200 m offshore. The total number of grid points is 346 by 250 cells. The model was forced, through prescribed surface elevations from FES95.2 global tidal solution (Le Provost *et al*., 1998) at the open boundaries in the Northeast, North west and Southwest (Figure 2.3a). The meteorological data used in the atmospheric forcing was obtained from the MAMBO project automatic station and was concurrent with the simulated period. The meteorological data used were wind speed (ms^{-1}) and direction (degrees from North, clockwise). The time step was 10 s and the horizontal eddy viscosity was 10 m^2s^{-1}. The model was initialized with 'null-free' surface gradients and zero velocities at all of the grid points. A bottom roughness (Manning) coefficient of 0.022 was adopted.

The second level included the Óbidos Lagoon and the transition zone between coastal waters. The total number of grid points is 300 by 340 cells, with a constant grid spacing of about 25 m. The solution of level one was downscaled, to this level. Freshwater fluxes from river run off were specified at three locations within the Óbidos Lagoon model, at constant rates for each of the three small rivers: Arnóia, Cal and Vala do Ameal (Figure 2.3b). These data, typical of winter and summer months, are described in more detail in Section 2.5. The time step was sand the horizontal eddy viscosity was 2 m^2 s^{-1}.

A 2D depth-integrated model was used, because it was assumed that the study area presents an homogeneous water column, due to the shallow depth and minor fresh water inputs.

2.2.4. Wave model

To simulate the wave propagation, the Steady-State spectral Wave model (STWAVE), developed by the US Army Corps of Engineers (Smith *et al*., 1998, 2001) was used. STWAVE simulates depth-induced wave refraction and shoaling and it includes additional effects such as current interaction, wave breaking, diffraction (simplified approach), wave–wave interaction and white-capping. The STWAVE model is based up on the assumption that relative phases of the spectral components are random and, thus, phase information, is not tracked (e.g., it is a phase-averaged model).

Wave radiation stresses were calculated with the wave propagation model, which assume the wave's effect over the currents. Since the opposite (current effects over the waves) was not considered, the sea level was simulated assuming 1 m sea- level classes. This meant that for each wave condition, simulations were performed from the hydrographic up 0 to 5 m above the maximum possible tidal level. Afterwards, it was considered acceptable to interpolate wave radiation stresses within the sea- level range of each meter. The contribution of waves to bed roughness was considered also in the model simulations.

For the bottom shear stresses it was considered that total roughness is provided by the sum of the components associated with current and waves. Wave roughness was considered to be the maximum of the 3*D90 value (the sieve size for which 90% of the grains by weight are smaller; It provides an estimate of the largest sand grains present in a sample) and an estimation based on the bed forms (ripple sand dunes), following the approaches proposed by Van Rijn (1989).

Boundary wave conditions used Hs, Tp and average direction derived from the ADCP (see location, in Figure 2.1). To make the number of wave simulations feasible, the wave record was split into classes of Hs, Tp and direction, using the criteria of approaching: the Hs for the next half meter; the Tp to the closest second; and the direction to the limit of each 25º interval. As such, 27 different off shore wave conditions were adopted. The theoretical JONWASP spectrum was applied at the model boundary. This approach allowed the simulation of a wave sequence, similar to that recorded by the ADCP, using a limited number of wave conditions.

2.2.5. Simulations

Hydrodynamic simulations were set-up for different physical forcings, representative of distinct situations: (i) tide; (ii) tide and wind; (iii) tide and fresh water river discharges; and (iv) tide and waves. Tidal forcing was considered throughout the model simulations. Others, such as wind, fresh water discharges and waves were used as additional forcing, to highlight the lagoon hydrodynamics. Fresh water flux values are typical of a wet and dry year. The values used for the dry year were 0.1 and 1.6 m^3s^{-1} for Cal and Arnóia River, respectively; and 0.04 m^3s^{-1} for Vala do Ameal (Vão, 1991). The values for the wet year were 0.5 m^3s^{-1} for the Cal River, 5.7 m^3 s^{-1} for the Arnóia River and 0.2 m^3s^{-1} for Vala do Ameal (Vão, 1991). The model was run for the time period between November 1st and December 30th, 2000. The first 15 days of results were considered as a 'spin-up' period; these were not included in the results.

2.3. Results and discussion

The consistency between the simulations and the observations (LSL and currents) were analysed, at the location of measurements carried out in the Óbidos Lagoon (see Figure 2.1, for locations). Results of the inlet-lagoon idealized model were also analysed, together with numerical model simulations, to provide a better comprehension of the coastal system.

2.3.1. Lagoon sea level

Figure 2.4 depicts the observations and simulations of LSL at Station B (near the inlet), wind data and observed and simulated coastal waves, for the period where the wave height increases slightly. This extends from November 24th, through to December 18th, 2000. The LSL was obtained considering tidal forcing alone (Figure 2.4a). The agreement between the simulations and observations is least effective between December 1st and 12th, 2000. During this period, the predicted sea levels do not agree with the measurements because an ‘‘abnormal’’ rise occurs. This behaviour is detected also at the other stations inside the lagoon (Station D and E). This is an important result, because it indicates that other relevant physical forcings should be considered, to explain noticeable variations in LSL. Hence, when we analyse the LSL data (a low-pass filter was used to remove the influence of high- frequency processes in measurements), we discovered that tide explains 80% of the variability.

To provide a better idea about how other physical forcing affects the LSL, additional simulations were performed, which introduced forces from wind and freshwater river runoff. Comparisons between these effects and the tidal forcing do not show any significant differences in amplitude. According to other case studies, the sea-level rise caused by river flood occurs only for discharges above 120 m^3s^{-1}, as observed in the Natsui River, Japan (Nguyen *et al.*,2007). Here, freshwater fluxes are less than 10 m^3s^{-1} during a period of heavy rain, whilst average fluxes lie close to 3 m^3s^{-1}. By observing the wave data and the STWAVE model simulations, it appears that increases in LSL occur often at the same time as a peak in the wave height during a storm, then the sea-level elevation (Figure 2.4a and c). The dominant period (wave height values within the range 3–7 m) occurs in the first 10 days of December 2000 and is concurrent with strong winds (of more than 10 ms^{-1}, see Figure 2.4 b). These intense waves are generated by local winds (sea or wind waves).

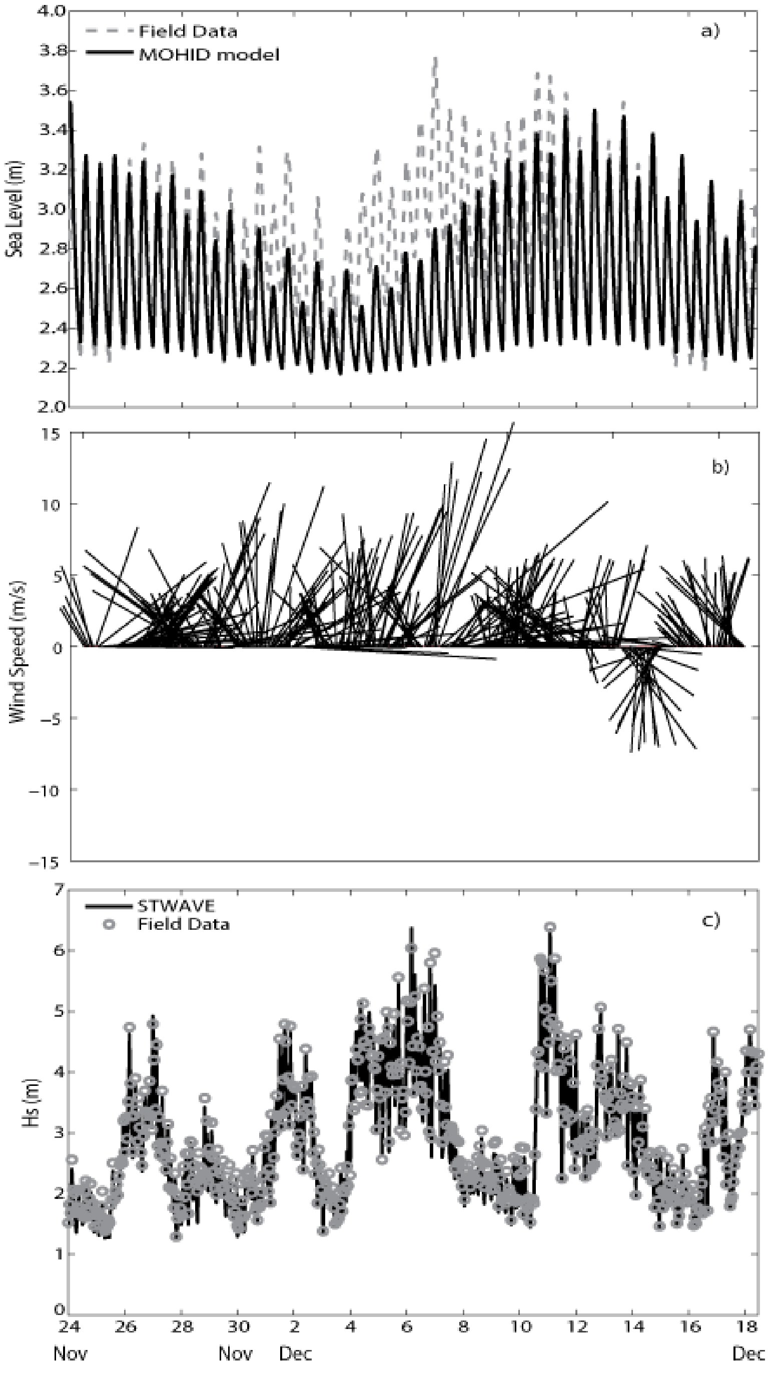


Figure 2.4. Comparison between modelled and observed sea-level time-series, at Station B. The simulation period is from November 24th to December 18th, 2000 and includes the forcing due to tide only. Wind data and waves (observations and simulations) are also represented for the same period.

To analyze the consistency of these events, we performed comparisons not only for the period of our model simulations, but also for two other periods, including: high wave activity (Hs greater than 3 m) or storm waves (November 28th to December 10th, 2000) and low wave activity (May 11th - 23rd, 2001). A correlation was found with wave height and sea-level elevation, during high wave activity periods; no correlation was found for low wave activity. This statement is justified from Figure 2.5 which provides simulated and observed LSL for the two periods mentioned above. For both periods, two hydrodynamic model simulations were performed. Wave forcing was not applied in the first simulation (Figure 2.5a and b), but it was applied in the second (Figure 2.5c and d).

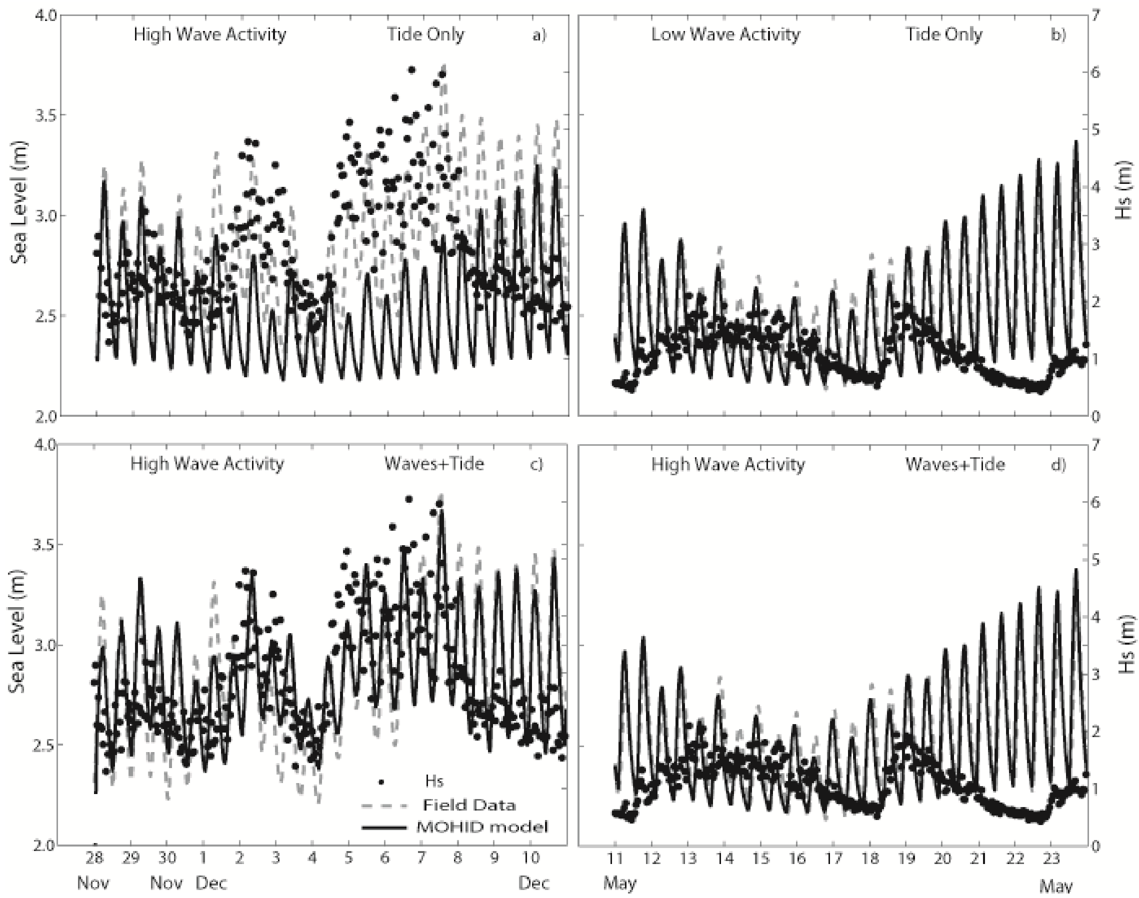


Figure 2.5. Lagoon sea level predicted by the model and their comparison with measurements for tidal forcing during high wave (a) and low wave (b) activity periods. The wave-induced forcing for high and low wave activity periods are represented in (c) and (d), respectively. The wave height is represented too.

Model results from both simulations and wave scenarios show that the model (physic) reproduces the tide and wave forcing, in such a way that simulation and observations agree reasonably well. Not only the general characteristic of the LSL variability is well reproduced by the model, but also the SLR related to wave-induced period, which occurs from November 28th to December 10th, 2000(Figure 2.5c). At the time of SLR occurrence, the wave height is equal to 3 m. Subsequently, SLR increases (~1 m in amplitude) together with wave height (reaching 6 m).This kind of response is not observed for low wave activity, because its impact on LSL is negligible (Figure 2.5d). This suggests that SLR in the Óbidos Lagoon is influenced by wave motion, such as wave breaking at the entrance, during high wave activity periods. These episodes of storm waves can affect the LSL by about 20%, whereas 1% is affected during low wave activity periods.

The coherence between the two model-sets, in terms of Root Mean Square Error (RMSE), correlation coefficient (r) and model performance (skill), are presented in Table 2.1. The RMSE errors are discussed as a percentage of the field data mean value. In general, the highest disagreement was found for tidal forcing during high waves activity, with a RMSE around 36% of the field data mean value. Such an error (RMSE = 1.0 m) might be expected, because tidal forcing includes only the signal of the tide, excluding the wave motion. Minor errors (RMSE = 0.10m) were obtained when additional wave forcing was included in the model set-up. In this case, the RMSE is ~6%. A strong correlation (r = 0.90), between model predictions and observed data, was obtained also for tidal and wave forcing, whereas a weaker correlation (0.77) was obtained for tidal forcing. This difference suggests that the model was able to capture well the relative differences between both forcing conditions, demonstrating the importance of waves on the LSL fluctuations. An improved index of agreement (0.94) was found for tidal and wave forcing, which means that the model tends to reproduce, more appropriately, the mean tendency in the field data.

For the period with low wave activity, the disagreement between the computed and observed sea levels, in both cases is small, with the RMSE values lower than 4%. As expected, r was maintained in both cases (0.92).This is evident from the fact that, during low-wave energy fluxes, there are no significance changes in sea-level elevation. The skill index presents a broad interval of 0.90 - 0.99 (within perfect agreement yielding a skill of 1.0), indicating that the model shows good accuracy. It may be concluded that the dominant forcing on the hydrodynamic features of the Óbidos Lagoon is tidal forcing. However, to obtain a more realistic representation of the system, it is important to include the wave motion, coupled to the tidal signal.

Table 2.1. Correlation coefficient, root mean square error and skill between measurements and model predictions, for both simulations: high wave activity and low wave activity.

	High wave activity		Low wave activity	
	Tide	Tide+Waves	Tide	Tide+Waves
r	0.77	0.90	0.92	0.92
RMSE (m)	1.0	0.10	0.15	0.15
Skill	0.68	0.94	0.99	0.90

2.3.2. Ocean sea level

The sea level inside the coastal lagoon was analysed through various physical forcings and quantitative approaches, to under- stand the variability introduced by storm waves, during certain periods. However, it is important to understand if the same variability occurs in the ocean sea level (OSL). Figure 2.6a, b presents the OSL and the LSL at Station B (lower lagoon) and Station E (upper lagoon), which extends from December 3rd to 10th, 2000 (high wave activity) and from May 14th to 21th, 2001 (low wave activity), respectively. The wave energy flux (E_f) derived from the Hs, Tp and wave direction data, is also shown. As shown by the data, LSL with wave forcing (period of high wave activity) is above that of the ocean recorder (see Figure 2.6a). The same behaviour was not related by the data provided during low wave activity periods, which shows the LSL at the same level as the OSL (Figure 2.6b). This behaviour reveals that LSL increases with increasing E_f and is higher than the OSL. It appears that E_f is responsible for the LSL rise (Figure 2.6a).

A similar behaviour was observed in Manihikiand Rakahanga atolls of the Cook Islands in South Pacific Ocean, where the average of the LSL increases significantly during large wave periods (Callaghan *et al*., 2006). It has been shown that LSL is above the OSL for certain wave periods, but there are some questions to be answered. The following section provides a simplified inlet-lagoon idealized model, to understand the major dynamic controls on the coastal system.

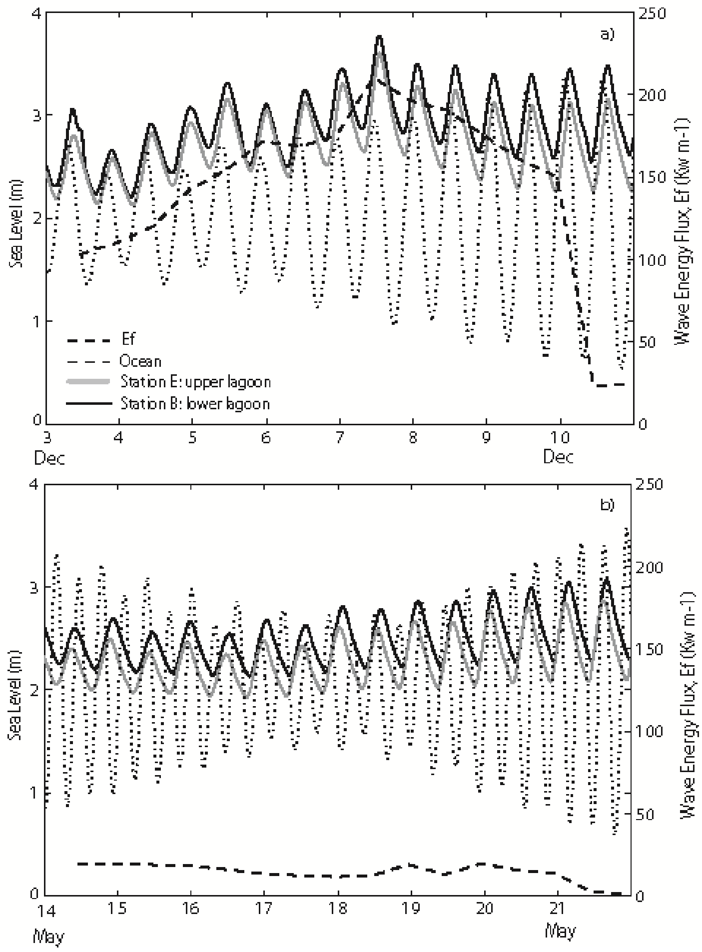


Figure 2.6. Measured ocean and lagoon sea levels at Station B (lower lagoon) and Station E (upper lagoon), from December 3rd to 10th, 2000 (a) and May 14th to 10th, 2001 (b). Averaged wave energy flux derived from wave data (wave height, period and direction) is presented also.

2.3.3. Simplified inlet-lagoon model

Numerical models are complex and involve long computation calculus, because they deal with many variables and parameterizations. For this reason, relatively simple analytical expressions of an inlet-lagoon idealized model were derived to understand the role of the wave radiation stresses in the super-elevation, or wave set-up, of the LSL. A simple inlet-lagoon idealized model, based upon mathematical expressions is prescribed considering the configuration depicted in Figure 2.7.

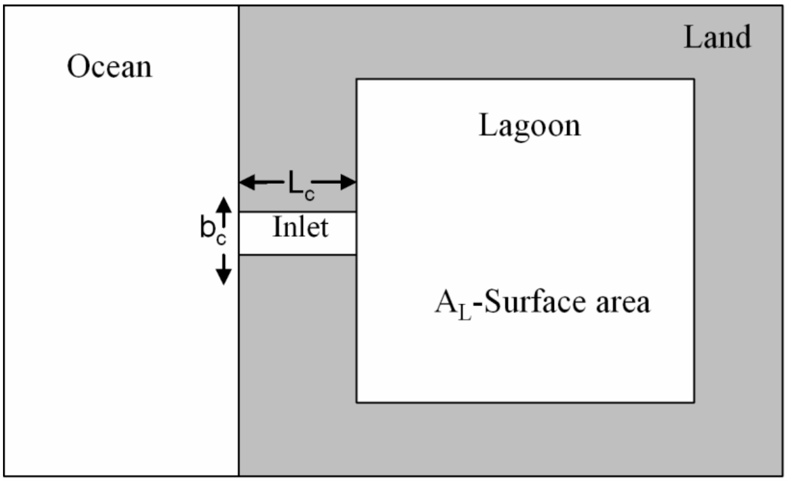


Figure 2.7. Schematic representation of the inlet-lagoon system.

A simple inlet-lagoon model is now developed, implemented easily on a spread sheet, to predict the lagoon dynamics under different physical forcings. The simple inlet-lagoon model can be described by the following system of equations. Considering conservation of water volume for the system, when assuming the lagoon fluctuations uniformly over its horizontal area, the LSL can be expressed by

$$\eta_L(t+\Delta t)=\eta_L(t)+\Delta t\,\frac{Q_c(t+\Delta t)}{A_L} \qquad (1)$$

Where A_L and η_L are the area and the sea level of the lagoon, respectively (the index "*L*" stands for "lagoon"), t is the time, Δt is the time step and Q_c is the total rate of inflow at the inlet (or channel, "c" stands for "channel"). The evolution of inlet flow is presented in the form of Eq. (2), which is based upon a transport equation that considers the pressure gradient, bottom friction and wave radiation stresses.

$$Q_c(t+\Delta t)=Q_c(t)+\Delta t\left(g\,\frac{\eta_o-\eta_L}{L_c}A_c(t)-C_d\,\frac{Q_c(t)Q_c(t)}{A_c(t)^2}b_c+R_S\cdot b_c\right) \qquad (2)$$

where η_0 is the ocean sea level, A_c , L_c and b_c the cross-sectional area of the inlet and its length and width, R_s is the radiation stresses along the waves and C_d is the drag coefficient. The OSL is prescribed as

$$\eta_o=a\cos(\omega t) \qquad (3)$$

where a is the tidal amplitude and ω is the tidal angular frequency. The drag coefficient is given by a Manning formula (Chow, 1973),

$$C_d = gn^2 h_c^{-1/3} \qquad (4)$$

where g is the acceleration due to gravity (g ~10 ms^{-2}), n is the Manning coefficient and h_c is the inlet depth. The cross-sectional area of the inlet is given by

$$A_c(t) = b_c \cdot \left(h_c + \frac{\eta_L + \eta_o}{2} \right) \qquad (5)$$

where b_c and h_c is the inlet width and depth, respectively, η_0 is the ocean sea level and η_L is the sea level in the lagoon.

In order to investigate the effect of wave radiation stresses on the SLR, an inlet-lagoon simplified model of the Óbidos Lagoon was applied. This adopted a lagoon horizontal area of about 7.0x10^6 m^2, an inlet of 100 m in length, 1 m depth and 25 m width. The value of R_s (0.10 m^2s^{-2}) was obtained through the STWAVE model. This value was calculated based upon the linear wave theory for shallow water-waves (Smith *et al.*, 2001). The data provided for the model calculations were Hs, Tp and direction. The results are shown in Figure 2.8a, for two cases, with and without R_s forcing. This distinction is important because, under the two different situations, the physical balances differ substantially. The dark grey curve shown in Figure 2.8a, demonstrates super-elevation in the LSL above the OSL (black dashed curve), in the case of the R_s. The impact of wave radiation stresses on sea level in the lagoon is controlled by wave pumping inflow in the inlet. As a result, an increase in the LSL occurs above the OSL. This means that the sea level increases to maintain the pressure gradient and friction equilibrium.

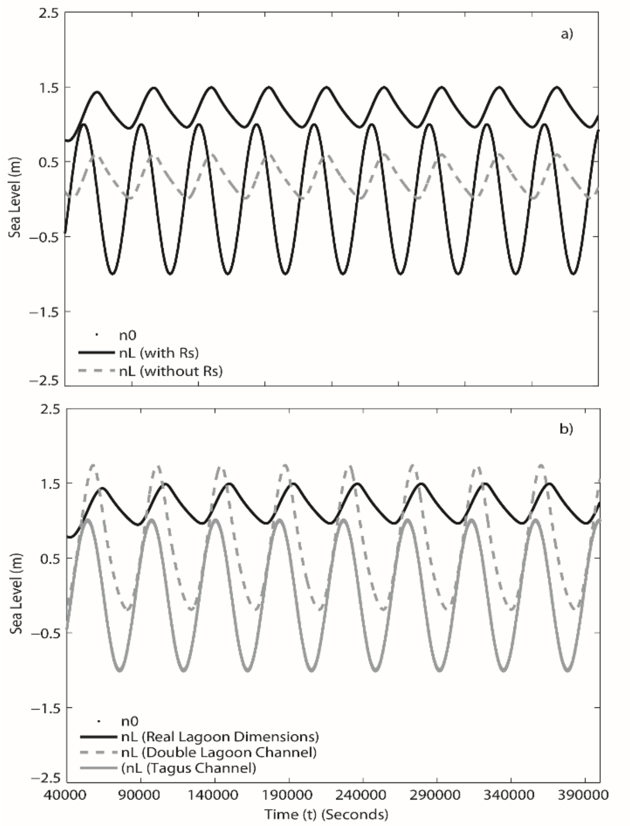


Figure 2.8. Lagoon and ocean sea level predicted using the simplified inlet-lagoon model, for the case with and without waves forcing (a); and with waves forcing for different channel cases: real lagoon dimensions, a channel with double of dimensions of the real one and the Tagus estuary channel (b).

At this phase, it is clear that wave radiation stresses are relevant to the pumping of water inside the lagoon; however, what is the role of the inlet? If an inlet cross-sectional area is assumed which is that double of the real inlet and the channel ($1.2x10^4$ m length, 30 m depth and 2000 m width) of the Tagus Estuary (the largest estuary in Portugal, located near Lisbon), we obtain the light gray curve and the dark curve shown in Figure 2.8b, respectively. In this case, the super-elevation in the lagoon tends to diminish and within the estuary, the sea level remains over that of the ocean curve (black dashed). This kind of response is due to the fact that the export of water through the inlet depends upon the relationship between the capacity of the cross-sectional inlet area (A_c) and the volume of the lagoon ($A_L \times h_L$). This difference is well illustrated when comparing the Tagus Estuary, mean volume ~$3x10^9$ m^3 and the cross-sectional channel area ~$6x10^4$ m^2, with the lagoon mean volume ~$1.4x10^7$ m^3 and the inlet area ~25 m^2. Similar conclusions were reached by Stanev *et al.* (2003a), in terms of the response of tidal basins to ocean forcing. It has demonstrated that the import and export of water through the inlet depends upon the ratio between the maximum storage capacity of the basin and the amount of water permanently stored within it. In fact, the adjustment of the sea surface in the bay, to oscillations in the open sea is controlled by the ratio between the cross-sectional area of the inlet and the area of the bay.

2.3.3.1. Simplified inlet-lagoon model

The idealized model described here is similar that prescribed for the narrow tidal inlets of the East Frisian Wadden Sea, adding the effect of wave radiation stresses. Our simplified inlet-lagoon model indicates that the dominant balance is between waves, pressure forces and friction (Eq. 6). In comparison, according to the idealised model described by Stanev *et al.* (2003a), the major response is between the pressure forces and friction. In addition, Stanev *et al.* (2003b) considered also the channel area (A_c), constant over time, and a linear friction dissipation term. These simplifications were introduced, by the authors, in order to derive an analytical solution to the inlet-lagoon model. In the present study, an analytical solution of Eq. (9) is proposed, which includes the effect due to wave radiation stresses.

$$\frac{dQ}{dt} = g\,\frac{\eta_o - \eta_L}{L_c}\,A_{c_{mean}} - C_d\,\frac{u_{mean}}{h_c}\,Q_c(t) + R_S \cdot b_c \qquad (6)$$

Assuming ω_H^2 as the pumping frequency given by

$$\omega_H^2 = \frac{gA_{c\,mean}}{L_c A_L} \qquad (7)$$

and the differential form of Eq. (1) is

$$\frac{d\eta_L}{dt} = \frac{Q_c(t)}{A_L} \qquad (8)$$

From Eq. (6) and Eq. (8) we obtained the mathematically continuous form of Eq. (2):

$$\frac{d^2\eta_L}{dt^2} + \delta\,\frac{d\eta_L}{dt} + \omega_H^2\eta_L = \omega_H^2\eta_o + \frac{R_S \cdot b_c}{A_L} \qquad (9)$$

The bottom friction parameterization was obtained from Eq. (4).

$$\delta = C_d \frac{u_{mean}}{h_c} = \frac{gn^2}{h_c^{4/3}} u_{mean} \qquad (10)$$

In Stanev *et al.* (2003b) an analytical solution of Eq. (9) was presented, assuming the following solution for the ocean sea level:

$$\eta_o = a\cos(\omega t), \omega = \frac{2\pi}{T} \qquad (11)$$

In fact, Eq. (9) is the classical damped, driven harmonic oscillator, whose class of analytical solutions is well known. The damping term is parameterized by Eq. (10). The intrinsic oscillation frequency, characterized solely by the lagoon geometry, is parameterized by Eq. (7), whilst the driving frequency, which represents ocean forcing, is parameterized by Eq. (11). The damped, driven harmonic oscillator is characterized over time, by two regimes: a transient regime, where the intrinsic part of the solution is calculated by solving the homogeneous form of Eq. (9), coexists with the driving part of the solution, where both characteristic frequencies (ω_H and ω) play a role in the level motion; and a driven regime, where the intrinsic part of the solution is completely damped by the system, and where the sole remaining characteristic frequency is ω , affected only by a phase and amplitude shift. The transient regime occurs at the “turn on” of the harmonic oscillator and is eventually dissipated. It is assumed that the system is permanently in the purely driven regime. This assumption has the benefit of discarding the task of considering the solutions for the homogeneous equation. Hence, only a particular, non-trivial solution of Eq. (9) needs to be considered, to predict the sea level in the lagoon. The particular solution of Eq. (9) can be described by

$$\eta_L(t) = \alpha a\cos(\omega t - \theta) + \frac{R_S b_c}{A_L \omega_H^2} \qquad (12)$$

where α is the attenuation of ocean tidal wave inside the lagoon

$$\alpha = \sqrt{\frac{\omega_H^4}{\left(\omega_H^2 - \omega^2\right)^2 + \delta^2\omega^2}} \qquad (13)$$

and θ is the phase delay associated with the lagoon inlet

$$\theta = \arctan\left(\frac{\delta\omega}{\omega_H^2 - \omega^2}\right) \qquad (14)$$

the solution can be simplified in the follow equation

$$\eta_L(t) = \alpha a \cos(\omega t - \theta) + \frac{R_S L_c}{g H_c} \qquad (15)$$

This solution is similar to that presented by Stanev *et al.* (2003b), with a difference in the second term of the right hand side of equation - wave radiation stress forcing. Note how the intrinsic frequency of the system (ω_H) only affects a shift in the amplitude (Eq. 13) and phase (Eq. 14) of the ocean driven system Eq. (15). The harmonic oscillator is a simplified model of the lagoon and is adequate, in the sense that it represents the nature of the flushing tide and waves.

Based upon the linear solution of Eq. (15), it is possible to estimate the sea-level elevation (second term on the right hand side of the equation), due to the gradient of radiation stresses. In the Óbidos Lagoon case study, the sea-level elevation due to sea waves over the inlet is of the order of 1 m (considering the same values referred to in the previous Section); this is confirmed by the observations and numerical model outputs (2D primitive equation and simplified model). The term associated with the wave´s effect (or any other shear stress aligned with the channel, e.g., wind) shows that the longer the inlet or channel, the more intense is the difference between OSL and LSL. In other words, the sea-level gradient is proportional to R_s ; this means that, for the same gradient, the difference between the ocean and the lagoon sea level increases with L_c . The term shows also that the difference in sea level decreases with increasing channel depth, for the same shear stress.

Only sea waves can introduce a shear stress which, in turn, induces a significant sea-level gradient between the ocean and the lagoon. The wind stress (Eq. 16, ρ_w is the water density) can be considered also as a forcing term in the solution of Eq. (16). An extreme wind of 100 kmh^{-1}, aligned with the inlet direction, corresponds approximately to a shear stress of 0.001 m^2s^{-2}. Thus, it corresponds to an increase of only 1 cm in sea level, in the case of the Óbidos Lagoon.

$$\eta_L(t) = \alpha a \cos(\omega t - \theta) + \left(R_S + \tau_{Wind}/\rho_w\right)\frac{L_c}{gH_c} \qquad (16)$$

Figure 2.9a,b compares the results obtained with the analytical model, using the results of the simplified inlet-lagoon idealized model. The analytical model is able to reproduce the main differences between OSL and LSL. It is able also to reproduce the effect of a constant shear stress associated with sea waves over the inlet. However, the simplifications introduced to obtain the analytical solution generate some differences. The most important is the disappearance of the tidally-driven residual difference, between ocean and LSL. This residual difference, present in the real data, is of the order of 20 cm, between the ocean and the lower station in the lagoon (Figure 2.6b). A similar difference can be observed in the simplified model results, without the effect of waves (see Figure 2.9a). When the cross-sectional channel area is considered constant over time and equal to $A_{c_{mean}}$ in the idealized model, the difference between OSL and LSL disappears; and only minor amplitude and phase differences are maintained. This is due to the fact that the friction term in the analytical solution is linear and; if it is assumed to be linear in solutions (numerical and analytical), then they match (Figure 2.9b). The simplified model assumes a variable cross-sectional channel area over time and, considering a null drag coefficient, the residual gradient would disappear. On the other hand, if the drag coefficient is not considered as being null, the residual gradient will appear in the results.

These result shows that the residual gradient is generated by tidal asymmetry associated with the non-linear terms present in the simplified model: friction $\left(C_d \left|u_c\right| u_c / H_c\right)$ and mass conservation $\left(\frac{d\eta_L}{dt} = \frac{u_c A_c}{A_L}\right)$.

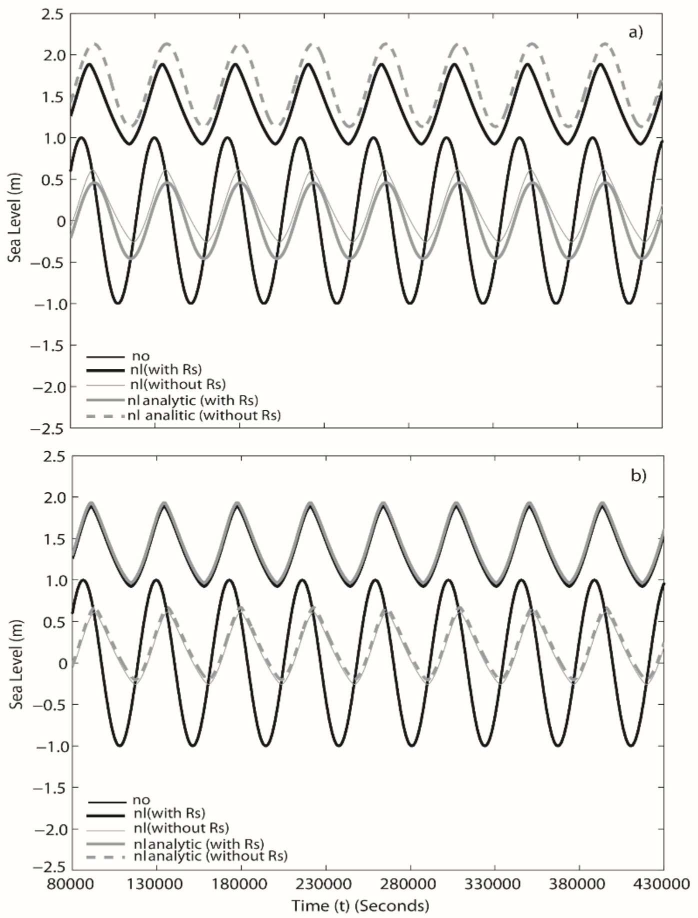


Figure 2.9. Comparison between analytical solution and simplified model results, with and without wave forcing, considering a cross-sectional channel area variable in time (a) and assuming a constant cross-section channel area (b).

2.3.4. Current velocities

Figure 2.10 shows the measured and simulated time-series of current velocity near the inlet (Station A) and along the channel (Station B) for November 29th, 2000. The LSL at Station B is also shown; this is the only station with available current and sea level data. The variability in the surface currents (Figure 2.10a and 10b) is well reproduced by the model, revealing stronger currents near the inlet and weaker along the channel. However, in spite of the high skill score (0.80 and 0.85), the model results underestimate the observations. The simulated currents reveal also semi-diurnal variations.

Another interesting feature captured by the model is the agreement between the tidal asymmetry and the current velocity, at Station B (Figure 2.10b and 10c). As shown by observations and simulations, the lagoon is flood-dominated, with the duration of the ebb phase (~7h) being longer than that of the flood phase (~5h). This tidal asymmetry results in stronger currents (~1.0 ms^{-1}) during the flood phase, whilst weaker currents (~0.5 ms^{-1}) during the ebb phase.

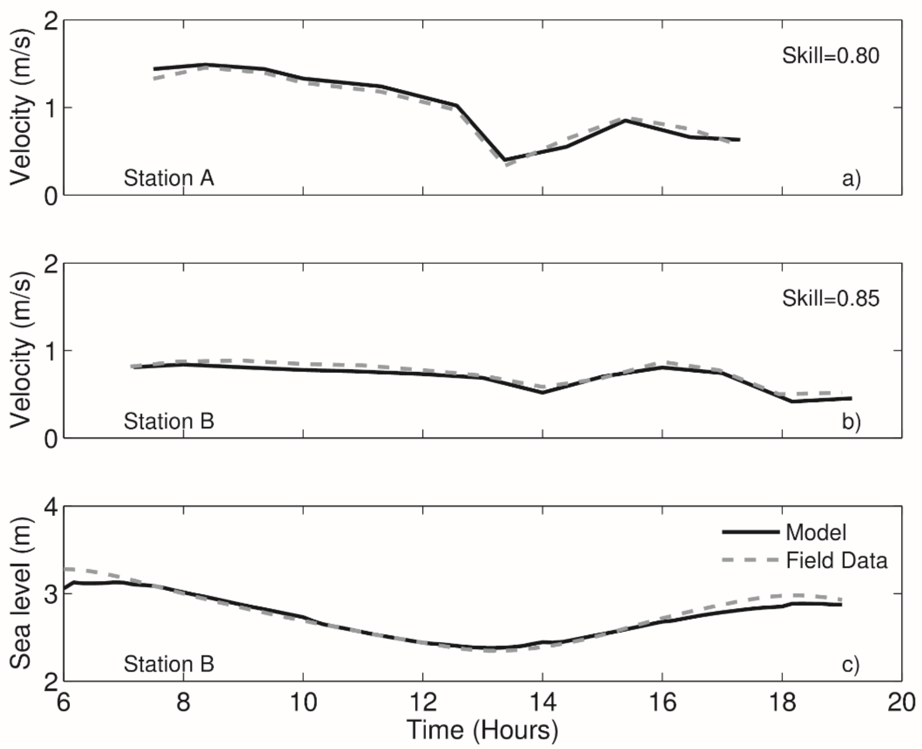


Figure 2.10. Measured and simulated time-series of current velocity, near the inlet (Station A, a) and along the channel (Station B, b) for the 29th November 2000. The lagoon sea level at Station B is also shown (c).

The spatial patterns of currents in the lower lagoon, for tidal forcing and tide-wave forcing, are presented in Figure 2.11. The upper lagoon was not presented because there are no significant differences between phases (ebb and flood) and the physical forcings (tide and waves). The times of the flood and the ebb, for tidal and wave forcing, can be seen in Figure 2.11a,b, respectively. Predictions with no wave forcing are presented in Figure 2.11c,d for flood and ebb phases, respectively. The timing chosen to analyze the currents patterns reflects the case of the time that corresponds to the current maximum. The major difference between the simulations is the presence of the alongshore current, revealing that the model is able to reproduce the wave motion when forcing is supplied by waves. In terms of magnitudes there are no significant differences between the simulations. As shown by the simulated time-series, the spatial pattern reveals also a flood phase characterized by stronger velocities. Regarding the main hydrodynamics features of the study area, the forcing due to tide and waves is more realistic, than forcing with only by the tide.

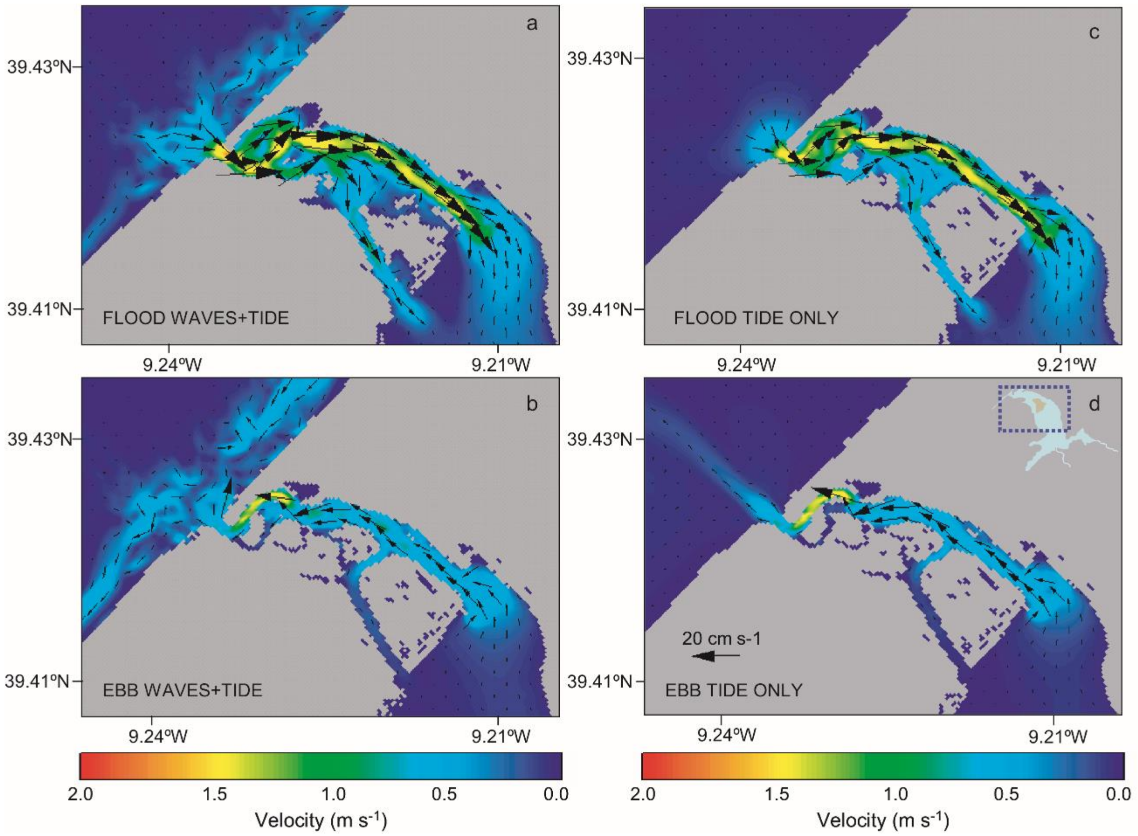


Figure 2.11. Spatial patterns of currents in the lower lagoon, for tidal and wave forcing at the times of flood (a) and ebb (b). The times of flood and ebb for tidal forcing are represented in (c) and (d), respectively.

2.4. Conclusions

Sea level variations in the Óbidos Lagoon are related to tidal forcing, as well as wave-induced forces. Good model predictions were obtained for the lagoon tidal amplitude, under different physical forcings. The model shows an ability to reproduce the observed temporal variability in the LSL and current velocities, presenting skill coefficients of higher than 0.68.

Field measurements and model predictions show that sea-level elevation in the lagoon is above the OSL during high wave activity periods. In addition, the simplified inlet-lagoon idealized model provides a good understanding of the wave pumping inflow, showing the importance of wave radiation stresses in the super-elevation. Dynamically, this could have two explanations: (1) wave set-up or radiation stress, due to waves; and (2) the tidal inlet morphology. Wave set-up height depends not only upon offshore wave height but also on tidal inlet morphology (mainly depth and length). The deeper and shorter is the morphology, the more the wave set-up is reduced, as shown by the numerical solution of the simple idealized model.

2.5. Acknowledgements

This work was carried out with the financial support of Águas do Oeste S.A (AdO), as part of the project "Monitoring and modelling the Óbidos Lagoon and Foz do Arelho submarine outfall". In July 2004, AdO initiated the supervision of a Monitoring Program in the Óbidos Lagoon and coastal area, with the support of Instituto Superior Técnico (IST) from the Universidade Técnica de Lisboa (IST) and Instituto de Investigação das Pescas e do Mar (IPIMAR).

The authors also wish to thank to Nuno Vaz from Aveiro University working in MARETEC/IST at this time, for suggestions and incentive provided during this work.

2.6. References

Angwenyi, C.M. and Rydberg, L., 2005. Wave-driven circulation across the coral reef at bamburi Lagoon, Kenya. Estuarine, *Coastal and Shelf Science*, 63, pp. 447-454.

Callaghan, D. P., Nielsen, P., Cartwright, N., Gourlay, M. R., Baldock, E. T., 2006. Atoll lagoon flushing forced by waves. *Coastal Engineering*, 53, pp. 691-704.

Carvalho, S., Moura, A., Gaspar, M. B., Pereira, P., Fonseca; L. C., Falcão, M., Drago, T., Leitão, F., Regala, J., 2005. Spatial and inter-annual variability of the macrobenthic communities within a coastal lagoon (Óbidos Lagoon) and its relationship with environmental parameters. *Acta Oecologica*, 27, pp. 143–159.

Carvalho, S., Gaspar, M. B., Moura, A., Vale, C., Antunes, P., Gil, O., Fonseca; L. C., Falcão, M., 2006. The use of the marine biotic index AMBI in the assessment ofthe ecological status of the Óbidos Lagoon (Portugal). *Marine Pollution Bulletin* 52, 1414–1424.

Chow, 1973. *Open-Channel Hydraulics. McGraw-Hill International Editions*. Civil Engineering Series. 1973. ISBN 0.07-Y85906-X.

Costa, M., Silva, R. and Vitorino, J., 2001. *Contribuição para o estudo do clima de agitação marítima na costa Portuguesa. 2as Jornadas Portuguesas de Engenharia Costeira e Portuária*. Sines, Outubro de 2001 (in Portuguese).

Dunn, S.L., Nielsen, P. Nielsen, Madsen, A.P., Evans, P., 2000. Wave setup in Rivers. *ASCE International Conference on Coastal Engineering*, Sydney, Australia, pp. 3432-3445.

Dunn, S.L., 2001. *Wave setup in River entrances*. Doctor Thesis in Department of Civil Engineering, University of Queensland. Brisbane, Australia, 191 p., published.

Fortunato, A.B. and Oliveira A., 2007. Case Study: Promoting the Stability of the Óbidos Lagoon Inlet. *Journal of Hydraulic Engineering*, 133 (7), pp. 816-827.

Guza, R.T. and Thorton, E.B., 1981. Wave set-up on a natural beach. *Journal of Geophysical Research*, Vol. 86, N.º C5, pp. 4133-4137.

Hanslow, D.J. and Nielsen, P., 1992. Wave setup on beaches and in River entrances. *In Proceedings of 23rd International Conference on Coastal Engineering*, pp. 240-252.

Hanslow, D.J., Nielsen, P. and Hibbert, K. 1996. Wave setup in River entrance. In Proceedings of 25th International Conference on Coastal Engineering, pp. 2244-2257.

IHPT, 2001a. *Monitorização Ambiental da Lagoa de Óbidos NOV 2000 – JUN 2001*. Relatório Técnico Final, Report TF. 08/ 2001 (in Portuguese).

IHPT, 2001b. *Monitorização Ambiental da Lagoa de Óbidos JUL 2001 – DEZ 2001*. Relatório Técnico Final, Report PT. OC. 06/2001 (in Portuguese).

IHPT, 2002a. *Monitorização Ambiental da Lagoa de Óbidos DEZ 2001 – ABR 2002*. Relatório Técnico Final, Report PT. OC. 02/2002 (in Portuguese).

IHPT, 2002b. *Monitorização Ambiental da Lagoa de Óbidos MAI 2002 – AGO 2002*. Relatório Técnico Final, Report PT. OC. 05/2002 (in Portuguese).

Leitão, P., Coelho; H., Santos, A., Neves, R., 2005. Modelling the main features of the Algarve coastal circulation during July 2004: A downscaling approach. *Journal of Atmospheric and Ocean Science*,10 (4), pp. 1-42.

Le Provost, C., Lyard, F., Molines, J. M., Genco, M. L., Rabilloud, F., 1998. A hydrodynamic ocean tide model improved by assimilating a satellite altimeter derived data set. *Journal of Geophysical Research-Oceans*, 103, pp. 5513-5529.

Longuet-Higgins, M.S. and Stewart, R.W., 1960. Changes in the form of short gravity waves on long waves and tidal currents. *Journal of Fluid Mechanics*, 8, pp. 565-583.

Longuet-Higgins, M.S. and Stewart, R.W., 1962. Radiation stress and mass transport in gravity waves with application to surf beat. *Journal of Fluid Mechanics*, 13, pp. 481-504.

Longuet-Higgins, M.S. and Stewart, R.W., 1964. Radiation stress in water waves; a physical discussion with application. *Deep Sea Research*, 11, pp. 529-540.

Longuet-Higgins, M.S. and Stewart, R.W., 1973. The mechanics of the surf zone. *In Proceedings of the 13th International Congress on Theoretical and Applied Mechanics*. Springer Verlag, pp. 213-228.

Malhadas, S.M., 2008. *Modelação do impacte de emissários submarinos em zonas costeiras-caso da Foz do Arelho*. Msc. Thesis for the Msc. degree in environmental engineering. Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisboa, Portugal, 95 p.), published (in Portuguese).

Martins, F., Leitão, P.C., Silva, A., Neves, R., 2001. 3D modelling in the Sado estuary using a new generic vertical discretization approach. *Oceanologica Acta*, 24 (1), pp. 551-562.

Nielsen, C. and Apelt, C., 2003. The application of wave induced forces to two-dimensional finite element long wave hydrodynamic model. *Ocean Engineering*, 30, pp. 1233-1251.

Nguyen, X., Tanaka, H. and Nagabayashi, H., 2007. Wave setup at River and Inlet Entrances Due to an Extreme Event. *To appear in Proceedings of International Conference on Violent Flows*, Organized by RIAM, Kyushu University, Fukuoka, Japan.

Oliveira, A., Fortunato, A.B. and Rego, J.R.L., 2006. Effect of morphological changes on the hydrodynamics and flushing properties of the Óbidos Lagoon (Portugal). *Continental Shelf Research*, 26, pp. 917-942.

Oshiyama, S., Lee and H., Tanaka, H., 2001. Fluctuation characteristics of water level in medium-and-small scale River mouths. *In Proceedings of 25th International Conference on Coastal Engineering*, JSCE, Vol. 48, pp. 411-415 (in Japanese).

Rego, J., 2004. *Hidrodinâmica da Lagoa de Óbidos*. B.Sc. Thesis for the B.Sc. degree in Geophysical Sciences—Oceanography, Faculdade de Ciências da Universidade de Lisboa, published (in Portuguese).

Santos, M., Neves, R., Leitão, P.C., Pereira, P., Pablo, H., Fernandes, L. D., Carvalho, S., Alves, C., 2006. Qualidade da água da lagoa de Óbidos: Que futuro? *In Proceedings of 12º Encontro nacional de Saneamento Básico*, 24-27 Outubro, Cascais. ISBN:978-972-95302-8-9.

Smith, J. M., Militello, A. and Smith, S. J., 1998. Modeling waves at Ponce de Leon Inlet, Florida. *In Proceedings of 5th International Workshop on Wave Hindcasting and Forecasting*, Environment Canada, Downsview, Ontario, pp. 201-214.

Smith, J. M., Sherlock, A.R., and Resio, D.T., 2001. STWAVE: Steady-state wave model user's manual for STWAVE, Version 3.0. ERDC/CHL SR-01-1, U.S. Army Engineer Research and Development Center Vicksburg, MS (http://chl.wes.army.mil/research/wave/wavesprg/numeric/wtransformation/downld/erdc-chl-sr-01-11.pdf).

Stanev E.V., Wolff, J.O., Burchard, H., Bolding, K., Floser, G., 2003a. On the circulation in the East Frisian Wadden Sea: numerical modeling and data analysis. *Ocean Dynamics*, 53, pp. 27-51.

Stanev E.V., Floser, G. and Wolff, J.O., 2003b. First- and higher-order dynamical controls on water exchanges between tidal basins and the open ocean. A case study for the East Frisian Wadden Sea. *Ocean Dynamics*, 53, pp. 146-165.

Stanev E.V., Flemming, B.W., Bartholoma, A., Staneva, J., Wolff, J.O., 2007. Vertical circulation in shallow tidal inlets and back-barrier basins. *Continental Shelf Research*, 27, pp. 798-831.

Tanaka, H., Nagabayashi, H. and Yamauchi, K., 2000. Observations of wave set-up height in a River mouth. *In Proceedings of 27th International Conference on Coastal Engineering*, pp. 3458-3471.

Tanaka, H., Lee, H.S. and Furumichi, K., 2003. Influence of morphological change on water level rise at the Shiribetsu River mouth. *Journal of hydroscience and Hydraulic Engineering*, 21 (1), pp. 71-78.

Troussellier, M. (Lead Author) and Gattuso, J. P. (Topic Editor), 2007. *Coastal Lagoons*. In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). [First published in the Encyclopedia of Earth November 21, 2006; Last revised August 13, 2007; Retrieved November 15, 2007]. <http://www.eoearth.org/article/Coastal_lagoon>.

Van Rijn, L.C, 1989. *Sediment Transport by Currents and Waves Handbook*. Delft Hydraulics, Report H 461 p.

Vão–Arquitectos Associados, 1991. *Estudo de Recuperação e Ordenamento da Lagoa de Óbidos, Concha de São Martinho do Porto e Orla Litoral Intermédia*. Vols. I, II and V (in Portugese).

Vaz, N., Dias, J.M., Leitão, P.C. and Nolasco, R. 2007. Apllication of the MOHID-2D model to a mesotidal temperate coastal lagoon. *Computers & Geosciences*, 28, pp. 1204-1209.

3. Influence of tide and waves on water renewal in Óbidos Lagoon, Portugal

Madalena S. Malhadas[a], Ramiro Neves[a], Paulo C. Leitão[b] and Adélio Silva[b]

[a] *Instituto Superior Técnico, Depto. de Mecânica, Av. Rovisco Pais, 1049-001 Lisboa, Portugal*
[b] *Hidromod, Modelação em Engenharia, Lda., Av. Manuel da Maia, nº 36, 3º Esq., 1000-201 Lisboa, Portugal*

Published in: Ocean Dynamics (2010) 60:41–5, **Impact Factor:** 1.677

Abstract

The role of oceanic tide, wind stress, freshwater river inflows and waves in the long-term circulation and residence time (RT) in Óbidos Lagoon is investigated using a sensitivity analysis carried out by means of a two-dimensional model. MOHID modeling system coupled to STWAVE model for simulate Óbidos Lagoon circulation were implemented. For RT calculus a Lagrangian transport model was used.
Tidal forcing is shown to be the dominant forcing, although storm waves must be considered to simulate accurately the long-term circulation. Tidal forcing enhances a spatial distribution in water RT. Renewal time scales varies from values of 2 days in the near-ocean areas and 3 weeks in the inner areas. Freshwater river inflows decrease the RT, while waves increase. In heavy rainy periods the water RT decreases by about 40% in the upper lagoon. When wave forcing is considered, the RT increases between 10% and 50% depending on lagoon area. The increasing in RT is explained by the sea level rise within lagoon (~1 m above average lagoon sea level) during storm wave periods. Average RT is 16 days for tidal forcing, 9 days when the rivers are included (wet period) and 18 days when the waves are considered.

Keywords: MOHID; Hydrodynamic; Tide and waves forcing; Sea level rise; Residence time; Óbidos Lagoon.

3.1. Introduction

The time history of a pollutant once it is released in a costal system is relevant for evaluating its ecological impacts. Hence, it is important to know the time required for the pollutant to leave the system, and this can vary depending on different external forcing functions (Arega *et al.*, 2008).

Reviewing literature, there are several concepts of exchange-time scales, such as age, RT, transit time and turnover time. It seems there are no uniquely agreed definitions for these different time scales or agreed standard methods for their determination (Monsen *et al.,* 2002).

In the past Bolin and Rodhe (1973) reviewed the definition for the scales of time ‘age’, ‘transit time’, and ‘turnover time’, introducing a more rigorous concepts. According to these authors, each element in such a reservoir can be characterized by the time that has elapsed since it entered the reservoir under consideration (e.g., the time is the ‘age’ of the element).

Zimmerman (1976) introduced a new concept of RT different from that defined by Bolin and Rodhe (1973). Zimmerman definition deals with moving individual particles for a spatially varying situation. He applied these concepts to the Dutch Wadden Sea and concluded that the RT for each material element was defined as the time for the element to reach the outlet. Latter, Takeoka (1984) defined that RT at a given point in a lagoon, is the period of time that a water parcel, initially located at the point considered, needs to leave the lagoon through the pass and enter the Pacific. Additionally, he concluded that turnover time can be obtained by averaging the RT over the volume of the lagoon. Following the definition given by Takeoka (1984), Hakanson *et al.* (1986), Persson *et al.* (1994) and Aure *et al.* (1996) establish simplest form equations between the domain’s volume and volumetric through flow, and thus complemented the concept of RT. Recently, Rasmussen and Josefson (2002) applied similar equations and concepts to study the RT in sub-catchments of the River Dee (Cairngorm Mountains, Scotland). The same definitions were used also by Soulsby and Tetzlaff (2008) to calculate the water exchange and RT in 31 small Danish estuaries.

Knudsen (1900) introduced the concept of salt budget. For this method to be applicable, a series of conditions must be fulfilled, for instance, a significant salinity difference between the system and the ocean is needed. Rougerie *et al.* (1984) used similar means to calculate the RT of the deep eastern part of Mururoa lagoon (French Polynesia) and concluded that is about 92 days. Mudge *et al.* (2007) estimated in this way the RT of the Ria Formosa lagoon (Portugal) finding values of about 7 days.

However, the different time scales are associated with the exchange processes between the system and the open-sea, and are a complicated function of the freshwater runoff, tidal range, coastal waves, topography and bathymetry, density stratification, and wind. Nonetheless, numerical simulations are the best way to tackle the estimation of water renewal because they can account with realistic coastal geometry and bottom topography, as well as different physical factors. The first models that appeared in the literature were the box models. This are based through mass balance inside a box and does not count with the advection processes. In the first applications stands Soetaert and Herman (1995) for estimating estuarine RT in the Westerschelde (The Netherlands) using a box model with fixed dispersion coefficients. They concluded that RT varied from about 50 days in winter to about 70 days in summer. Sheldon and Alber (2002) applied the similar compartment models to estimate the RT of the Altamaha River Estuary (Georgia). According to these authors, mixing time estimates from box models were incorrect when boxes were improperly scaled, since mixing time scales vary nonlinearly with water flows. Due to these model limitations, methods of assessing the circulation patterns and for including external forcings are needed. Consequently, researchers investigate the potential of other numerical approaches and introduced the depth or laterally-integrated two-dimensional circulation models and the complex three-dimensional general circulation models. Ideally, three-dimensional modeling is most desirable but uncertainties in boundary conditions and eddy viscosities prohibit its application to large-scale problems. Alternatively, the vertically-integrated shallow water models are a practical approach for coastal problems. It is an attempt to simplify a very complex problem by eliminating dependence on vertical coordinate. In shallow water system a depth or laterally-integrated two-dimensional is enough to study the circulation and thus RT. But, if the stratification has an important role in long-term circulation a 2D-model application does not simulate the main features in hydrodynamic and erroneous estimations for RT will be made. From the 2D-model applications described in the literature referred the work of Chen (1998) that estimates the RT on the coral reef at Bora Bay (Miyako Island) using a numerical simulation that includes a depth dependent formulation of the wind-wave forced cross-reef water flow, Gillibrand (2001) calculated the exchange times in a Scottish fjord with a two-dimensional, laterally-integrated numerical model, Braunschweig *et al.* (2003) proposed a methodology to estimate renewal time scales in estuaries and applied it to the Tagus Estuary (Portugal) using a 2D depth integrated model, Bilgili *et al.* (2005) used a Lagrangian particle method embedded within a 2D finite element code, to study the transport and ocean-estuary exchange processes in the Great Bay Estuarine system (New Hampshire, USA), Umgiesser and Cucco (2006) computed the water RT of the Venice Lagoon (Italy) using a 2D hydrodynamic model based on the finite element method, Stamou *et al.* (2007) applied a hydrodynamic model to calculate the flow field and the renewal time in Salman Bay a semi-enclosed coastal water body in the region of Jeddah (Saudi Arabia) and Aure *et al.* (2008) carried out a numerical modeling study based on the total variation diminishing (TVD) finite-volume method, to compute average RT in a tide-dominated East Scott Creek Estuary (South Carolina).

From 3D model applications briefly summarized the work of Jozsa and Kramer (2000) with estimations of water exchange in semi-enclosed bays at Helsinki coasts by modelling the spatial distribution of mean RT, Andrejev *et al*. (2004) estimate the water-renewal time of the Gulf of Finland with a 3D numerical model simulating the years 1987–1992, Banas and Hickey (2005) used the numerical model GETM to examine transport pathways and RT in a macrotidal estuary with a complex channel geometry (Willapa Bay, Washington), Garcia (2008) estimated the water RT in Nazaré Canyon (Portugal) applying a 3D circulation model coupled to a Lagrangian particle model.

Undoubtedly, using numerical models carries distinct advantages. Numerical model enables a range of sensitivity analyses to be carried out, which help understand the hydrodynamic of the system and the role of the various forcing. Moreover, in contrast to the first techniques mentioned previously for water RT calculus, a numerical model is capable of estimating the RT with a high spatial resolution. Howsoever, in the wide range of numerical model applications described herein, authors omitting the importance of coastal waves on RT, considering only the tide and wind-driven circulation. To our knowledge, wave driven circulation has been already addressed in coastal lagoons by Kraines *et al.* (1998), Thattai and Kjerfve (2003), Angwenyi and Rydberg (2005), Callaghan *et al.* (2006) and Malhadas *et al.* (2009) but the effect of coastal waves on RT has never been studied. The presence of waves can cause large differences in terms of sea level variations. From the works mentioned above, authors concluded that coastal waves may affect significantly the estimation of RT.

Óbidos Lagoon is a coastal system located on the western Portuguese coast (Figure 3.1), connected to the sea through a narrow, shallow and mobile inlet. Little is known about lagoon's circulation and RT, other than the findings of a few papers published in the last 3 years (e.g., Oliveira *et al*. (2006), Fortunato and Oliveira (2007a, 2007b), Bertin *et al.* (2009), Malhadas *et al.* (2009a, 2009b), Malhadas *et al.* (2009a) found that tide and waves are important in defining the lagoon's dynamic. During storm wave periods occurs a significant super-elevation on lagoon sea level and it may reach about 1 m in amplitude above the mean lagoon sea level (~2.6 m). This over-elevation induces an increasing in the mean lagoon water volume affecting the hydrodynamic.

In this paper, an estimation of RT in Óbidos costal lagoon considering distinct physical forcing is presented. Fluctuations in RT were analyzed considering the following forcing: (i) tide; (ii) tide and wind; (iii) tide and freshwater river discharges; and (iv) tide and waves. The model adopted in this work is MOHID modeling system. As modeling technique a 2D application of two on-line nested models one-way coupled is presented. The implemented modeling system is able to simulate circulation and RT driven by tide, waves, river flows and wind. Circulation patterns were simulated with MOHID hydrodynamic module coupled to a wave model and RT with MOHID Lagrangian model coupled to the circulation model.

In the following, a brief description of the study site will be given. This is followed by the numerical models description and implementation for the Óbidos Lagoon case study. Results (model validation and simulations) are presented and discussed in the Section 4 and conclusions in the final section.

3.2. Study site

The Óbidos Lagoon is a shallow coastal system with 2 m average depth. The lagoon occupies a surface area of 4.4 km^2 at mean sea level and 8.0 km^2 at high spring (Oliveira *et al.*, 2006). Two main regions with distinct morphological and hydrodynamic characteristics can be identified (Figure 3.1): the lower and the upper lagoon.

The lower lagoon is connected to the Atlantic Ocean by an inlet and composed by several channels (Carvalho *et al*., 2006). The water flows by a main channel called the northern channel. Current velocities often exceed 1 ms^{-1} along the northern channel and by about 1.6 ms^{-1} in the inlet (Malhadas *et al.*, 2009a). The upper lagoon consists of a shallow basin, elongated arms (Barrosa and Bom Sucesso) and a small embayment in the south (Poça das Ferrarias, Oliveira *et al*., 2006). In the lagoon arms, current velocities of about 0.4 ms^{-1} are observed (Malhadas *et al.*, 2009a).

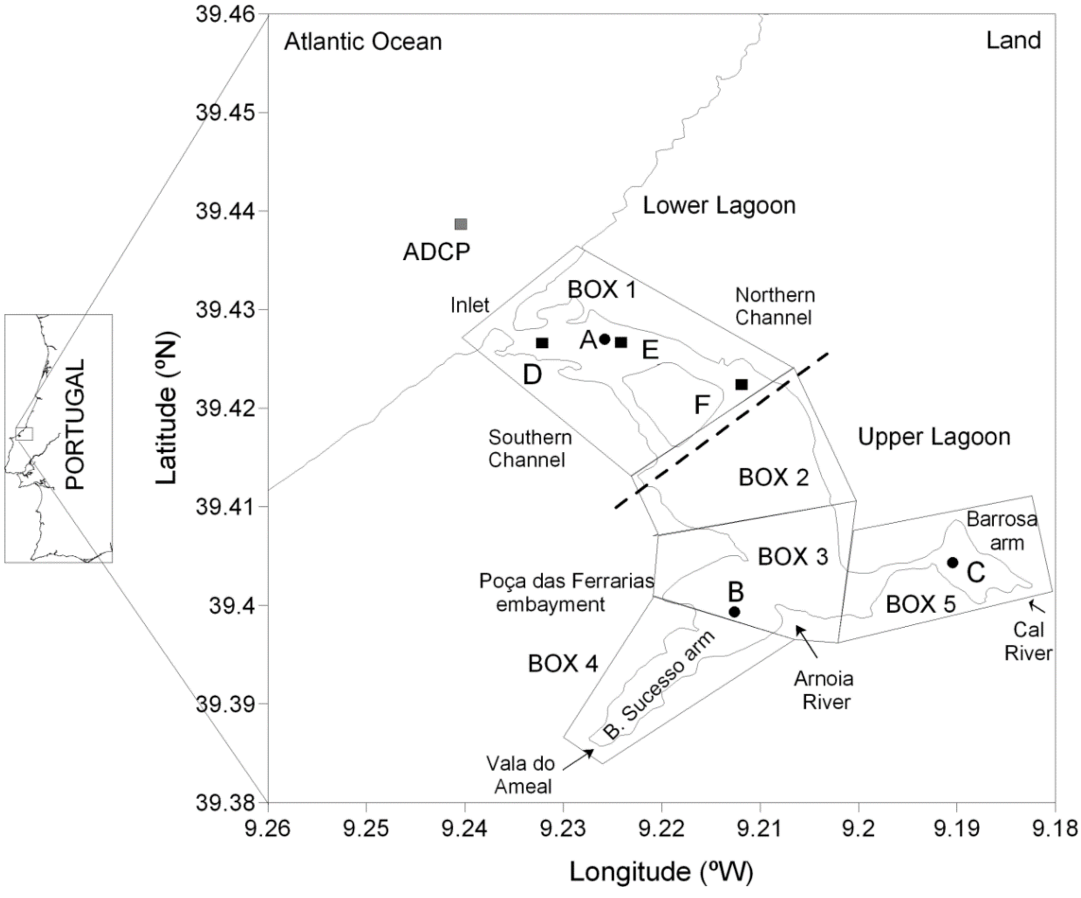


Figure 3.1. Geographical location of the Óbidos Lagoon. Major freshwater tributaries and main basins are marked. The location of the stations used in the hydrodynamic validation procedure are marked: tidal gauge (●) and current measurement (■) stations. Boxes used for residence time calculus are also designed.

The main freshwater supplies into the lagoon are: Cal and Arnóia River (two main river discharges); and Vala do Ameal (a drainage creek). Cal River enters the lagoon at the Barrosa arm and Vala do Ameal at the Bom Sucesso arm. Arnóia River enters the lagoon between the arms, contributing with 90% of the freshwater fluxes into the lagoon. This river discharge is the major source of sediments, whose deposition has created an extensive sand bank between lagoon arms.

The lagoon is well-mixed, strongly influenced by semi-diurnal tides and in a small extension by storm waves (wave height values ranging between 3 and 7 m). Tidal prism is 6×10^6 m^3 for neap tide and 10^7 m^3 for spring tide (Malhadas *et al.*, 2009a). Freshwater input plays a minor role, with average flow rates of the order of 3 m^3s^{-1}. This are less than 5% of the average tidal prism scaled by the M2 period (Rego, 2004).

3.3. Modeling efforts

The model adopted in our study was MOHID water modeling system (www.mohid.com). The model was developed in the Technical University of Lisbon (IST) and is under continuous progress. MOHID is a 3D baroclinic finite volumes numerical model, designed for coastal and estuarine shallow applications. Cancino and Neves (1998) applied the hydrodynamic and sediment suspension model to Sado Estuary (Portugal), Taboada *et al.* (1998) evaluated the seasonal variations in residual patterns at Ria de Vigo (NW Spain) with a 3D baroclinic model, Martins *et al.* (1999) performed numerical simulations to study the internal tides, Coelho *et al.* (1999) studied the slope current along the Western European Margin, Martins *et al.* (2001) modeled the Sado estuary (Portugal) using a new generic vertical discretization approach, Santos *et al.* (2002) developed a circulation model application for the European ocean margin, Leitão *et al.* (2005) modeled the Algarve coastal circulation during July 2004 using a downscaling approach, Vaz *et al.* (2007) applied the 2D model to a mesotidal temperate coastal lagoon (Ria de Aveiro lagoon, Portugal), Vaz *et al.* (2009) performed a three-dimensional modeling application of a tidal channel (Espinheiro Channel, Portugal), Malhadas *et al.* (2009a) analyzed the effect of coastal waves on sea level in Óbidos Lagoon (Portugal) and Malhadas *et al.* (2009b) evaluated the effect of the bathymetric changes on the hydrodynamics and RT of the Óbidos Lagoon (Portugal).

The model is composed by several modules which can be easily coupled between them or to other external models, as such STWAVE, the model used in this study to simulate wave propagation.

3.3.1. Description of the models

3.3.1.1. The MOHID hydrodynamic module

MOHID hydrodynamic module was used to achieve accurately the circulation in the study area. The hydrodynamic module solves the 3D, vertically hydrostatic, free surface equations of motion, together with continuity and mass balance equations:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_1}{\partial t} + \frac{\partial (u_j u_1)}{\partial x_j} = +fu_1 - g\frac{\rho_n}{\rho_0}\frac{\partial \eta}{\partial x_1} - \frac{1}{\rho_0}\frac{\partial p_s}{\partial x_1} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho'}{\partial x_1} dx_3 + \frac{\partial}{\partial x_j} \times (A_j \frac{\partial u_1}{\partial x_j}) \tag{2}$$

$$\frac{\partial u_2}{\partial t} + \frac{\partial (u_j u_2)}{\partial x_j} = +fu_2 - g\frac{\rho_n}{\rho_0}\frac{\partial \eta}{\partial x_2} - \frac{1}{\rho_0}\frac{\partial p_s}{\partial x_2} - \frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho'}{\partial x_2} dx_3 + \frac{\partial}{\partial x_j} \times (A_j \frac{\partial u_2}{\partial x_j}) \tag{3}$$

$$\frac{\partial p}{\partial x} = -\rho g \tag{4}$$

where u_i are the velocity vector components in Cartesian x_i directions positive to the east, to north and upward, g is the free surface elevation, f is the Coriolis parameter, A_j the turbulent viscosity, p_s is the atmospheric pressure, ρ is the density and ρ' its anomaly.

Density is calculated as a function of temperature (T) and salinity (S) by the equation of state (Leendertsee and Liu, 1978):

$$\rho = \left(5890 + 38T - 0.375T^2 + 3S\right) / \left(\left(1779.5 + 11.25T - 0.0745T^2\right) - \left(3.8 + 0.01T\right)S + 0.698\left(5890 + 38T - 0.375T^2 + 3S\right)\right) \quad (5)$$

The equations are resolved using finite-differences on Arakawa-C staggered grid. The temporal discretization is carried out by means of a semi-implicit (ADI, alternate direction implicit) algorithm with two time levels per iteration (Leitão *et al*., 2005). The ADI approach computes the internal and external modes with different time steps (mode splitting approach). The horizontal and vertical advection of momentum, heat and mass is computed using the total variation diminishing (TVD-Superbee) finite-volume method.

Free surface elevation is computed through integration of Eq. (1) over the water column. The two components of the horizontal velocity are globally centered in t + 1/2 leading to second-order time accuracy (Martins *et al.*, 2001). Vertical fluxes are computed by continuity (considering the hydrostatic approach), integrating over each cell volume.

For horizontal diffusion of heat, salt and momentum, a choice can be made between Laplacian or biharmonic operators with constant coefficients.

3.3.1.2. The MOHID Lagrangian module

The methodology to estimate RT in Tagus Estuary (Portugal) has been already published by Braunschweig *et al*. (2003). This methodology was used recently by Saraiva *et al*. (2007) to estimate renewal time scales in several Portuguese estuaries and by Malhadas *et al*. (2009b) to estimate the RT due to effect of bathymetric changes in Óbidos Lagoon (Portugal). Here we only describe the main key features about RT estimation.

In this study a Lagrangian module to estimate the RT in Óbidos Lagoon and by areas of the lagoon was used. In accordance with our working hypothesis, a Lagrangian particle may represent a certain amount of water or a relevant tracer. For that purpose, the lagoon was divided into five boxes (Figure 3.1). Boxes were divided, on the basis of previous knowledge of physical and biologic characteristics of the lagoon: Box 1 represents all inlet part until the central body of lagoon, box 2 represents all the central body, and box 3 represents the delta of Arnóia River. The branches are covered by box 4 (Bom Sucesso) and box 5 (Barrosa). The boxes were filled with Lagrangian tracers equal and proportional to the volume of the grid box considered.

The water fraction inside box i in each instant of time, with origin from box $j(f_{i,j})$ is calculated as

$$f_{i,j} = \frac{V_{i,j}(t)}{V_{i,j}(0)} \tag{6}$$

where $V_{i,j}(t)$ is the volume of tracers emitted in box j, present inside box i at time t and $V_{i,j}(0)$ represents the water volume in box i at the beginning of the simulation. Integrating the water fraction defined by Eq. (6) and normalizing by time we can obtain the interaction between boxes over the time:

$$F_{i,j}(T) = \frac{1}{T}\int_0^T \frac{V_{i,j}(t)}{V_{i,j}(0)} dt \tag{7}$$

As the water is renewed inside a box, the contribution of the initial water for the total volume of the box decreases and F tends to 0. Since F never becomes equal to zero because a few particles are trapped in the lagoon for an exceedingly time, the RT was estimated assuming that 80% of the tracers in the domain have been replaced. It is assumed also that every particle reaching the inlet leaves the lagoon forever.

3.3.1.3. The STWAVE model

To simulate wave propagation, the Steady-State Spectral Wave model (STWAVE) developed by the U.S. Army Corps of Engineers (Smith *et al*., 1998, 2001) was used. The purpose of applying nearshore wave transformation models is to describe quantitatively the change in wave parameters (wave height, period, direction, and spectral shape) between the offshore and the nearshore (typically depths of 40 m or less).

STWAVE is a steady-state, finite difference, spectral model based on the wave action balance equation. The model simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wave growth because of wind input, and wave-wave interaction and white capping that redistribute and dissipate energy in a growing wave field. STWAVE is based on the assumption that the relative phases of the spectral components are random, and thus phase information is not tracked (e.g., it is a phase-averaged model). In practical applications, wave phase information throughout a model domain is rarely known accurately enough to initiate a phase-resolving model. Typically, wave phase information is only required to resolve wave-height variations near coastal structures for detailed, near-field reflection and diffraction patterns.

Wave radiation stresses were calculated from wave conditions obtained with the Acoustic Doppler Current Profiler (ADCP, see location in Figure 3.1). These included wave height (Hs), period (Tp) and direction. In order to make the number of wave simulations feasible, the wave record was split into classes of Hs, Tp and direction, using the criteria of approaching: the Hs for the next half meter; the Tp to the closest second; and the direction to the limit of each 25 degrees interval. As such, 27 different offshore wave conditions were adopted. This approach allowed the simulation of a wave sequence, similar to that recorded by the ADCP, using a limited number of wave conditions. Since the calculus of wave radiation stresses does not assume the effect of the currents over the wave's propagation, the tide level variation was simulated by assuming classes of sea level varying 1 meter. This means that for each of the considered wave conditions it were performed simulations every meter from the hydrographic zero till the 5 meters sea level (above the maximum possible tide level). Afterwards it was considered that it was acceptable to use interpolated wave radiation stress values within the tide level range of each meter.

To generate the spectrum at a near shore point, the model ran (STWAVE) with a refined grid (10 m of resolution). Results from these simulations were used as a boundary condition in the Óbidos Lagoon hydrodynamic domain model (see Section 3.2).

The bottom shear stresses, considered a total roughness as the sum of a component associated to the current plus a component associated with the waves (Van Rijn, 1989). For our case the wave roughness was evaluated as the maximum of the 3*D90 (the sieve size for which 90% of the grains by weight are smaller; it provides an estimate of the largest sand in a sample).

3.3.2. *Model configuration for the Óbidos Lagoon*

The modeling system applied to the Óbidos coastal lagoon is able to simulate the circulation and RT driven by tide, wind, waves and rivers flows, coupling STWAVE model to MOHID hydrodynamic module. Lagrangian particle module was coupled to the circulation model.

The methodology used in this study consists in a downscaling technique with two nesting levels (one domain for level) on-line coupled (Figure 3.2). The first level includes the coast between Nazaré to Peniche (Figure 3.2a) and the second, the Óbidos coastal lagoon (Figure 3.2b). Bathymetric data for the first level was extracted from European Margin Strata Formation Project (EUROSTRATAFORM) marine cruises (IST, 2003) and, for the second, from the Monitorização Ambiental da Lagoa de Óbidos Project (MAMBO) carried out by Portuguese Hydrographic Institute-IHPT (IHPT, 2001a, b; IHPT, 2002a, b). Bathymetry domains were rotated ~45º (see the North indicator, in Figure 3.2a and Figure 3.2b) in order to reduce the number of land points in the model area.

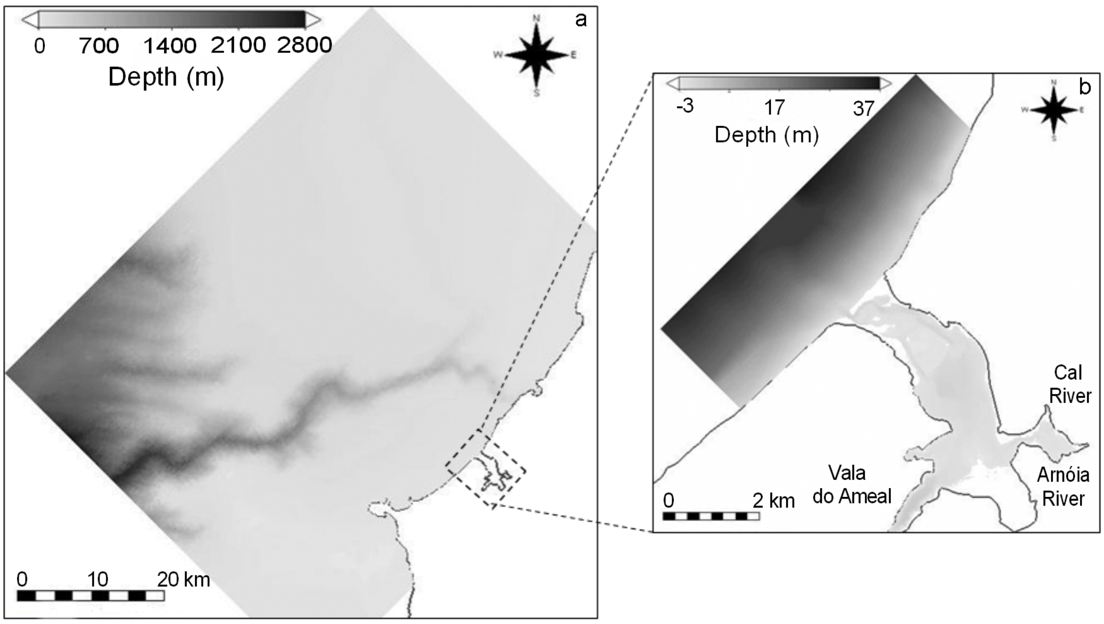


Figure 3.2. Domain bathymetry for the two-nested model implemented: (a) Nazaré-Peniche coast; and (b) Óbidos Lagoon. The freshwater fluxes are marked in the Óbidos Lagoon domain.

The first level covers the Nazaré-Peniche coast (between 39.1ºN and 39.8ºN) and uses a variable spatial step Cartesian grid with higher resolution nearshore (100 m) and approximately 200 m offshore. The total number of grid points is 346 by 250 cells. The model was forced through prescribed surface elevations from FES95.2 global tidal solution (Le Provost *et al*., 1998) at the open boundaries in the Northeast, Northwest and Southwest (Figure 3.3a).

The time step was 10 s and the horizontal eddy viscosity was 10 m^2s^{-1}. The model was initialized with 'null-free' surface gradients and zero velocities at all of the grid points. A bottom roughness (Manning) coefficient of 0.022 was adopted.

The second level included the Óbidos Lagoon with a total number of grid points of 300 by 340 cells, and a constant Cartesian grid with higher resolution (25x25 m, the computational grid includes whole area of the lagoon and coastal adjacent waters).

The open boundary conditions were prescribed from the level one assuming the issues for the downscaling process described in Leitão *et al.* (2005). Very briefly, the downscaling methodology consists of interpolating directly the large scale reference solution from Nazaré-Peniche model to the higher resolution model (Óbidos Lagoon). These interpolated fields are the low-frequency reference solution, used to define the initial conditions and the low-frequency open boundary conditions (OBC). The OBC is a hybrid condition that uses a flow relaxation scheme for velocities and a radiation scheme for sea levels.

The sea level was radiated using a boundary condition type proposed by Blumberg and Kantha (1985). For the velocity OBC a Flow Relaxation Scheme (FRS) developed by Martinsen and Engedhal (1987) was used. The method consists of applying a relaxation scheme at the boundary in an extension of 10 cells, considering a decay time that tends to infinite in the cells far away from the open boundary. In this case the relaxation zone considered a distance of 2000 m from the open boundary.

For atmospheric forcing the data from MAMBO Project automatic station (recorded every hour) and concurrent with the simulated period was used. The model was forced by wind speed (ms^{-1}) and direction (degrees from North, clockwise) depicted in Figure 3.3b. This data was imposed in all grid points of the domain assuming only temporal variability. Spatial variability in the area of interest it is not important because a small variability was found in wind data (IHPT, 2001a, b; IHPT, 2002a, b). Wind stress values were calculated by the model throughout the quadratic friction law:

$$\vec{\tau}_w = C_D \rho_a \vec{W} \left| \vec{W} \right| . \tag{8}$$

where C_D the drag coefficient function of wind speed, ρ_a is the air density and W is the wind speed at a height of 10 m over the sea surface. For waves forcing the data from the ADCP (recorded every hour) and concurrent with the simulated period was used (Figure 3.3c). The model was forced by applying the theoretical JONWASP spectrum in the open boundary. Radiation stress values were calculated by STWAVE model and integrated in the refined grid of the Óbidos Lagoon model.

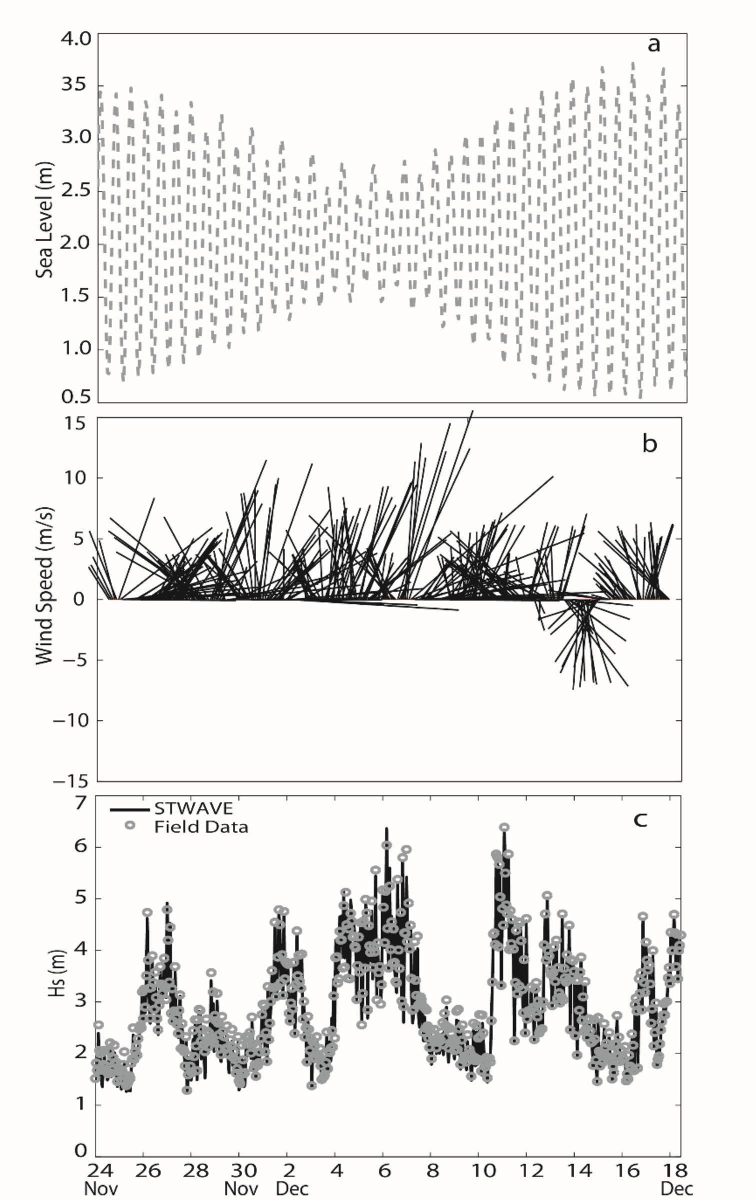


Figure 3.3. Oceanic tide (a), meteorological (b) and coastal waves (c, STWAVE model and ADCP data) forcing for the simulated period.

At the land boundaries (in the upper lagoon) were considered three freshwater fluxes from river runoff: Arnóia, Cal and Vala do Ameal. As the river discharges are relatively small, they are treated as point sources in the model. The data used are constant values, typical of winter and summer months. These are described in more detail in Section 3.3.

The time-step was 5 s and the horizontal eddy viscosity was 2 m^2s^{-1}. The wave roughness was calculated by the model following the approaches proposed by Van Rijn (1989).

A 2D depth integrated model was used, because it was assumed that the study area presents a homogeneous water column, due to the shallow depths and minor freshwater inputs.

3.3.3. Simulations set-up

Water renewal time scales are affected by oceanic tide, wind stress, freshwater fluxes and coastal waves. Though the studies described in the literature about Óbidos Lagoon, it was assumed that tidal forcing is the main driving force of the long-term circulation in the lagoon. Field data of Malhadas *et al.* (2009a) also point for the predominance of storm waves in some periods. So, according to the definitions of Atkinson *et al.* (1981) and scientific knowledge about Óbidos Lagoon circulation, it is believed that lagoon belongs to the class of shallow lagoons, in which the circulation is overwhelmingly tidal.

The RT estimations consist of five model runs, conducted in a similar way. The sole difference between these simulations lies in the selection of the forcings. In the first model run the tidal forcing only is taken into account. Then, the wind stress, the freshwater fluxes and the coastal waves are successively included as steady state processes. The simulations are identified by numbers related to the phenomena in question (Table 3.2). In the table for each model run is included additional information about the forcing (e.g., figures number where the forcing is shown or typical values).

The tidal forcing is activated in all numerical experiments, so that a periodic hydrodynamic regime, independent of the initial conditions, prevails after a few days of simulation. The model was run for the time period between November 1st and December 30th, 2000, being the first 15 days of results considered as a 'spin-up' period. After flow conditions are established the tracer transport module is started. The simulation starts from a distribution of tracers that fill the whole lagoon volume at high tide. The particles are uniformly distributed in the lagoon at the initial instant (t=0).

Table 3.1. Numerical simulation characteristics. The tidal signal is imposed according to **Figure** 3.3a, wind **Figure** 3.3b and waves **Figure** 3.3c. Freshwater fluxes are constant for the two rivers (Cal and Arnóia) and drainage creek (Vala do Ameal). Constant values included dry and wet years (Vão, 1991). The X means that forcing was not taken into account.

	Tide	wind	Freswater Fluxes (m^3s^{-1})			Waves
			Cal	Arnóia	V.Ameal	
1st Simulation	Figure 3.3a	X		X		X
2nd Simulation	Figure 3.3a	Figure 3.3b		X		X
3rd Simulation (dry year)	Figure 3.3a	X	0.1	1.6	0.04	X
4th Simulation (wet year)	Figure 3.3a	X	0.5	5.7	0.2	X
5th Simulation	Figure 3.3a	X		X		Figure 3.3c

3.4. Results and discussion

In the following results from hydrodynamic model validation are presented, comparing sea level and currents measurements with model predictions. To elucidate the renewal process, the spatial patterns of the currents and residual circulation are shown and discussed. Finally, results of RT are presented.

3.4.1. Hydrodynamic model validation

The role of oceanic tide, wind stress, freshwater flows and coastal waves in Óbidos Lagoon sea level fluctuations was investigated by Malhadas *et al.* (2009a). The work was carried out by sensitivity analysis of a two-dimensional model application. Authors concluded that tidal forcing is the main driving force of the long-term circulation in the lagoon. However, in some periods of waves (storm waves) the wave forcing can cause noticeable variations in lagoon sea level.

In our study, is presented the hydrodynamic model validation procedure within lagoon, when the tide is the only forcing (1st simulation) and when coastal waves are included to tide-only simulation (5th simulation). Results from other simulations were not included because it was observed that freshwater fluxes and wind are not relevant in lagoon sea level variability. Figure 3.4 shows the comparison between measurements and model predictions for 1st (tide-only) and 5th simulations (tide with coastal waves included) in the stations depicted in Figure 3.1. Lagoon sea level was compared near the inlet (Station A, Figure 3.4a) and in the arms, Bom Sucesso and Barrosa (Station B, Figure 3.4b and Station C, Figure 3.4c). Current velocities were compared near the inlet (Station D, Figure 3.4d) and along the northern channel (Station E, Figure 3.4e and Station F, Figure 3.4f). The gray dashed curve represents the measurements, the gray curve the tide-only simulation (1st) and the black curve the tide and waves simulation (5th). The comparison was made for 1 tidal cycle, November 29th, 2000 (the only period with available data for currents and sea level).

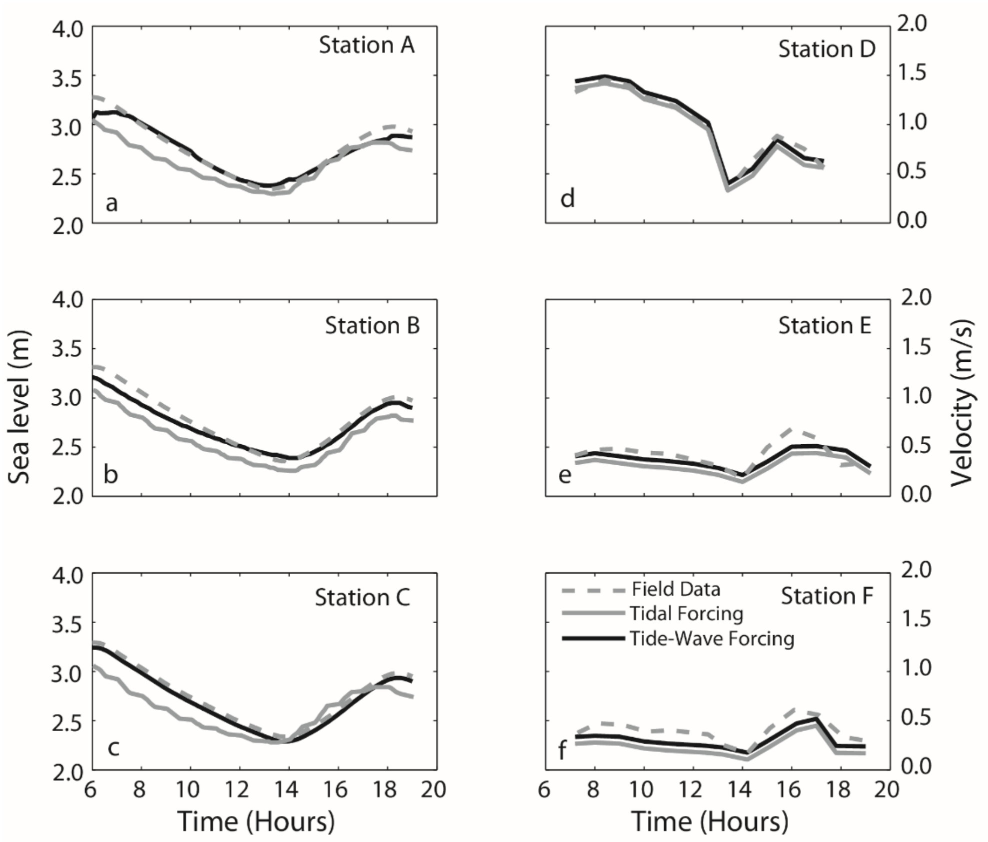


Figure 3.4. Measured and simulated time-series of lagoon sea level in the northern channel (Station A, a) and in the arms –Bom Sucesso e Barrosa (Station B, b and Station C, c) for 29th November 2000. The current velocities are measured and simulated for 29th November 2000, near the inlet (Station D, d) and along the northern channel (Station E, e and Station F, f).

The coherence between the two model-sets was analyzed in terms of correlation coefficient (r), Root Mean Square Error (RMSE), and model performance or accuracy (skill).

The correlation coefficient is a statistical method developed by Pearson (1938). This measures the strength and the direction of a linear relationship between two variables. The mathematical formula for computing r is:

$$r = \frac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{\sqrt{n\left(\sum x^2\right) - \left(\sum x\right)^2}\sqrt{n\left(\sum y^2\right) - \left(\sum y\right)^2}}, -1 \leq r \leq 1 \quad (8)$$

where x is the measured variable and y the predicted variable and n is the number of pairs of data.

The RMSE is a frequently-used measure of the differences between values predicted by a model or an estimator and the values actually observed from the thing being modelled or estimated (Anderson and Woessner). The RMSE is given by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - y_i\right)^2}{n}}$$

where x are the observed values and y the predicted values by the model and n is the number of measurements.

The predictive skill is a statistical method developed by Wilmott (1981) and used recently by Warner *et al.* (2005) and Li *et al.* (2005). This is based on the agreement between model results and observations and it is given by:

$$Skill = 1 - \frac{\sum_{i=1}^{n}\left(x_{Modi} - x_{Obsi}\right)^2}{\sum_{i=1}^{n}\left(\left|x_{Modi} - \overline{x}_{Obs}\right| + \left|x_{Obsi} - \overline{x}_{Obs}\right|\right)^2}, 0 \leq Skill \leq 1 \quad (9)$$

where x is the variable being compared, $\overline{x}$ its time mean and n is the number of measurements.

Results of r, RMSE and skill are presented in Table 3.2. This includes the sea level and current comparisons for tide-only simulation (1st) and tide and waves simulation (5th). The RMSE errors are discussed as percentage of the field data mean value.

In general, results reveal a good agreement between model and observations. However, higher errors were observed when the tide is the sole forcing activated (wave motion is not included). If coastal waves are taken into account, the errors diminish. Sea level predictions present a RMSE between 7% and 9% for tide-only simulation; and 2% and 3% for tide and waves simulation. Current velocity predictions present also higher errors (between 8% and 20%) when the tide is the only forcing. A better correlation coefficients (higher than 0.89) and skills (between

0.80 and 0.98) were obtained when coastal waves are included to tidal forcing. This means that the model tends to reproduce more appropriately the mean tendency in the field data, when wave motion is coupled to the tidal signal. In these conditions, the model accuracy is improved, showing the importance of waves in lagoon sea level variability.

Table 3.2. Correlation coefficient, root mean square error and skill between measurements and model predictions for sea level (A, B, C) and current stations (D, E, F) considering the forcing of tide and tide plus wave forcing.

Stations		Tidal forcing (1st simulation)			Tide-Wave forcing (5th simulation)		
		r	RMSE (m)	Skill	r	RMSE (m)	Skill
A	Sea level	0.97	0.15	0.91	0.98	0.06	0.98
B		0.98	0.16	0.91	0.99	0.07	0.98
C		0.93	0.17	0.88	0.99	0.05	0.99
D	Currents	0.97	0.08	0.79	0.98	0.06	0.80
E		0.88	0.09	0.80	0.89	0.07	0.85
F		0.91	0.10	0.85	0.92	0.08	0.89

Despite statistical differences between both simulations (1st and 5th), the model can qualitatively capture some of the long-term circulation in the lagoon. The variability in the surface currents is well reproduced by the model, revealing the semi-diurnal variation founded in the measurements. As shown by observations and model predictions, the lagoon is flood-dominated, with the duration of the ebb phase (~7h) longer than that of the flood phase (~5h). This tidal asymmetry results in a flood-dominated channel with strong currents in the flood phase. During flood the current velocity is by about 0.75 ms^{-1} (see Figure 3.4c and Figure 3.4f) whilst during ebb 0.20 ms^{-1} (25% weaker in ebb).

3.4.2. Circulation patterns

As known so far away from the Óbidos Lagoon circulation, tide is the most important forcing in defining the lagoon hydrodynamic (Bertin *et al.*, 2009; Malhadas *et al.*, 2009a, 2009b). However, tide does not explain the variability founded in lagoon sea level data, and in some extensions, waves are relevant to understand and highlight the lagoon circulation. The upper lagoon circulation reveals also a dependence of freshwater river discharges in certain periods (e.g., heavy raining periods with freshwater flows higher than average flow rate). Based on this issues the simulations chosen for comparison in the lower lagoon are the 1st (only the tide) and the 5th (tide and waves forcing); and in the upper lagoon are the 1st and the 4th (the tide with freshwater flows for wet year). The other simulations do not introduce additional information and for that reason they were not included. Circulation patterns obtained for tide-only simulation (1st) in the lower lagoon for flood and ebb phases are depicted in Figure 3.5a and Figure 3.5b, respectively. The circulation patterns depicted in Figure 3.5c and Figure 3.5d involve the flood and ebb phases when coastal waves are included to tide-only case (5th simulation). The modelled velocities obtained in both cases agree qualitatively with the measurements displayed in Figure 3.4, with maximum velocities along northern channel during the flood (~1.0 ms^{-1}). Including the wave motion do not modify the current velocities, but significantly alters the circulation scheme. In other words, the intensity of the current velocity is similar in both cases (1st and 5th simulation), but in 5th simulation a noticeable current is present along the coast. If coastal waves are taken into account (5th simulation) it appears an alongshore current (drift current) with southwest direction, not showed in the tide-only circulation scheme.

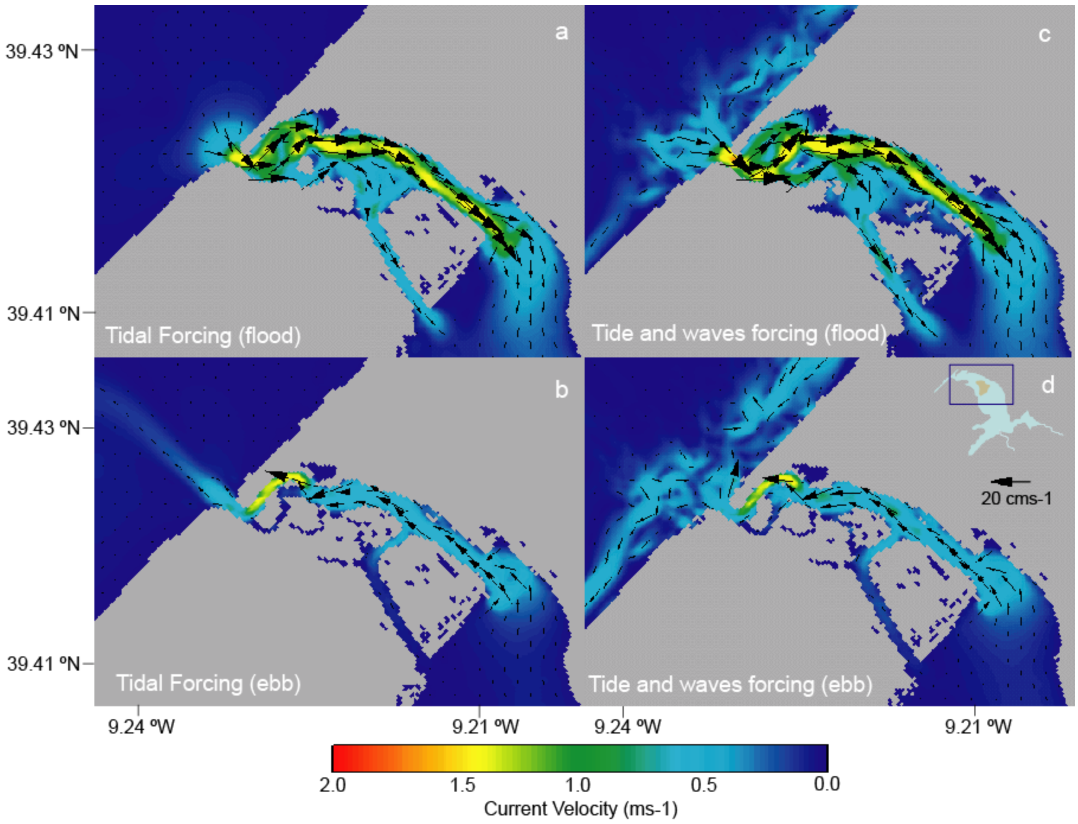


Figure 3.5. Spatial patterns of currents in the lower lagoon, for tidal-wave forcing in flood (a) and ebb (b). The flood and ebb for tidal forcing are represented in (c) and (d), respectively.

Results in the upper lagoon for tide-only simulation (1st) for flood and ebb phases are shown in Figure 3.6a and Figure 3.6b, respectively. Figure 3.6c and Figure 3.6d represents the 4th simulation (the tide with freshwater flows for wet year) for flood and ebb phases. The main difference between these simulations (1st and 4th) is the freshwater river discharge values imposed in the model land boundaries. This means that tidal circulation for the 4th simulation is supplied by river discharges, assuming the typical values during a period of heavy rain (two times more than that the average flux ~3 m^3 s^{-1}). The current velocity exhibit values around 0.4 ms^{-1} if the rivers forcing is zero (activating solely the tide). If the river discharges (flow fluxes to orders of magnitude higher than average fluxes) are taken into account, the water flows with higher current velocities (0.6 ms^{-1}) when compared with the tide-only case (1st simulation). Allowing water to flow through the rivers slightly modifies the magnitude of current velocity and circulation patterns. In particular, the circulation scheme in the upper lagoon exhibits a circulation pattern with current velocities higher 40% than tide-only case.

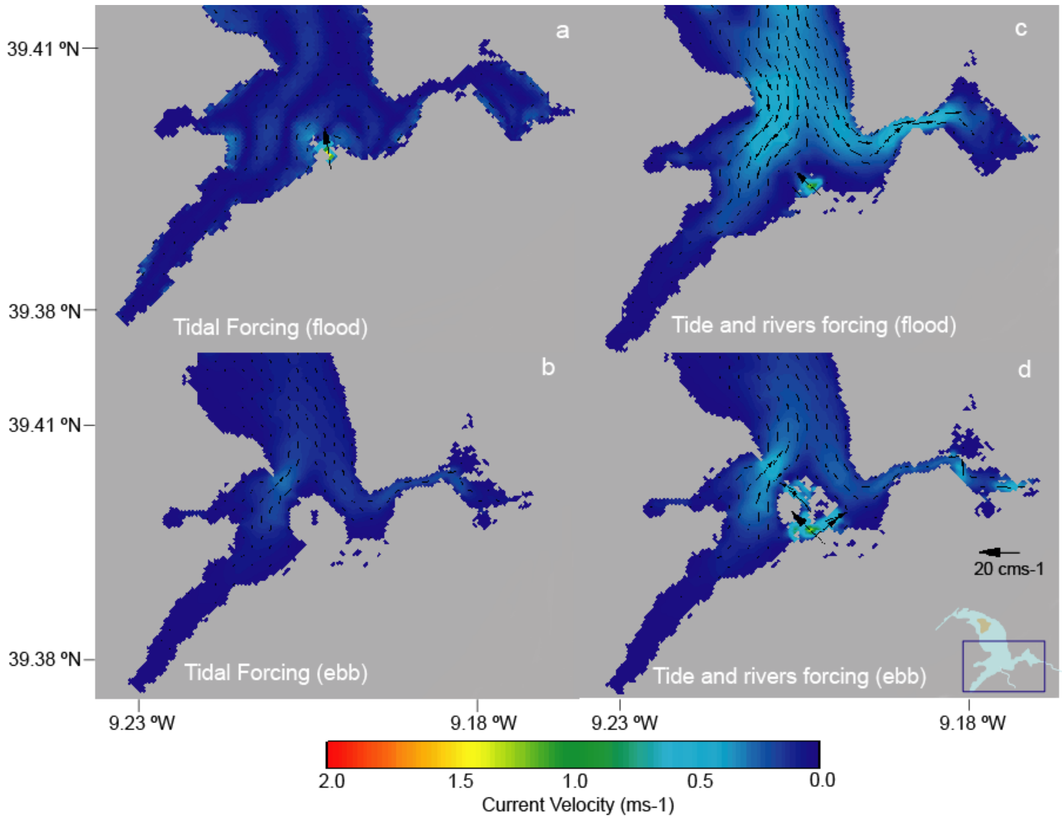


Figure 3.6. Spatial patterns of currents in the upper lagoon, for tidal forcing in flood (a) and ebb (b). The flood and ebb for tidal forcing supplied by river discharges (wet year) are represented in (c) and (d), respectively.

3.4.3. Characteristics of the residual circulation

The residual patterns presented in Figure 3.7 refers to the lower lagoon for 1st (Figure 3.7a, only the tide) and 5th (Figure 3.7b, the tide with waves forcing included). Results from other model simulations are not showed because there are no significant differences between simulations. The residual values were calculated by tidally averaging the transient solution computed by the model for 30 days of integration.

Results reveal a noticeable residual circulation in most of the upper lagoon with a time scale similar to the tidal cycle and amplitude one or two orders of magnitude lower than that of tidal currents. Circulation pathways show two regions for water flows: along the northern channel and in the central body. In particular, a large clockwise gyre develops near the central body (it induces water mixture).

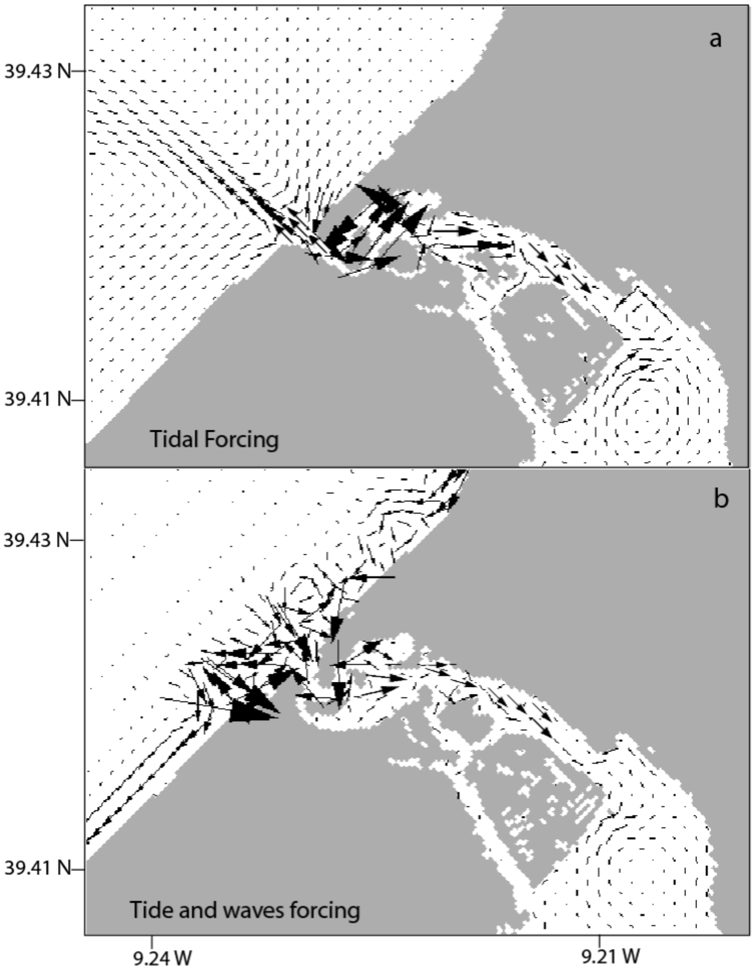


Figure 3.7. Averaged residual flow in the lower lagoon for tidal forcing (a) and tide and wave-induced forces (b).

In the northern channel the residual currents are toward the upper lagoon. These residual currents (induced by tidally circulation) create a transport into the lagoon. The only difference observed between the 1st (tide-only case) and 5th (tide with wave motion included) simulations, is the presence of the drift current. The transport along the coast is negligible if the wave motion in the open boundary is zero. The drift current flows to southward, in response of the incoming waves (90% are from the sectors West and Northwest).

3.4.4. Residence time

Results of RT are presented in Figure 3.8 and Table 3.3. Water RT was estimated for the model runs described in the Section 3.3 and boxes depicted in Figure 3.1. The average RT in lagoon is also estimated and presented.

In the 1st simulation (tidal forcing alone - Figure 3.8a), RT varies between values less than 2 days, close to the inlet, and values over 26 days in the Bom Sucesso arm. A quick renewal is expected at the lower lagoon, because most of the particles are 'flushed out' during the ebb, which is in agreement with residual circulation pathways (Figure 3.7a). The upper lagoon is characterized by weaker velocities (less than 0.4 ms^{-1}, Figure 3.6a and Figure 3.6b) and large RTs. As such, water remains several days over their origin region. When compared to the Venice lagoon, the inner areas of the basin are characterized by a low water renewal capacity and RTs for more than 2 months were obtained by Umgiesser and Cucco (2006). When tidal forcing is supplemented by wind action (2nd simulation - Figure 3.8b) a slight change occurs in the circulation pattern at the lower lagoon. In this case, a residual circulation generated by meteorological forcing promotes the mixture of the water masses near the inlet and also in the central body. Activating the wind forcing decreases slightly water RT (less than 1 day than tidal-only case) in these lagoon areas (inlet and central body). However, water circulation in deepest areas of the lagoon (e.g., Bom Sucesso arm) is not affected, at all, by wind stress. If wind stress is applied slightly modifies the overall circulation within lagoon but is important in the upper lagoon areas (shallow areas). This explains why the average RT for the whole is not affected (~16 days). For the 3rd simulation (Figure 3.8c, tide with river discharges included-dry year flow rate values), similar values of water RT in the lower and upper lagoon were obtained compared with the tide-only case (1st simulation). The effect of river discharges in a dry year is negligible and it is similar to consider the rivers forcing equal to zero (the case of tide alone simulation). It is does not surprising, because freshwater flow rates are of the order of 2-3 m^3s^{-1} which are less than 5% of the average tidal prism.

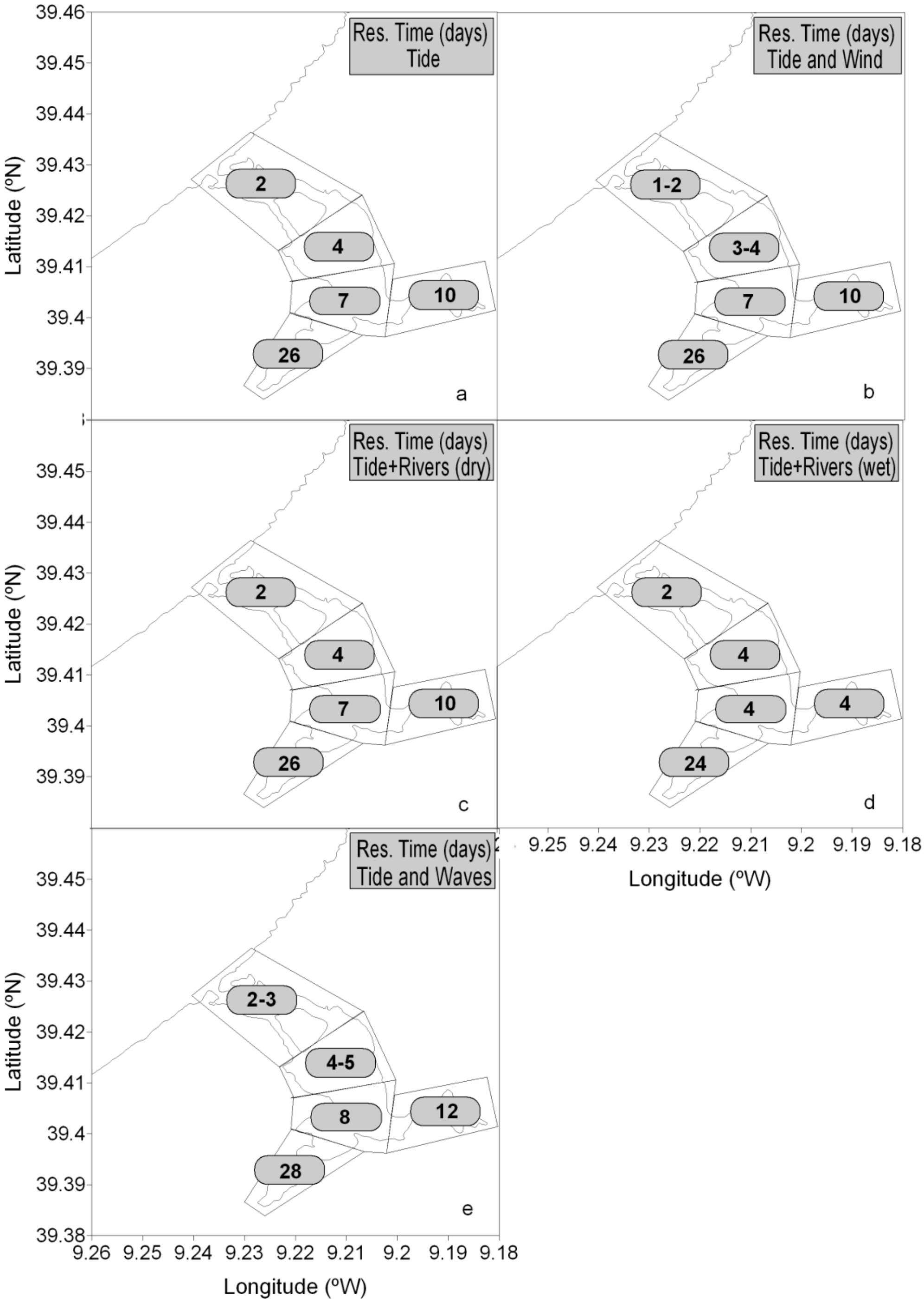


Figure 3.8. Residence time estimation (in days) for each box of Figure 3.1 considering the forcings of: (a) tide, (b) tide and wind stress, (c) tide and river discharges (dry year), (d) tide and river discharges (wet year) and (e) tide and coastal waves.

By comparing the 4th simulation (Figure 3.8d, tide with river discharges forcing-wet year flow rate values) with the 1st simulation in the lower lagoon, no differences were observed. As expected the differences between these two simulations were observed in the upper lagoon, since land boundaries (freshwater river discharges) are located in these part of the lagoon and freshwater flow rates were increased. An increasing in the freshwater flows affect the upper lagoon circulation promoting an increasing in the current velocities by about 40% (Figure 3.6c and Figure 3.6d) when compared with the results provided by the 1st simulation (Figure 3.6a and Figure 3.6b). In response to these changes, water RT decreases in the upper part of the lagoon. Therefore, Box 3 (Arnóia River delta) by about 43%, Box 4 (Bom Sucesso arm) reveals a reduction in RT by about 8% and Box 5 (Barrosa arm) by about 60% (these are always scaled with the 1st simulation).

Table 3.3. Water residence time estimations (days). The values are calculated for each model run in whole lagoon and boxes presented in Figure 3.1.

	Water residence time (days)					
	Box 1	Box 2	Box 3	Box 4	Box 5	Whole lagoon
1st Simulation	2	4	7	26	10	16
2nd Simulation	1-2	3-4	7	26	10	16
3rd Simulation (dry year)	2	4	7	26	10	16
4th Simulation (wet year)	2	4	4	24	4	9
5th Simulation	2-3	4-5	8	28	12	18

When waves are included in tidal forcing (Figure 3.8e), substantial differences were observed in all the regions of the lagoon. In all cases, RT had an excess of 1 or 2 days (10% and 50% depending on the location of the box) compared with the tide-only case. These results reveal the importance of the tide as also waves in water RT. In other words, the average RT in lagoon increases ~11% when compared with the tide-only simulation. It is not surprise that the RT is larger in the tide and waves model simulation than in the tide-only run. The fact is that during storm wave periods, the lagoon sea level rise-up and the water volume increases in the lagoon. This rise in sea level was explained by Malhadas *et al.* (2009) and can be attributed due to radiation stress gradients generated along the waves and also by inlet morphology (depth and length).

3.5. Conclusions

A numerical study was carried out to analyze the influence of physical forcing (tide, waves, wind and freshwater inflows) on the water RT in the Óbidos coastal lagoon. MOHID modeling system with set-of models was implemented. Circulation was studied with hydrodynamic module coupled to STWAVE model (waves model). For the RT a Lagrangian transport module was coupled. The model was validated and verified with measured water-surface levels and currents. The cursory comparison of the computed values with in situ measurements was reassuring as to the realism of the numerical simulations. The model shows ability to reproduce the observed temporal variability founded in measurements, presenting skill coefficients higher than 0.80. However, thoroughly validating the model was not the primary objective of this work, which instead, focused on the identification of the mechanisms affecting the water RT in Óbidos Lagoon.

Using the verified model, were performed five model simulations (varying the selection of the forcings) to estimate water RT in the Óbidos Lagoon. Though the present model results, we conclude that tide and waves are the main driving forces of the long-term circulation in Óbidos Lagoon. RT is not homogeneous in space varying significantly from the upper to the lower lagoon. The different time scales observed from the upper to lower lagoon are enhanced by circulation, which is overwhelmingly tidal. When the waves are activated, the distribution of RT varies, presenting an increasing between 10% and 50% depending on site and box location. It is conceivable that taking into account the variability of coastal waves will modify the modeled RT and reasonable estimations can be obtained if waves are not taken into account. The increasing in RT when coastal waves are included to tidal forcing is explained by the lagoon sea level rise (~1m above the mean lagoon sea level) during storm wave periods. This rises in sea level increase the water lagoon mean volume and consequently a reduction in water exchange between lagoon and sea occurs. In the Óbidos Lagoon case study, it is well known that Barrosa arm (located in the upper lagoon) was exposed along decades to principle sewage discharge of the urban area of Caldas da Rainha. For that reason, this area of the lagoon presents high nutrient concentrations in reduced forms (ammonia and phosphate) and macroalgae (*Ulva sp*) predominance. These conditions combined with episodes where the RT relatively increases in the lagoon, may be harmful for marine species and ecosystem.

The present sensitivity study also points to the importance of the rivers overflow, which surprisingly tends to decrease the water RT in heavy rainy periods. In Box 3 (Arnóia River delta) water RT decreases by about 43%, in Box 4 (Bom Sucesso arm) by about 8% and in Box 5 (Barrosa arm) by about 60% (these are scaled with the tide-only simulation). As expected, the rivers flows modify the circulation in the upper lagoon (higher velocities are created) and diminish RT. Finally, the numerical experiments carried out suggest that water RT in Óbidos Lagoon is approximately 16 days for tide-only case, 9 days if freshwater flows (typical values for wet years) are included to tidal forcing and 18 days when the waves are activated in the tide-only simulation. Nonetheless, these estimations must be regarded with some reservation. In particular, it is believed that taking into account a different variability of coastal waves and other freshwater river flows will modify the modeled RT and the presented values.

3.6. Acknowledgements

This work was carried out with the financial support of Águas do Oeste S.A (AdO), as part of the project “Monitoring and modelling the Óbidos lagoon and Foz do Arelho submarine outfall”. AdO has started on July of 2004, under its direct supervision, a Monitoring Program in the Óbidos lagoon and coastal area, with the support of Instituto Superior Técnico (IST) from the Universidade Técnica de Lisboa (IST) and Instituto de Investigação das Pescas e do Mar (IPIMAR).

3.7. References

Andrejev, O., Myrberg, K. and Lundberg, P.A., 2004. Age and renewal time of water masses in a semi-enclosed basin e application to the Gulf of Finland. *Tellus* 56A, pp. 548-588.

Angwenyi, C.M. and Rydberg, L., 2005. Wave-driven circulation across the coral reef at bamburi Lagoon, Kenya. *Estuarine, Coastal and Shelf Science* 63, pp. 447–454.

Arega, F., Armstrong, S. and Badr, A.W., 2008. Modeling of RT in the East Scott Creek Estuary, South Carolina, USA. *Journal of Hydro-environment Research* 2, pp. 99-108.

Atkinson, M., Smith, S.V, Stroup, E.D., 1981. Circulation in Enewetak atoll lagoon. Limnol. Oceanogr. 26, pp. 1074-1083.

Aure, J., Molvær, J. and Stigebrandt, A., 1996. Observations of inshore water exchange forced by a fluctuating offshore density field. *Marine Pollution Bulletin* 33, pp. 112–119.

Banas, N.S. and Hickey, B.M., 2005. Mapping exchange and residence time in a model of Willapa Bay,Washington, a branching, macrotidal estuary. *Journal of Geophysical Research* 110, C11011. doi:10.1029/2005JC002950.

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

Bilgili, A., Proehl, J.A., Lynch, D.R., Smith, K.W., Swift, M.R., 2005. Estuary/ocean exchange and tidal mixing in a Gulf of Maine Estuary: a Lagrangian modelling study. *Estuarine Coastal and Shelf Science* 65, pp. 607-624.

Blumberg, A. F. and G. L. Mellor, 1987. A description of a three-dimensional coastal model. *Coastal and Estuarine Sciences* 4, pp. 1-16, AGU, Washington, DC.

Bolin, B. and Rodhe, H., 1973. A note on the concepts of age distribution and transit time in natural reservoirs. *Tellus* 25, pp. 58-62.

Braunschweig, F., Martins, F., Chambel, P., Neves R., 2003. A methodology to estimate renewal time scales in estuaries: the Tagus estuary case. *Ocean Dynamics*, 53, pp. 137-145.

Callaghan, D.P., Nielsen, P., Cartwright, N., Gourlay, M.R., Baldock, E.T., 2006. Atoll lagoon flushing forced by waves. *Coastal Engineering* 53, pp. 691–704.

Cancino L. and Neves, R. J. J., 1998. Hydrodynamic and sediment suspension modelling in estuarine systems. Part I: description of the numerical models. *Journal of Marine Systems*, 22, pp. 105-116.

Carvalho, S., Gaspar, M. B., Moura, A., Vale, C., Antunes, P., Gil, O., Fonseca; L. C., Falcão, M., 2006. The use of the marine biotic index AMBI in the assessment of the ecological status of the Óbidos lagoon (Portugal). *Marine Pollution Bulletin* 52, pp. 1414–1424.

Chen, X.J., 1998. Wind-wave driven circulation on the coral reef at Bora Bay, Miyako Island. *Earth and Environmental Science* 17(2), pp. 133-143.

Coelho, H.S., Neves, R.J.J., Leitão, P.C., Martins, H., Santos, A., 1999. The slope current along the Western European Margin: a numerical investigation. Oceanography of the Iberian Continental Margin. *Bol. Inst. Esp. Oceanography* 15, pp. 61– 72.

Fortunato, A.B. and Oliveira A., 2007a. Case Study: Promoting the Stability of the Óbidos Lagoon Inlet. *Journal of Hydraulic Engineering*, 133 (7), pp. 816-827.

Fortunato, A.B. and Oliveira A., 2007b. Improving the Stability of a Morhodynamic Modeling System. *Journal of Coastal Research*, 50, pp. 486-490.

Garcia, A.C.M., 2008. Fine Sediments resuspension processes and transport in Nazaré Submarine Canyon" Dissertation presented to the Instituto Superior Técnico of the Universidade Técnica de Lisboa, for the PhD degree in Environmental Engineering. 150 p., published (in English).

Gillibrand, P.A., 2001. Calculating exchange times in a Scottish fjord using a two-dimensional, laterally-integrated numerical model. *Estuarine Coastal and Shelf Science* 53, pp. 437-449.

Hakanson, L., Kvarnas, H. and Karlsson, B., 1986. Coastal Morphometry as regulator of water exchange—a Swedish example. *Estuarine, Coastal and Shelf Science* 23, pp. 873–887.

IHPT, 2001a. *Monitorização Ambiental da Lagoa de Óbidos NOV 2000 – JUN 2001*. Relatório Técnico Final, Report TF. 08/ 2001 (in Portuguese).

IHPT, 2001b. *Monitorização Ambiental da Lagoa de Óbidos JUL 2001 – DEZ 2001*. Relatório Técnico Final, Report PT. OC. 06/2001 (in Portuguese).

IHPT, 2002a. *Monitorização Ambiental da Lagoa de Óbidos DEZ 2001 – ABR 2002*. Relatório Técnico Final, Report PT. OC. 02/2002 (in Portuguese).

IHPT, 2002b. *Monitorização Ambiental da Lagoa de Óbidos MAI 2002 – AGO 2002*. Relatório Técnico Final, Report PT. OC. 05/2002 (in Portuguese).

IST, 2003. EUROSTRATAFORM. Relatório Técnico Final, MARETEC, pp.11 (in Portuguese).

Jozsa, J. and Kramer, T., 2000. Assessing Water Exchange Mechanisms in Complex Lake and Coastal Flows By Modelling the Spatial Distribution of Mean residence time. In Proceedings of XXIX. IAHR Congress (http://www.vit.bme.hu/kt/doc/peking_a.pdf).

Le Provost, C., F. Lyard, J.M. Molines, M.L. Genco and F. Rabilloud, 1998. A Hydrodynamic Ocean Tide Model Improved by assimilating a satellite altimeter derived dataset. *J. Geophys. Res*., Vol. 103 N. C3.

Leendertsee, J., Liu, S., 1978. A three-dimensional turbulent energy model for non-homogeneous estuaries and coastal sea systems. In: Nihoul, J. (Ed.), Hydrodynamics of Estuaries and Fjords. Elsevier, Amsterdam, pp. 387– 405.

Leitão, P., Coelho; H., Santos, A., Neves, R., 2005. Modelling the main features of the Algarve coastal circulation during July 2004: A downscaling approach. *Journal of Atmospheric and Ocean Science*, 10 (4), pp. 1-42.

Knudsen, M., 1900. Ein hydrographischer Lehrsatz. Annalen der Hydrographie und Maritimen Meteorologie. Juli, 1900, 316–320 (in German).

Kraines, S.B., Yanagi, T., Isobe, M., Komiyama H., 1998. Wind-wave driven circulation on the coral reef at Bora Bay, Miyako Island. *Earth and Environmental Science* 17 (2), pp. 133-143.

Malhadas, M.S.., Leitão, P.C., Silva, A., Neves, R., 2009a. Effect of coastal waves on sea level in Óbidos Lagoon. *Continental Shelf Research* 29 (9), pp. 1240-1250.

Malhadas, M.S., Silva, A., Leitão, P.C., and Neves, R., 2009b. Effect of the bathymetric changes on the hydrodynamics and residence time of the Óbidos Lagoon (Portugal). *Journal of Coastal Research* SI56, pp. 549-553.

Martins, H., Santos, A., Coelho, E.F., Neves, R., Rosa, T.L., 1999. Numerical simulation of internal tides. *J. Mech. Eng. Science*. 214C, pp. 867– 872.

Martins, F., Leitão, P.C., Silva, A., Neves, R., 2001. 3D modelling in the Sado estuary using a new generic vertical discretization approach. *Oceanologica Acta*, 24 (1), pp. 551-562.

Martinsen, Eivind A. and Harald Engedhal, 1987. Implementation and testing of a lateral boundary scheme as an open boundary condition in a barotropic ocean model, *Coastal Engineering* 11, pp. 603-627.

Monsen, N.E., Cloern, J.E., Lucas, L.V., Monismith, S.G., 2002. A comment on the use of flushing time, residence time, and age as transport time scales. Limnology and Oceanography 47 (5), pp. 1545-1553.

Mudge, S.M., Icely, J.D. and Newton, A. 2007. RTs in a hypersaline lagoon: Using salinity as a tracer. *Estuarine, Coastal and Shelf Science* 77, pp. 278-284.

Oliveira, A., Fortunato, A.B. and Rego, J.R.L., 2006. Effect of morphological changes on the hydrodynamics and flushing properties of the Óbidos Lagoon (Portugal). *Continental Shelf Research*, 26, pp. 917-942.

Pearson, E. S., 1938. *An appreciation of some aspects of his life and work*. Cambridge University Press.

Persson, J., Hakanson, L. and Pilesjo, 1994. Prediction of surface water turnover time in coastal water using digital bathymetric information. *Environmetrics* 5, pp. 433–449.

Rasmussen, B. and Josefson, A.B., 2002. Consistent Estimates for the residence time of Micro-tidal Estuaries. *Estuarine, Coastal and shelf Science* 54, pp. 65-73.

Rego, J., 2004. *Hidrodinâmica da Lagoa de Óbidos*. B.Sc. Thesis for the B.Sc. degree in Geophysical Sciences—Oceanography, Faculdade de Ciências da Universidade de Lisboa, published (in Portuguese).

Rougerie, F., Ricard, M., Mazaury, E. 1984. Le lagon de atoll de Mururoa. Notes et Documents Oceanographiques, vol 16, ORSTOM, Papeete.

Santos, A., Martins, H., Coelho, H., Leitão, P., Neves, R., 2002. A circulation model for the European ocean margin. *Applied Mathematical Modelling* 26 (5), pp. 563-582.

Saraiva, S., Pina, P., Martins, F., Santos, M., Neves, R., 2007. Modelling the influence of nutrient loads on Portuguese estuaries. *Hydrobiologia* 587, pp. 5–18.

Sheldon, J. and Alber, M., 2002. A comparison of RT calculations using simple compartment models of the Altamaha River Estuary, Georgia, *Estuaries* 25 (6B), pp. 1304–1317.

Smith, J. M., Sherlock, A.R., and Resio, D.T., 2001. STWAVE: Steady-state wave model user's manual for STWAVE, Version 3.0. ERDC/CHL SR-01-1, U.S. Army Engineer Research and Development Center Vicksburg MS (http://chl.wes.army.mil/research/wave/wavesprg/numeric/wtransformation/downld/erdc-chl-sr-01-11.pdf).

Soetaert K. and Herman, M.J., 1995. Estimating estuarine residence times in the Westerschelde (The Netherlands) using a box model with fixed dispersion coefficients. *Biomedical and Life Sciences* 311 (1-3), pp. 215-224.

Soulsby, C. and Tetzlaff, D., 2008. Towards simple approaches for mean residence time estimation in ungauged basins using tracers and soil distributions. *Journal of Hydrology* 363 (1-4), pp. 60-74.

Stamou, A.I., Memos, C.D. and Kapetanaki, M.E., 2007. Modelling water renewal in a coastal embayment. *Maritime Engineering* 160 (3), pp. 93-104.

Taboada, J.J., Prego, R., Ruiz-Villarreal, M., Montero, P., Gómez-Gesteira, M., Santos, A.P., Pérez-Villar, V., 1998. Evaluation of the seasonal variations in the residual patterns in the Ria de Vigo (NW Spain) by means of a 3D baroclinic model. *Estuarine, Coastal Shelf Science*. 47, pp. 661– 670.

Takeoka, H., 1984. Fundamental concepts of exchange and transport time scales in a coastal sea. *Continental Shelf Research* 3, pp. 311-326.

Thattai, D.V. and Kjerfve, B., 2003. Numerical modeling of tidal and wind-driven circulation in the Meso-American barrier reef lagoon, Western Caribbean. *Oceans* 5 (22-26), pp. 2930-2937.

Umgiesser, G. and Cucco, A., 2006. Modeling the Venice Lagoon residence time. *Ecological Modelling* 193 (1-2), pp. 34–51.

Van Rijn, L.C, 1989. *Sediment Transport by Currents and Waves Handbook*. Delft Hydraulics, Report H 461 p.

Vão–Arquitectos Associados, 1991. *Estudo de Recuperação e Ordenamento da Lagoa de Óbidos, Concha de São Martinho do Porto e Orla Litoral Intermédia*. Vols. I, II and V (in Portugese).

Vaz, N., Dias, J.M., Leitão, P.C. and Nolasco, R. 2007. Apllication of the MOHID-2D model to a mesotidal temperate coastal lagoon. *Computers & Geosciences*, 33, pp. 1204-1209.

Vaz, N., Dias, J.M., Leitão, P.C., Nolasco, R., 2009. Three-dimensional modelling of a tidal channel: The Espinheiro Channel (Portugal). *Continental shelf Research* 29 (1), pp. 29-41.

Warner, J.C., Geyer, W.R. and Lerczack, J.A., 2005. Numerical modeling of an estuary: a comprehensive skill assessment. *Journal of Geophysical Research* 100 (CO5001).

Wilmott, C.J., 1981. On the validation of models. *Physical Geography* 2, pp. 184-194.

Zimmerman, J.T.F., 1976. Mixing and flushing of tidal embayments in the Western Dutch Wadden Sea. Part I: distribution of salinity and calculation of mixing time scales. *Neth J Sea Res* 10, pp. 149-191.

4. Effect of bathymetric changes on the hydrodynamic and residence time in Óbidos Lagoon (Portugal)

Madalena S. Malhadas[a], Adélio Silva[b], Paulo C. Leitão[b] and Ramiro Neves[a]

[a] *Instituto Superior Técnico, Depto. de Mecânica, Av. Rovisco Pais, 1049-001 Lisboa, Portugal*
[b] *Hidromod, Modelação em Engenharia, Lda., Av. Manuel da Maia, nº 36, 3º Esq., 1000-201 Lisboa, Portugal*

Published in: Journal of Coastal Research, SI 56 (549-553), **Impact Factor:** 0.98

Abstract

Óbidos Lagoon is a small coastal system connected to the sea through a shallow, narrow and mobile inlet. The lagoon is characterized by large accretion rates and cyclic water quality problems due to large water renewal time scales. Over the years the inlet position often drifted from north-south and south-north. As a consequence, every time the inlet position approaches to the north or south shoreline the associated erosion threatens local houses and some emergency interventions to protect the northern shoreline were needed in the past. In the 1990s Danish Hydraulic Institute (DHI) proposed some local solutions to improve the water fluxes between the lagoon and the ocean, and to create conditions to maintain the inlet in a central position. These interventions included the construction of a guiding wall to prevent the inlet migration to the north. However, in the last years an extreme migration of the inlet to south was observed, generating severe erosion problems and damage to the local houses. This paper investigates the effect of artificial morphological changes (e.g., dredging works) on tidal propagation and residence time (RT) in Óbidos coastal lagoon. Hydrodynamic and RT simulations were performed for three bathymetric configurations of the lagoon, representing the reference or present situation and two dredging scenarios. The results confirmed that tidal propagation depends strongly on the bathymetric configuration. Dredging the channels and relocating the inlet may increase the tidal prism by about 20% to 35% in relation to the reference scenario. The major differences are observed in the lower lagoon with an improving in velocity fields in the north and south channels and the reposition of the inlet to the central position. The tidal prism increasing promotes higher water renewals in the lower lagoon and contributes to improve the water quality in this area. In the upper lagoon the effects of the dredging, it are less visible and relevant changes in the water RT (of the order of 3 weeks) were not observed. The most relevant changes can be observed after dredging the Barrosa branch, with an increasing in the RT on the order of 50% compared to reference situation.

Keywords: MOHID, Bathymetric changes, Hydrodynamic, Residence time, Inlet, Óbidos Lagoon.

4.1. Introduction

Óbidos Lagoon is a small and shallow, Portuguese coastal lagoon located between Nazaré-Peniche at west coast (39º24´N, 9º17’W, Figure 1). The lower lagoon, connected to the sea trough a shallow, narrow and mobile inlet (on the order of 100 m width), is characterized by narrow channels and large sand banks. The velocities in this region often exceed 1 ms^{-1} along the northern channel and of about 1.6 ms^{-1} in the inlet (Malhadas, 2008). The upper lagoon is characterized by small velocities (less than 0.4 ms^{-1}, Malhadas, 2008) and muddy bottom. A detailed description of the system is given in Malhadas *et al.* (2009, 2010).

The bathymetry can vary significantly on monthly time scales. The morphological evolution is essentially driven by tidal currents and, in a smaller extent, by waves (Fortunato and Oliveira, 2007a). For instance, the main channel can migrate very rapidly and, within a few months, a meander can form and disappear.

The lagoon problems are mostly related to its morphological evolution (Fortunato and Oliveira, 2007b), differing substantially from the lower to the upper lagoon. In the lower lagoon the instability of the inlet constitute the major problem. In the upper lagoon-characterized by progressive accretion rates- the low water renewal rates are one of the major problems. This contributes to water quality deterioration in this lagoon area.

In the past, several strategies were implemented to minimize the problems referred to above. These strategies include several dredging works in the northern and southern channels as well as the inlet reposition in 1995, 1999, 2001 and 2003 (Fortunato and Oliveira, 2007b). These dredging efforts were complemented by the construction of a guiding wall that was built near the northern shoreline (DHI, 1997). After this intervention, until the winter of 2008 the inlet remained close to the south margin suggesting that the structure solved one of the major concerns-the protection of the northern shoreline (Fortunato and Oliveira, 2004). However, the southward migration of the inlet to started top pose new security problems in the south shoreline, and, to prevent the excessive erosion in this area, a temporary solution based on the disposal of sandbags in the beginning of the winter, was adopted in recent years (Figure 4.1, location of the sandbags). This, was however a remediation solution requiring sometimes recharging during the winter period because the sandbags are often removed by waves and current actions, and falls into the channel. In order to achieve more effective and permanent solutions different studies were conducted by Laboratório Nacional de Engenharia Civil-LNEC (LNEC, 2002). As a result of these studies, were proposed two type of interventions (Figure 1): the construction of a new guideline wall to keep the inlet in a central position and the execution of a number of dredging operations in the northern and southern channels (solution 1) to increase the tidal prism and to achieve better self-maintenance conditions. The second intervention (solution 2) proposed as a part of this project; include the same interventions for the solution 1 plus dredging Barrosa branch and Arnóia river delta.

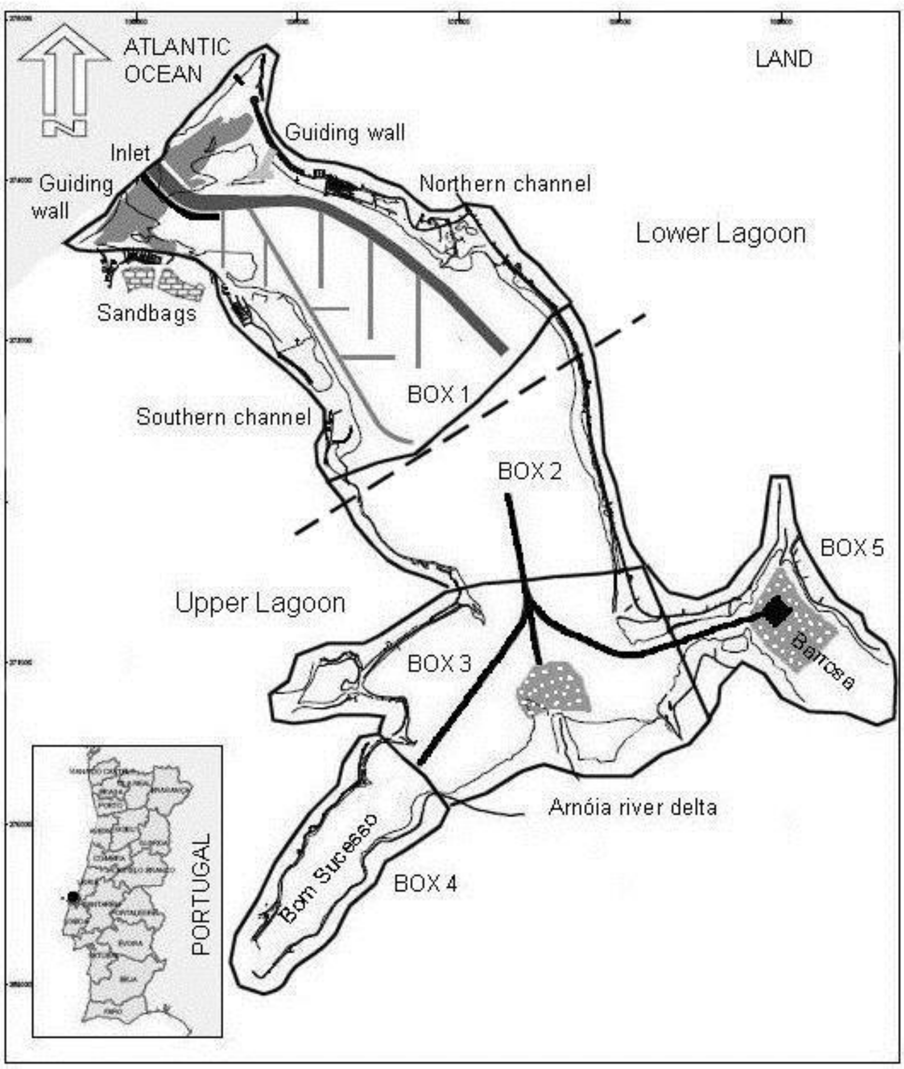


Figure 4.1. Geographical location and place names of the Óbidos Lagoon. The lagoon is divided into 5 boxes for the residence time analysis. Bathymetric configurations proposed within the lagoon are also marked (solution 1- guideline wall, main channels, 7 transverse channels and a main channel in the central body with connection to Bom Sucesso and Barrosa branch, solution 2- the same strategy referred previously plus dredging the Barrosa branch and Arnóia river delta).

The study described herein aims to evaluate the effect of the bathymetric changes on the hydrodynamic and RT in Óbidos Lagoon, in face of the proposed dredging works. This evaluation was based in the execution of numerical simulations using MOHID modelling system. A total of three scenarios including the reference situation and two project solutions were evaluated. For all of these scenarios tidal propagation and current fields were analysed with the support of the hydromorphological model. The wave-current interaction was computed coupling STWAVE (Steady-State Spectral Wave-STWAVE) model to MOHID. The RT was evaluated using a Lagrangian transport approach, coupled with the circulation model.

The paper structure is as follows: Section 2 describes the model physics and configuration for the Óbidos Lagoon; and in the following sections the results and conclusions are presented.

4.2. Methods

4.2.1. Morphodynamic modelling system (MOHID)

The MOHID modelling system is a fully non-linear, three-dimensional, baroclinic water model developed in the Technical University of Lisbon (IST). MOHID is under continuous development; the home page can be found at http://www.mohid.com. Some of the key features of the model are highlighted below and a complete description of the model can be found in Martins *et. al.* (2001).

The implemented modelling system (Figure 4.2) is able to simulate the non-cohesive sediment-dynamics in lagoon driven by tide, waves and rivers flows. It integrates MOHID hydrodynamic (Aires *et al*., 2005; Neves *et al*., 2000), sand transport modules (Silva *et al*., 2004) and STWAVE model (Smith *et al.*, 2001).

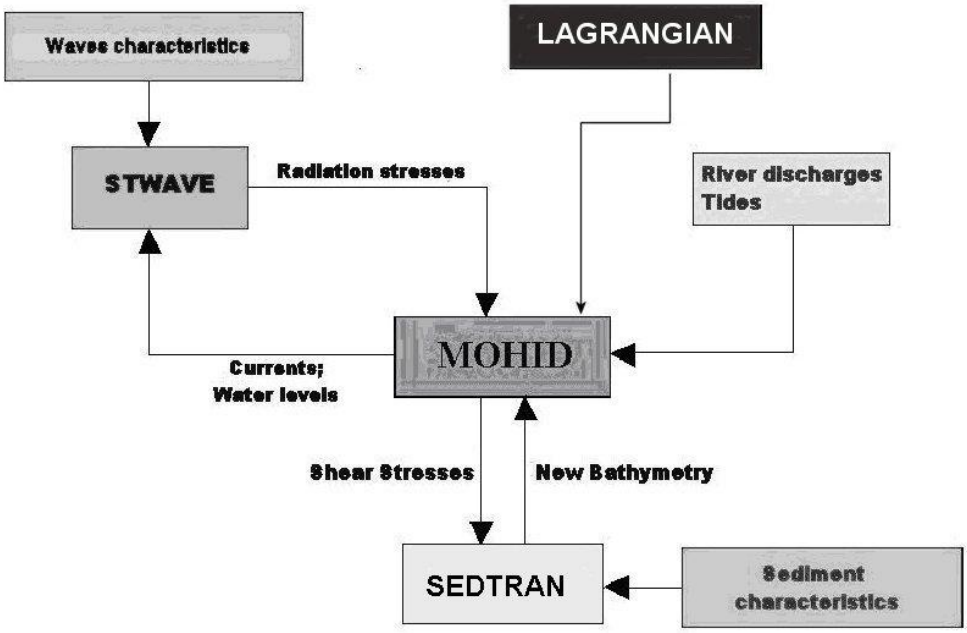


Figure 4.2. MOHID morphodynamic modeling system.

The MOHID hydrodynamic model solves the equations of motion with a finite volume technique for volume conservation. Wave radiation stresses were computed with STWAVE model based upon the linear wave theory for shallow water-waves (Smith *et al*., 2001). The sediment fluxes due to waves and currents were computed with the Van Rijin (1989) formula. Bottom is updated with a predictor corrector in time using a mobile bed approach.

MOHID Lagrangian transport module (Braunschweig *et al.*, 2003; Saraiva *et al*., 2007) was coupled to circulation model and used to evaluate RT in different areas of the lagoon, assuming the residence time as the time required to water or tracers leave the lagoon. For calculus, lagoon was divided into five boxes (Figure 4.1), filled with Lagrangian tracers having the volume, spatial coordinates, and the number of the box, where they were released as associated properties. Boxes were divided based on previous knowledge of physical and biologic characteristics of the lagoon. Box 1 represents all inlet part until the central body, box 2 represents the central body, and box 3 represents the delta of Arnóia River. The branches are covered by box 4 (Bom Sucesso) and box 5 (Barrosa).

4.2.2. Model configuration for the Óbidos Lagoon

The configuration applied in the Óbidos coastal lagoon included two levels of nested models with one-way coupling (Figure 4.3). This nesting methodology is described in detail in Leitão *et al*., (2005).

The first level covers the Nazaré-Peniche coast (between 39.1ºN and 39.8ºN) with a grid spacing less than 100 m nearshore and about 200 m offshore. The model is forced through prescribed surface elevations from FES95.2 global tidal solution (Le Provost *et al*., 1998) at the open boundaries (see Figure 4.3a). The model is 2D and is initialized with null-free surface gradients and zero velocities in all grid points. This level was used only to prescribe the open sea boundary conditions for the second level. For that reason a 2D model was implemented.

The second level includes the Óbidos Lagoon and the transition zone between coastal waters with a constant grid spacing of about 25 m. The solution of tide in level one was downscaled to this level. The open boundary was also forced with the coastal waves. Boundary wave conditions used Hs, Tp and average direction derived from typical values measured at west Portuguese coast (Malhadas *et al.*, 2009). The theoretical JONWASP spectrum was applied at the model boundary.

Freshwater fluxes from river runoff were specified at three locations at the Óbidos Lagoon model (Figure 4.3b) for each of the three small rivers: Arnóia (3 m^3s^{-1}), Cal (0.14 m^3s^{-1}), and Vala do Ameal (0.08 m^3s^{-1}) (Vão, 1991). A 2D depth integrated model was used because it was assumed that study area presents a homogeneous water column due to shallowness depths and minor freshwater inputs. A more detailed description and model validation of the 2D Óbidos Lagoon model can be found in Malhadas *et al.*, 2009).

The hydrodynamic and residence time simulations covered a period of 1 month. For sediment fluxes long periods were required and for that reason simulations have been performed for 5 years.

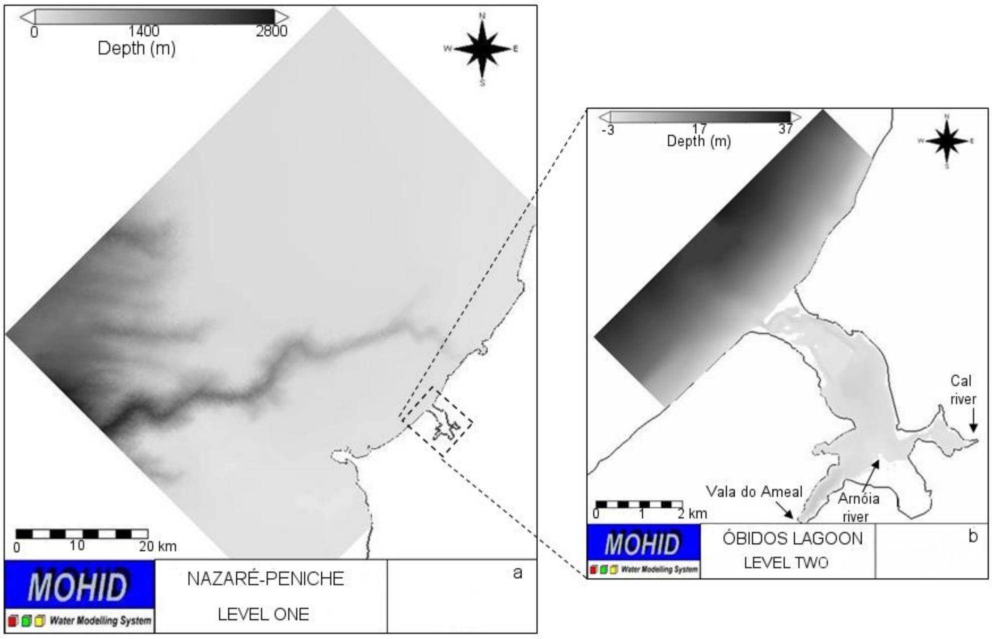


Figure 4.3. Domain bathymetry for the two implemented nested models: (a) Nazaré-Peniche coast and (b) Óbidos Lagoon. The freshwater fluxes are marked in the Óbidos Lagoon domain.

4.3. Results and discussion

4.3.1. Sea level and tidal prism

Figure 4.4 compares sea level model predictions in the reference situation and dredging scenarios for spring tide (Figure 4.4a) and for neap tide (Figure 4.4b) conditions, at a station measurement in the middle of the northern channel.

In general it can be concluded that substantial differences will be observed after dredging operations (dashed and light grey curve) in terms of amplitude and duration of the tide compared with the reference situation (black curve). Similar results were obtained for solution 1 and 2 because the dredging operations proposed for the upper lagoon are the same in both project solutions.

As we can see from the results, the reference scenario reveal a flood dominated lagoon-stronger currents during the flood phase with the duration of the ebb phase (~7h) longer than that of the flood phase (~5h). After dredging operations lagoon tidal asymmetry will be significantly reduced; the ebb phase lasts similar than the flood phase (~6h). In terms of the tide amplitude the differences it are more visible for spring tide and ebb conditions.

The feasibility of maximizing ebb dominance is achieved through transverse channels (optimal depth and orientantion-45º between main and secondary channels); they are the relevant part of the overall solution. This indicates that transverse channels improve the ability of the velocity flow during the ebb.

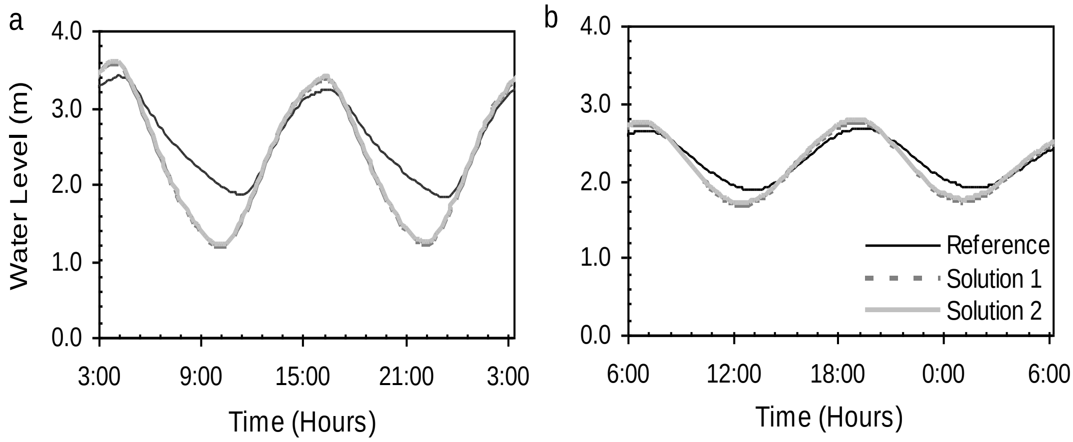


Figure 4.4. Lagoon sea level predicted by the model for the reference scenario (black curve), solution 1 (dashed grey curve) and solution 2 (light grey curve).Spring tide (a) and neap tide (b).

Tidal prism results are shown in Figure 4.5 during a spring-neap tide for reference scenario and project solutions. Model predictions suggest an increasing in tidal prism by about 20% to 35% (depending on the tide) after dredging. This is evident from the fact that tidal amplitude will be increasing as referred to above.

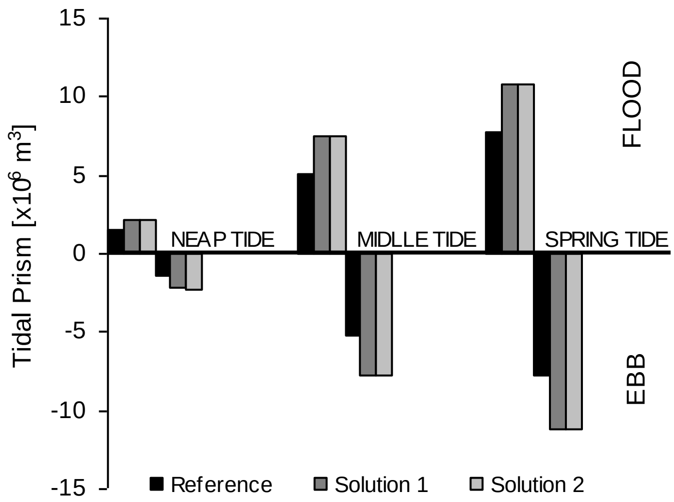


Figure 4.5. Tidal prism model predictions during a spring-neap tide cycle for the reference scenario (black bar), solution 1 (grey bar) and solution 2 (light grey bar).

4.3.2. Currents

Comparison between currents in the reference scenario (black arrows) and artificial changes (grey arrows) for flood and ebb times is depicted in Figure 4.6. The timing chosen to analyse the currents patterns reflects the case of the instant that corresponds to maximum current.

Here, only the results of one solution in the lower lagoon are presented, because the artificial changes proposed, are the same in both solutions. The upper lagoon is not represented because there are no significant differences between phases (ebb and flood) and scenarios.

Results reveal that one of the major differences observed in the circulation patterns is at the lagoon entrance, due to the reposition of the inlet to the central position. Other differences are introduced by the dredging operations and are most significantly visible for ebb times. After dredging the channels it appears a circulation along the south channel for ebb and flood, whereas in the reference scenario only occurs for flood. This result is explained due to the effect of the transverse channels, which improves the tidal propagation in the entire lagoon. For that reason, after dredging, the water flows easily. The effect of the transverse channels will be more visible on maximum sea level, which is in the end of the ebb and in the beginning of the flood. In terms of magnitude it will be observed strongest currents for ebb and flood, diminishing the flood dominance, as required.

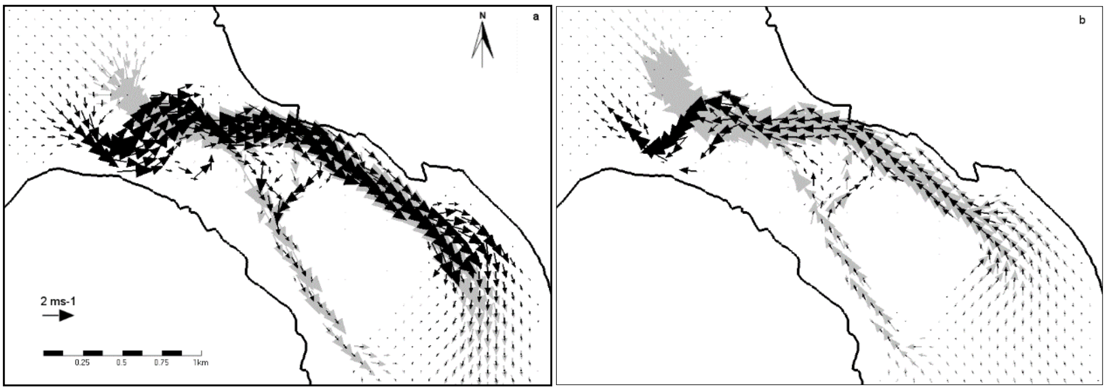


Figure 4.6. Spatial pattern of currents in the lower lagoon for flood (a) and ebb (b) times. Comparison between reference scenario (black arrows) and artificial changes (grey arrows).

4.3.3. Deposition zones

Accretion zones predicted by the model for the reference scenario are presented in Figure 4.7a and for the project solutions in Figure 4.7b. Results presented here are evaluated only qualitatively because sand model was not validated since we don’t have available data. In the first case (reference) accretion occurs mainly in northern channel and at the end of it. This result is a consequence from residual circulation which induces a residual transport within lagoon. After dredging’s the accretion along the main channel, will be reduced in line with the reduction of the flood currents. According to the models predictions these interventions contribute to minimize the problems of the sand accretion although they do not represent a definitive solution. Predictions suggest that accretion is not stopped and it still occurs in the lagoon.

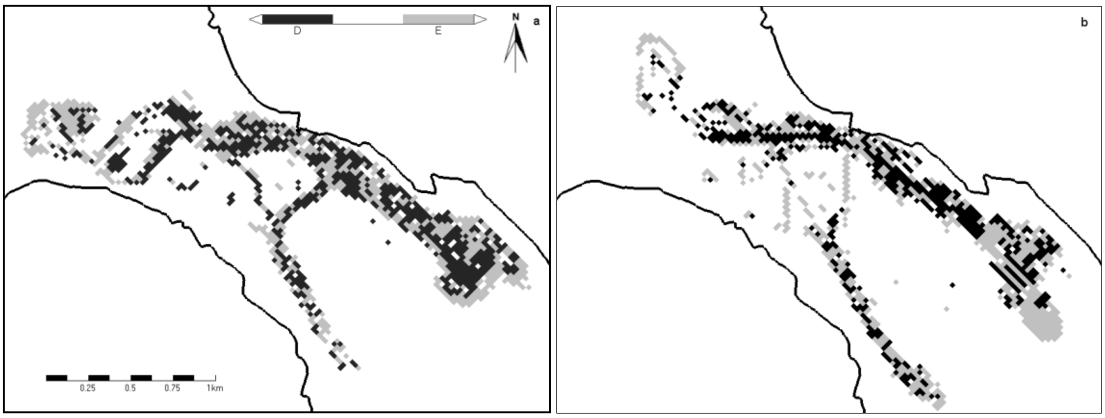


Figure 4.7. Accretion zones predicted by the model in the lower lagoon for the reference scenario (a) and artificial changes (b). The grey colour meant accretion.

4.3.4. Residence time

RT results for reference scenario, solution 1 and solution 2 are presented in Table 4.1. The residence time was calculated for the areas presented in Figure 4.1. In the reference scenario, residence time varies between values less than 2 days close to the inlet and about 24 days in the Bom Sucesso branch. A quick renewal occurs in the lower lagoon, because velocities are strong (~ 2 ms^{-1}); particles are “flushed out” in every tidal cycle. The upper lagoon is characterized by larger RT, because velocities are weaker-less than 0.4 ms^{-1}. As a consequence water remains several days over this region. For project solution 1, a reduction by about 50% in RT will be expected in Box 1 and Box 2 when compared with reference scenario. This occurs due to tidal prism increasing. In the lower lagoon, modest reductions could be expected, with a broad interval between 8% (Box 4) and ~30% (Box 3). In the project solution 2 larger differences will be expected in Box 5 relative to the reference scenario and solution 1. In this case model predictions suggest an increasing in residence time by about ~40% for Box 5 (Barrosa branch). This kind of response is due to the fact that the export of the water through the channel or lagoon branch depends on the relation between capacity of the cross-sectional channel area and the volume of the bay created after dredging. This could be an unfavorable result because Barrosa branch is the most sensible area of the lagoon, since it was exposed throughout the decades, to principle sewage discharge of the Caldas da Rainha urban area. Hence, the area presents peculiar conditions, with high nutrients concentration in reduced forms (ammonia and phosphate) and predominance of macroalgae, *Ulva sp.* (Santos *et al.*, 2006).

Table 4.1. Residence time (in days) for all scenarios (reference, solution 1 and solution 2).

BOX	Reference	Solution 1	Solution 2
Box 1	2	1	1
Box 2	4	2	4
Box 3	6	4	4
Box 4	24	22	22
Box 5	5	5	8

4.4. Conclusions

Strategies to avoid the lagoon´s accrettion and to prevent the safety of local houses at the lagoon margins were presented and compared providing MOHID model predictions. Two project solutions were evaluated: Solution 1 includes a guideline wall to limit the inlet migration, dredging of the main channels and 7 transverse channels in the lower lagoon, and a main channel in the central body with connection to Bom Sucesso and Barrosa branches; Solution 2 adds to the solution 1 the dredging of the Barrosa branch and Arnóia river delta. Numerical model results for solution 1 and solution 2 compared with the reference scenario, suggest the following remarks: Proposed dredging strategies minimizes flood dominance and maximize ebb dominance as required. Proposed guideline wall prevent inlet movements to the south and contributes for the safety of the local houses. In Bom Sucesso branch it will be expected an increasing in the RT by about 40% compared with the reference scenario. This could be an unfavourable result for this particularly area, due to its biologic activity.

4.5. Acknowledgements

This work was funded by INAG project “Revision of the environmental management plan for the Óbidos lagoon”. The writers would like to thank to NEMUS and HIDROMOD for the permission to publish the work.

4.6. References

Aires, J.P., Nogueira, J., Martins, H., 2005. Survival of sardine larvae off the Atlantic Portuguese coast: a preliminary numerical study. *Journal of Marine Science* 62, 634-644.

Braunschweig, F., Martins, F., Chambel, P., Neves, R., 2003. A methodology to estimate renewal time scales in estuaries: the Tagus estuary case. *Ocean Dynamics*, 53, 137-145.

Danish Hidraulic Institute, DHI, 1997. *Hydraulic and Sedimentologic Studies design of a Dike/Channel System*, Relatório realizado no âmbito do Projecto para a Fixação da Aberta da Lagoa de Óbidos, INAG, pp.112.

Fortunato, A.B. and Oliveira A., 2007a. Improving the stability of a morphodynamic modeling system. *Journal of Coastal Research*, 50 pp. 486-490.

Fortunato, A.B. and Oliveira A., 2007b. Case Study: Promoting the Stability of the Óbidos Lagoon Inlet. *Journal of Hydraulic Engineering*, 133 (7), pp. 816-827.

Fortunato, A.B. and Oliveira A., 2004. A modeling system for tidally driven long-term morphodynamics. *Journal of Hydraulic Reasearch*, 42 (4), pp. 426-434.

Leitão, P., Coelho; H., Santos, A., Neves, R., 2005. Modelling the main features of the Algarve coastal circulation during July 2004: A downscaling approach. *Journal of Atmospheric and Ocean Science*,10 (4), pp. 1-42.

Le Provost, C., Lyard, F., Molines, J. M., Genco, M. L., Rabilloud, F., 1998. A hydrodynamic ocean tide model improved by assimilating a satellite altimeter derived data set. *Journal of Geophysical Research-Oceans,* 103, pp. 5513-5529.

Laboratório Nacional de Engenharia Civil, LNEC, 2002. *Análise da Implementação do Plano de Gestão Ambiental da Lagoa de Óbidos: Simulação de Alternativas de Gestão,* Relatório, LNEC.

Malhadas, M.S., Leitão, P.C., Silva, A., Neves, R., 2009. Effect of coastal waves on sea level in Óbidos Lagoon. *Continental Shelf Research*, *Continental Shelf Research* 29 (9), pp. 1240-1250.

Malhadas, M.S., Neves, R., Leitão, P.C., Silva, A., 2010. Influence of tide and waves on water renewal in Óbidos Lagoon, Portugal. *Ocean Dynamics* 60, pp. 41-55.

Malhadas, S.M., 2008. *Modelação do impacte de emissários submarinos em zonas costeiras-caso da Foz do Arelho*. Msc. Thesis for the Msc. degree in environmental engineering. Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisboa, Portugal, 95 p.), published (in Portuguese).

Martins, F., Leitão, P.C., Silva, A., Neves, R., 2001. 3D modelling in the Sado estuary using a new generic vertical discretization approach. *Oceanologica Acta*, 24 (1), pp. 551-562.

Neves, R.J.J, Leitão, P.C, Braunschweig, F., Martins F., Coelho, H., Santos, A. and Miranda, R., 2000. The advantage of a generic coordinate approach for ocean modeling. *In Proceedings of Hydrosoft 2000 Conference*, Lisbon.

Santos, M., Neves, R., Leitão, P.C., Pereira, P., Pablo, H., Fernandes, L. D., Carvalho, S., Alves, C., 2006. Qualidade da água da lagoa de Óbidos: Que futuro? *In Proceedings of 12º Encontro nacional de Saneamento Básico*, 24-27 Outubro, Cascais. ISBN:978-972-95302-8-9.

Saraiva, S., Pina, P., Martins, F., Santos, M., Neves, R., 2007. Modelling the influence of nutrient loads on Portuguese estuaries. *Hydrobiologia* 587, 5–18.

Silva, A.J.R., Leitão, J.C. and Abecasis C., 2004, Improving the navigability and safety conditions in Douro estuary inlet, *In Proceedings of ICCE 2004, ASCE*, Ed. by Billy Edge, pp. 3277-3289.

Smith, J. M., Sherlock, A.R., and Resio, D.T., 2001. STWAVE: Steady-state wave model user's manual for STWAVE, V3.0. ERDC/CHL SR-01-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS: http://chl.wes.army.mil/research/wave/wavesprg/numeric/wtransformation/downld/erdc-chl-sr-01-11.pdf).

Van Rijn, L.C, 1989. *Sediment Transport by Currents and Waves Handbook*. Delft Hydraulics, Report H 461 p.

Vão–Arquitectos Associados, 1991. *Estudo de Recuperação e Ordenamento da Lagoa de Óbidos, Concha de São Martinho do Porto e Orla Litoral Intermédia*. Vols. I, II and V (in Portuguese).

5. Trophic state evaluation after urban loads diversion in a eutrophic coastal lagoon (Óbidos Lagoon, Portugal): A modelling approach

Madalena S. Malhadas[1,2]*, M. Mateus[2], D. Brito[2], R. Neves[2]

[1] HIDROMOD, Rua Rui Teles Palhinha, nº4 - 1º, Leião, 2740-278 Porto Salvo, Portugal
[2] MARETEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001, Lisboa, Portugal

Published in: Hydrobiologia, 740: 231-251, **Impact Factor:** 2.275

Abstract

Óbidos Lagoon is classified as a sensible system according to the eutrophication criteria in the Portuguese Decree-Law 149/2004, which transpose the standards of Urban Waste Water Treatment Directive (Council Directive 91/271/EEC) concerning urban waste-water treatment. From September 2005 onwards the urban loads of five Waste Water Treatment Plant (WWTP) were deviated to a submarine outfall to prevent water degradation and improve the lagoon trophic state (LTS). In this paper is evaluated the LTS after urban loads diversion, testing the hypothesis behind the management decision. First, the loads reaching the lagoon were determined with the Harp-Nut guidelines and watershed modelling (SWAT). Then, the water quality in the lagoon was simulated with a hydro-ecological model (MOHID) and compared with measured data. Finally, management scenarios corresponding to nutrient loads reduction were tested to determine hypothesis-driven LTS. Results showed that the loads from pig farms should be diverted instead of the WWTP, to improve the LTS and achieve a "Good/Bad" status.
The proposed method stresses the importance of integrated modelling tools in the Water Framework Directive, given their skill in testing various hypothesis, and ultimately ruling out inadequate management decisions before implementation.

Keywords: trophic state; hydro-ecological modelling; urban loads; pig farms; EU Water Framework Directive; Óbidos Lagoon.

5.1. Introduction

Coastal lagoons are characterized by high biological diversity and productivity, and they provide valuable ecosystem services. They are also among the areas with higher rates of human occupation and development, resulting in the degradation of their natural characteristics. The impact that human activities have on coastal lagoons, associated to the fact that they usually have a limited renewal of their water, makes them prone to nutrient enrichment and associated degradation in the water quality (Cloern 2001). This is particularly relevant when Waste Water Treatment Plant (WWTP) discharges are present because they are considered as a major nutrient input in coastal systems, with a high potential to deteriorate the water quality (Sanchez-Avila *et al*. 2009; Sanchez-Avila *et al*. 2012; Thieu *et al*. 2010; Volf *et al*. 2013). Despite the efforts in place to reduce point and non-point source nutrient loading, a massive amount of nutrients are tied up in the sediments (e.g., Druschel *et al.* 2005) which can be released under specific conditions (internal loading), perpetuating the eutrophic state and the presence of algae blooms.

The Óbidos Lagoon on the west coast of Portugal is such a system (Figure 5.1a). For decades the lagoon has been under a significant nutrient load pressure originated in the drainage basin, both in the form of point sources (e.g., WWTP and pig farm effluents) or diffusive sources (e.g., runoff from agriculture fields). As a consequence, the lagoon shows symptoms of eutrophication being classified as vulnerable system in the Portuguese Decree-Law n. º 149/2004, June 22, which transpose the standards of Urban Waste Water Treatment Directive- UWWTD (Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment). The UWWTD aims to protect the environment from the adverse effects of urban waste water discharges from certain industrial sectors requiring the collection and treatment of waste water in agglomerations with a population equivalent (p.e) over 2000, and more advanced treatment in agglomerations with a p.e. greater than 10000 in sensitive areas.

Increasing ecosystem degradation and associated demands for the ecological and chemical improvement of surface water quality status, has led the European Union to issue a directive to ensure the sustainable management of water resources throughout Europe, the so called European Union Water Framework Directive –WFD (Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000). Within the context of the WFD, diffuse and point-source nutrient inputs (particularly nitrates and phosphates) to surface and ground waters are viewed as a pressure that may result in an increased risk of eutrophication (Gikas *et al*. 2006, EEB 2001). The fundamental objectives of the WFD are to maintain a high status of inland surface waters, estuarine and coastal waters and groundwater where it exists, prevent any deterioration in the existing status of waters and achieve at least a good status by 2015 (Heinz *et al*. 2007; Krause *et al.* 2007). Member States will have to ensure that a coordinated approach for water management is adopted for the achievement of the objectives of the WFD and for implementation of acting programs for the purposes (Borowski and Hare 2007; de Kok *et al*. 2009).

Águas do Oeste, S.A (AdO), the entity responsible for water management in the west region of Portugal has set up a plan with environment-protected actions to comply with national legislation and WFD. The first action consisted of the reduction of nutrient loads reaching the lagoon by disposing the urban discharges (e.g., the classification as vulnerable system in the Portuguese Decree-Law was based on the WWTP discharges) in the sea through a submarine outfall. The second action aimed at the improvement of sewage treatment in urban discharges that were not connected to the sewage collector. Finally, the last action aimed at setting up a water quality monitoring programme for the lagoon to evaluate the evolution of its state and assess the adequacy of the implemented protective measures.

Despite all the efforts, the lagoon trophic state (LTS) has not changed after the implementation of the management strategies (MS). Eutrophication symptoms are still observed, such as high biomass of phytoplankton (chlorophyll *a* concentrations >15 µg l^{-1}), combined with hypoxia in the upper sediment layers and anoxia in the bottom layers (Pereira *et al*. 2012b; Pereira *et al*. 2009a; Pereira *et al*. 2009b). Apparently, the nutrient load reduction strategies have failed to induce a reduction in the LTS.

The present study established an integrated approach for the trophic state study design and conduction in Óbidos Lagoon. Point source pollution and their removal from the catchment area to a submarine outfall formed the basis for the hypothesis about the dominant loads in determining the LTS. The approach uses an integrated methodology designed in order to cover the hydro-ecological dynamics, and to test the hypothesis and its implication for the management of the lagoon. Field measurements, the combination of a nutrient accounting balance tool (Harmonized Quantification and Reporting Procedures for Nutrients or Harp-Nut guidelines) and a watershed model (SWAT) coupled to a hydro-ecological model (MOHID) for the lagoon were used. To test hypothesis-driven LTS a five years water quality model results and data of the Óbidos Lagoon was analyzed and combined with management scenarios.

The developed approach provides a tool for careful decision-making in WFD study design and might be applied to various types of catchments and pollution situations.

5.2. The study site

Óbidos Lagoon is a shallow coastal system, located in the west coast of Portugal (39º24´N, 9º17'W; see Figure 5.1a). It is 4.5 km long and has a maximum width of 1.8 km in the central body (Oliveira *et al*. 2005). Surface area is approximately 4.4 km^2 at mean sea level and 8.0 km^2 at high spring tide; the mean depth is ~2 m, and maximum depth is 3 m (Oliveira *et al*. 2006). The lagoon has a complex bathymetry, divided into two main regions, the lower and the upper lagoon (Figure 5.1a), each with its own set of physical conditions. The lower lagoon is connected to the sea by narrow and mobile inlet (100 m wide) and composed by one main channel (northern channel). Inlet position and channels configuration in this area have changed naturally during the last decades due to erosion-deposition processes (Oliveira *et al*. 2005). The upper lagoon comprises a large shallow basin, two elongated branches (Bom Sucesso and Barrosa, hereinafter BSB and BB) and a small embayment on the southern margin (Poça das Ferrarias). Two main rivers and a drainage tributary are identified in the upper lagoon: the Arnóia/Real River (3 $m^3 s^{-1}$ average flow), the Cal River (0.14 $m^3 s^{-1}$ average flow) and Vala do Ameal (0.08 $m^3 s^{-1}$ average flow).

For decades the lagoon has been the main receptor of urban discharges from the cities in the west region of Portugal. From September 2005 the urban loads of Óbidos, Carregal, Charneca, Caldas da Rainha e Foz do Arelho WWTP were deviated to the coastal adjacent waters through a submerged submarine outfall. The sewerage system serves 70 000 inhabitants generating a flow of 0.35 $m^3 s^{-1}$. Presently, the only urban discharge made directly into the lagoon is the Casalito WWTP. The treatment plant receives 0.01 $m^3 s^{-1}$ of daily inflow serving 920 residents. In summer months the generated flow is 0.06 $m^3 s^{-1}$ for 2000 fluctuate inhabitants. BB is the most impacted area, by the continuous loads of Caldas da Rainha WWTP that reach the branch via Cal River.

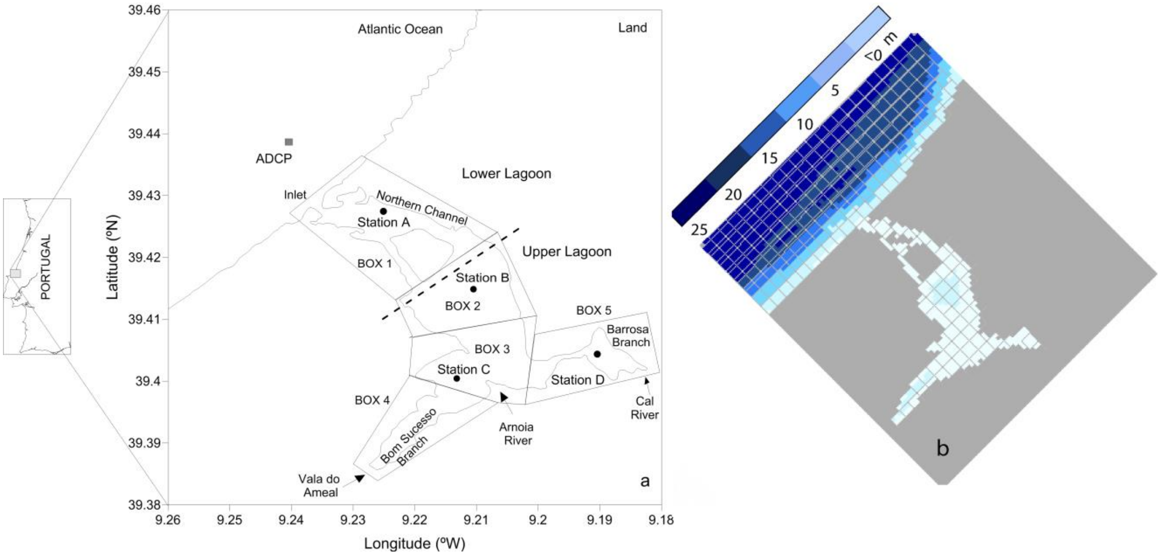


Figure 5.1. Geographical location of Óbidos Lagoon and sampling station locations (●): station A (near the inlet), station B (central bay), station C (Bom Sucesso Branch) and station D (Barrosa Branch). Major tributaries are also marked with arrows. Station providing waves condition is marked as ADCP station. (b) Model domain and bathymetry of the Óbidos Lagoon (depth in meters).

5.3. Methods

5.3.1. Field data

A water-quality monitoring programme was set up by AdO to assess the state of water quality before and after MS. The programme, named FASO (Foz do Arelho Submarine Outfall), was active from October 2004 to December 2009, and aimed at assessing the water quality in the lagoon. Sampling was performed at four stations (Figure 5.1a), located in areas with distinct flushing times (Malhadas *et al*. 2010): Station A near the inlet (-9.2235 W, 39.4270 N) is in an area characterized by a flushing time of 1-2 days, and is considered to be representative of ocean conditions; Station B in the central lagoon (-9.2119 W, 39.4118 N) is an area characterized by a flushing time of 2-4 days, and can be considered as representative of a transitional zone between coastal waters and a body of water under the influence of river discharges (mainly Arnóia/Real Rivers); Station C at BSB (-9.1973 W, 39.4029 N) and Station D at BB (-9.1973 W, 39.4029 N), both located in the upper lagoon near the main freshwater inputs (Vala do Ameal drainage creek, Arnóia/Real and Cal Rivers) in a region with flushing times of 3 weeks and 4-12 days, respectively.

The monitoring program had the periodicity of four times a year (representative of spring, summer, autumn and winter) during a 5-years period. Measured parameters, beside other, included nutrients (nitrate-NO_3^-, nitrite-NO_2^-, ammonia-$NH4^+$ and phosphate-PO_4^{3-}) and chlorophyll *a*. The first 3 campaigns occurred before the submarine outfall started operations, thus being representative of the system before the removal of WWTP inputs to the lagoon. All samplings were performed on the surface (<0.4 m depth) and centered in low-tide, under optimal conditions of riverine influence in the lagoon.

5.3.2. Estimating nutrient loads generated in the watershed

The nutrient loads generated in the basin, both from point and diffusive sources, were estimated before and after September 2005 (reference date for the beginning of the outfall discharge) using the Harp-Nut guidelines and a watershed model. The Harp-Nut or OSPAR guidelines rely on the "Source Orientated Approach" and "Load Orientated Approach" (SOA and LOA). SOA quantify and report on the individual sources of nitrogen-N and phosphorus-P (e.g., agriculture, discharge of urban and industrial effluents) to surface waters. LOA relies on the calculus of N and P with the total riverine loads measured at downstream monitoring points, as load reconciliation. This approach is however conditioned to the availability of data for the quantification of nutrient loads at a given section.

Harp-Nut guidelines validation consisted of a comparison between SOA and LOA in the Arnóia/Real Rivers basin before and after September 2005. The application of Harp-Nut guidelines to the lagoon used the delineation of the monitored basin and monitoring stations depicted in Table 5.2a. Arnóia/Real Rivers basin was chosen to tested and validated the guidelines because i) data is well represented in terms of quality and surface flow, and ii) it is the major basin of the Óbidos Lagoon catchment; ~387 km^2 while the remaining represents only ~40 km^2 (Table 5.2b).

The point sources (WWTP or farming and livestock industry connected to the public sanitation network) were estimated with: i) p.e. data freely available in INSAAR (Inventário Nacional de Sistemas de Abastecimento de Água e de Águas Residuais, http://insaar.inag.pt/), ii) p.e. data of pig farms in the region provided by AdO, iii) capitations recommended by the guidelines (12gN per 60gCBO_5, 2.5gP per 60gCBO_5, and 60g CBO_5 per day per p.e.), and iv) removal percentages recommend by Metcalf and Eddy (2003).

Diffuse pollution considered the resident population not connected to the sanitation network and nutrient runoff from agricultural and forest areas. The population not connected to public network was estimated with census 2001 data (Instituto Nacional de Estatistica, www.ine.pt) and calculated the capitation charges recommended by guidelines for homes with septic tanks (3.1 kgN and 0.43 kgP per p.e and per year). The remaining diffusive loads were calculated with the SWAT model, a continuous-time spatially distributed model that integrates hydrology, vegetation, soil properties and nutrients (total N and total P) at the river basin scale (Arnold *et al.* 1993). The sources of data used in the SWAT included rainfall stations INAG (http://www.inag.pt/), weather stations from IPMA (Instituto Português do Mar e da Atmosfera, https://www.ipma.pt/), NASA DEM (digital elevation model, https://earthdata.nasa.gov) and Land use data at a 1:250000 scale from the Corine Land Cover maps. The SWAT model results are validated with flow data and nutrient concentrations from INAG (Instituto da Água, http://snirh.pt/).

Data from Ponte de Óbidos station (Table 5.2a) was used for the validation of SWAT. Water balance and stream flow validation was first done for average annual conditions, and later was fine-tuned on the monthly records. Flow comparisons were performed from October 1982 to September 1990 (1984 and 1985 years were excluded due to inconsistent data) and concentrations (total N and total P) for 1988 to 2007. Concentrations were compared after a good fit was achieved for the stream flow. The model performance for flow and concentrations was evaluated calculating the correlation coefficient (R). Calibration was performed manually, by slightly changing i) aquifer runoff parameters, ii) land use and soil variables and iii) agricultural practices, such as fertilization.

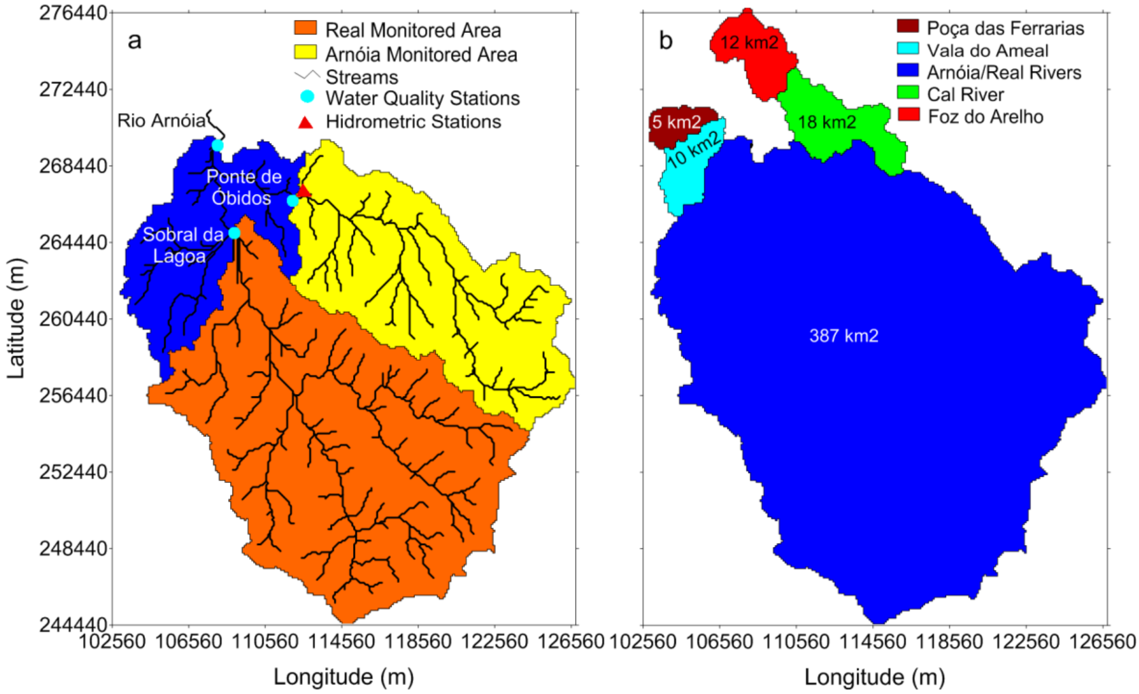


Figure 5.2. Real and Arnóia monitored and non-monitored area used in the Harp-Nut guidelines application (a). The delineation of the basin was made using the Rio Arnóia station. Water quality (dot) and hydrometric (triangle) stations are also marked. Óbidos Lagoon sub-basins area in km^2 (b).

5.3.3. The hydro-ecological model

The MOHID water modelling system was used in this study to simulate the hydrodynamic and ecological processes in the lagoon. The MOHID model (www.mohid.com) is a process-oriented model composed of several modules that address the functioning of different compartments of aquatic systems. These modules can be coupled, thus allowing simulating the complexity of these systems. Only the major features of the model are mentioned here since a detailed description can be found in the literature for the hydrodynamic and transport modules (Leitão *et al*. 2005; Malhadas *et al*. 2010; Martins *et al*. 2001; Mateus *et al*. 2012b), as well as the ecological modules (Martins *et al*. 2003; Saraiva *et al*. 2007; Trancoso *et al*. 2005).

Water quality processes are addressed by an ecological model coupled to the hydrodynamic model, using Euler forward scheme (explicit method). The parameterizations of the ecological processes in water column (pelagic system) follows a NPZD (Nutrient-Phytoplankton-Zooplankton-Detritus) philosophy (EPA 1985). The model solves a set of conservation equations based on the Fransz *et al*. (1991) scheme for phytoplankton, macroalgae, zooplankton, dissolved nutrients (NO_3^-, NO_2^-, $NH4^+$ and PO_4^{3-}), dissolved oxygen (DO), three pools (particulate, refractory and non-refractory) of organic matter (OM). Nutrients, DO and OM are simulated for the pelagic and benthic compartments. N and P biogeochemical cycles are simulated explicitly, and constant Carbon:Nitrogen:Phosphorous (C:N:P) ratios are assumed for OM and phytoplankton. Living components are described in terms of carbon concentration (mgC l^{-1}). Chlorophyll *a* concentrations (µg Chl*a* l^{-1}) were derived from phytoplankton biomass (mgC l^{-1}) using a C:Chl*a* ratio of 90 (Li *et al*. 2010; Mateus *et al*. 2012a). Limiting factors for phytoplankton growth include temperature, light and nutrient availability. Vertical transport fields include particulate material settling, resuspension and benthic diagenesis.

5.3.3.1. Model application

The ecological model was coupled to the hydrodynamic model implemented with one vertical sigma layer (two dimensional) assuming a homogenous vertical structure for the lagoon. The details about the implementation and validation of the hydrodynamic model are presented in previous works (Malhadas *et al*. 2010; Malhadas *et al*. 2009a; Malhadas *et al*. 2009b). As such, we will focus on the implementation of the ecological model. The modelled domain is defined by a 300×340 cells grid rotated by ~45º with constant spatial step of 25 m (Figure 5.1b) to solve hydrodynamic equations, and an integrated mesh with constant spatial step of 75 m for the ecological equations.

Prescribed boundary conditions are open ocean boundary (tide and sea-water biochemical concentrations), land boundary (river and WWTP discharges) and bottom boundary (grid/matrix of nutrients and sediments). Reliable *meteorological forcing* variables such as wind, air temperature, solar radiation and precipitation from Óbidos meteorological station (http://www.inag.pt) were prescribed. The tide was imposed with FES95.2 global tidal solution (Le Provost *et al*., 1998). Representative concentrations for nutrients, chlorophyll *a* and oxygen were also imposed at the ocean boundary (IST/IPIMAR, 2010). Rivers forcing (Arnóia/Real, Cal and Vala do Ameal) were done with SWAT model providing daily river flow and concentrations. Casalito WWTP discharge was defined using monthly flow and nutrient concentrations measured by AdO. Initial conditions were defined for each box depicted in Figure 5.1a, imposing annual average values from the FASO monitoring programme (IST/IPIMAR, 2010). A grid/matrix of non-cohesive sediments and nutrients concentrations was generated also using data from FASO programme and prescribed as bottom boundary condition. A wave model was coupled to the hydrodynamic model to account for the effect of waves on bottom shear stress. Wave conditions such as significant height (Hs), mean period (Tp) and wave direction were prescribed with the data gathered from Acoustic Doppler Current Profiler-ADCP (see location in Figure 5.1a). The model run for the period of the measurements (October 2004 to December 2009) with a time step of 20 s and 3-years spun-up period (October 2001 to October 2004) to achieve equilibrium in the areas of sediment erosion-deposition. Table 5.1 presents a list model parameters and values used in the simulations.

Since the general aim of validation was established the monthly and seasonal (annual and interannual) dynamics of the properties predicted by the model with respect to field data observations, the model performance was evaluated using R and skill. The skill was calculated using the method proposed by Willmott (1981) and other similar studies (e.g., Malhadas *et al*. 2010; Warner *et al*. 2005):

$$skill = 1 - \frac{\sum_{i=1}^{n}\left(x_{Modi} - x_{Obsi}\right)^2}{\sum_{i=1}^{n}\left(\left|x_{Modi} - \bar{x}_{Obs}\right| + \left|x_{Obsi} - \bar{x}_{Obs}\right|\right)^2}, \qquad 0 \le skill \le 1$$

with x as the variable being compared, $\bar{x}$ its mean, and n the number of measurements.

Table 5.1. Ecological model parameters and values used in Óbidos Lagoon simulations. References for parameter values: (1) EPA (1985); (2) Portela (1996); (3) Valiela (1995); (4) Pina (2001).

Parameter	Units	Value	Reference
light extinction water coefficient	none	0.08	(1)
Phytoplankton			
Maximum gross growth rate at the reference temperature (20ºC)	day^{-1}	2.0	Calibrated
Optimum light intensity for phytoplankton photosynthesis	Wm^{-2}	100	(1)
Endogenous respiration constant	day^{-1}	0.0175	(2)
Excretion rate	none	0.07	(2)
Maximum mortality rate at the reference temperature (20ºC)	day^{-1}	0.02	(2)
Phytoplankton growth limitation by P half-saturation coefficient	$mgPl^{-1}$	0.001	(3)
Phytoplankton growth limitation by N half-saturation coefficient	$mgNl^{-1}$	0.014	(3)
Phytoplankton carbon to Chlorophyll ratio	none	30	Calibrated
Zooplankton			
Zooplankton grazing rate on phytoplankton	day^{-1}	0.3	Calibrated
Half saturation constant for zooplankton grazing	$mgCl^{-1}$	0.85	(4)
Minimum prey concentration for zooplankton grazing	$mgCl^{-1}$	0.045	Calibrated
Zooplankton assimilation efficiency coefficient	none	0.80	(4)
Zooplankton mortality rate	day^{-1}	0.09	(1)
Oxygen			
Oxygen/Carbon Ratio in CO2	none	1.28	(4)
Oxygen/Nitrogen ratio in Nitrate	none	3.43	(4)
Oxygen/Nitrogen ratio in Phosphate	none	2.06	(4)
Organic matter Nitrogen/Carbon Ratio (Redfield)	none	0.18	(4)
Organic matter Phosphorus/Carbon Ratio (Redfield)	none	0.024	(4)
Photosynthesis Oxygen/Carbon Ratio	none	2.67	(3)
Nitrogen			
Nitrification rate at 20ºC	day^{-1}	0.06	(2)
Nitrification rate temperature coefficient	none	1.08	(1)
Denitrification rate at 20ºC	day^{-1}	0.125	(1)
Denitrification rate temperature coefficient	none	1.045	(1)
Half saturation constant for nitrification oxygen limitation	mgO_2l^{-1}	2.0	(1)
Half saturation constant for denitrification oxygen limitation	mgO_2l^{-1}	0.1	Calibrated
Phosphorus			
Mineralization rate of dissolved organic phosphorus at 20_C	day^{-1}	0.1	Calibrated
Temperature coefficient for mineralization rate of dissolved organic phosphorus	none	1.06	(3)

5.3.3.2. Management scenarios

Two different scenarios were simulated: Scenario 1 ("No Pig Farms") assumes the removal of N and P loads from pig farms (e.g., 454 tonsN/year and 95 tonsP/year); Scenario 2 ("No Cal

River") represents the elimination of the Cal River loads in the lagoon but maintaining the same loads for the other basins after MS. Scenario 1 is in accordance with the representative loads in the Arnóia/Real Rivers basin and Scenario2 is performed to target the importance of illegal discharges (they still occur after the removal of Caldas da Rainha WWTP). The loads of total N and P considered in the model input for each scenario as well as in the reference situation before and after urban loads deviation ("Ref - Before MS" and "Ref - After MS") are presented in Table 5.2. The results are spatially integrated in six boxes for analysis (Figure 5.1a), following the methodology proposed by Trancoso *et al.* (2005) and Saraiva *et al.* (2007). Boxes outline was based on previous knowledge of the residence time (Malhadas *et al*. 2009a; Malhadas *et al*. 2009b) and ecological dynamics of the lagoon: inlet section until the central body of the lagoon (box 1); the central bay (box 2); delta of Arnóia/Real Rivers (box 3); Poça das Ferrarias embayment (box 4) and branches (box 5, BSB; box 6, BB).

Table 5.2. Total loads of nitrogen and phosphorus considered in the model input for the scenarios and reference situation before and after the management strategies (MS).

Scenarios	N (tons/year)	P (tons/year)	Observations
Ref - Before MS	794	194	Total loads before MS
Ref - After MS	612	136	Considering the reductions in Arnóia/Real and Cal Rivers basin after MS
Scenario 1 - No Pig farms	340	99	Assuming the removal of the pig farms in the Arnóia/Real Rivers basin
Scenario 2 - No Cal River	615	140	Assuming the suppression of the Cal River

5.3.4. Trophic state multivariate index

The trophic state multivariate index (TRIX, Vollenweider *et al.* 1998) to characterize the status of the upper lagoon (problematic areas, BSB and particularly, BB) was used:

$$\text{TRIX} = \left(Log_{10}\left[Chl\, a \times \%DO \times DINP \times DIP + 1.5 \right] \right) / 1.2$$

where $Chla$ is the concentration of chlorophyll a (mg m^{-3}), DO is the dissolved oxygen saturation, $DIN = NO_3^- + NO_2^- + NH_4^+$ $(mg\ m^{-3})$ the dissolved inorganic nitrogen, and $DIP = PO_4^{3-}$ $(mg\ m^{-3})$ the dissolve inorganic phosphorus.

The index was calculated for the reference situation (before and after MS), and for scenarios using oxygen saturation (DO), chlorophyll *a* (Chl *a*) DIN and DIP concentrations provided by the model for the problematic areas (boxes 3, 4, 5 and 6).

5.4. Results

5.4.1. SWAT model validation

Figure 5.3 shows the predicted and measured mean monthly flow from August 1982 to April 1990 at Ponte de Óbidos (Figure 5.2 - 17C/04H INAG code). The model reproduced much of the observed variance and simulated the mean tendency of the measured flow, except in summer months with higher flows (May-August, in 1984, 1985 and 1987), when large discrepancies occurred (Figure 5.3a). These results indicated that the model substantially under-predicts the flows in summer, most probably due to null precipitation forcing. The variance explained by the model was significant in summer months ($P<<0.05$) and, consequently, an R value of 0.65 (Figure 5.4a) between predicted and measured data was obtained. The monthly flow correlation was 10% weakest than values reported by Fohrer *et al*. (2001) and Reungsang *et al.* (2005) for watershed in Germany (R=0.71) and USA (R=0.73), respectively. Overall, the monthly flow predictions were deemed satisfactory given the data limitations, including also some uncertainty for the flow measurements which may have impacted predictions. The comparison between modeled concentrations of total N (Figure 5.3b) and P (Figure 5.3c) and measured data from April 1989 to January 2007, shows that model reproduced the concentrations adequately with a R of 0.68 (Figure 5.4b) and 0.70 (Figure 5.4c), but failed in reproducing the highest peaks (more evident for total N), particularly in summer months. Some of the discrepancies may be attributed to the use of literature based model input parameters for N and P cycling and transport processes (Amatya *et al*., 2013). Other discrepancies may be attributed to the flow predictions in summer months, and sampling methods might also have contributed to model over-and underpredictions.

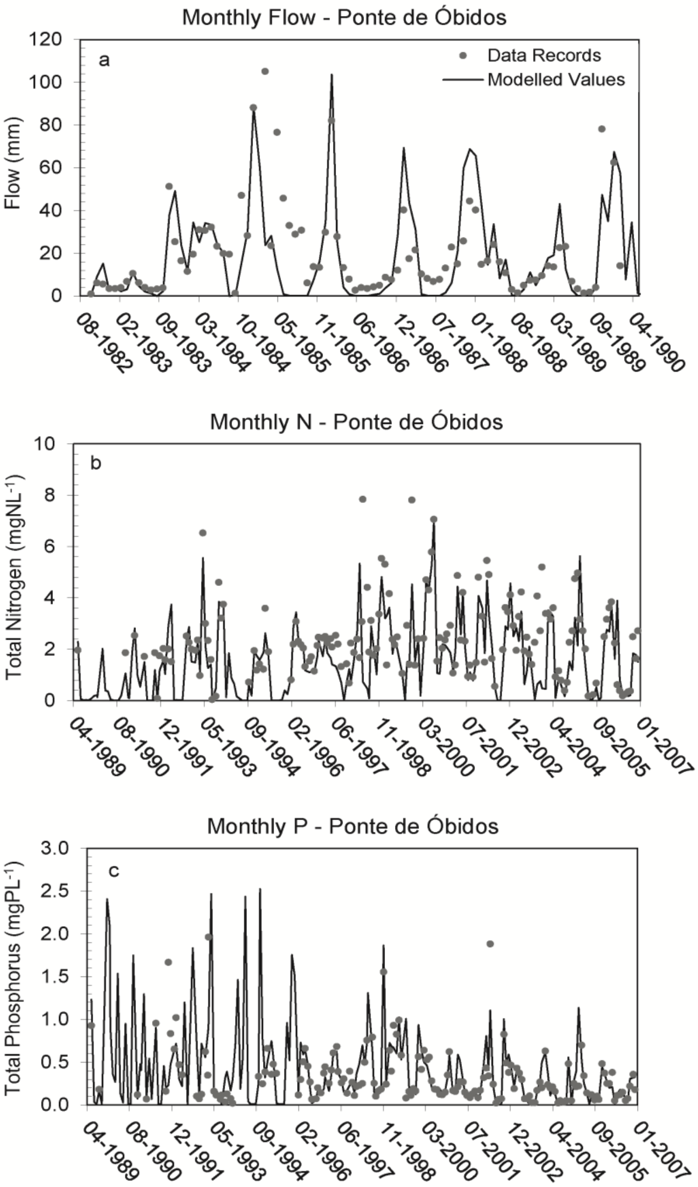


Figure 5.3. Time series of measured and modeled monthly flow (a), total nitrogen (b) and total phosphorus (c) at Ponte de Óbidos monitoring station (Figure 5.2 - 17C/04H INAG code). Data from August 1982 to April 1990 for flow, and April 1989 to January 2007 for concentrations.

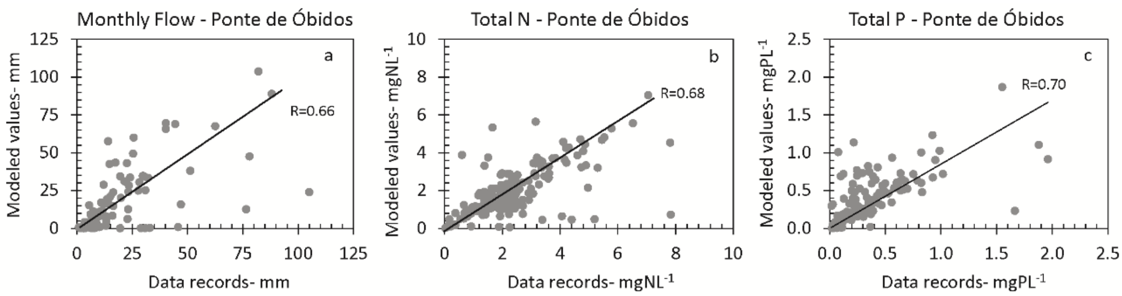


Figure 5.4. Monthly flow (a), total nitrogen (b) and total phosphorus (c): modelled versus measured values. Data measured at Ponte de Óbidos monitoring station (Figure 5.2 - 17C/04H INAG code) from August 1982 to April 1990 for flow, and from April 1989 to January 2007 for nutrients.

5.4.2. *Validation of the ecological model*

The simulated period from October 2004 till December 2009 corresponded to the period of seasonal samplings in the 4 stations within lagoon used for the model validation. Predicted and observed concentrations of nutrients are and phytoplankton biomass are depicted in Figure 5.5 and Figure 5.6. The best fit between data and model results were obtained for $NH4^+$ and NO_3^- $+NO_2^-$. It seems that seasonal and interannual variability is highly dependent on the model input in land (e.g., river discharges of point sources) and sea boundaries. Comparisons between NO_3^- $+NO_2^-$ model results and field data (Figure 5.5) showed high score skills (0.72 and 0.92) and also high correlations (0.73 < r < 0.94) at all stations. There is also a good agreement for $NH4^+$ with strong correlations (0.89 - 0.84) and high skill scores (0.84 - 0.91) in the upper lagoon (stations C and D, respectively). Despite SWAT model under-predict the summer flows; the model is able to reproduce the seasonal and interannual variability of $NH4^+$ and NO_3^-+NO_2^- concentrations since the measured peaks are associated to the winter season (e.g., higher flow rates).

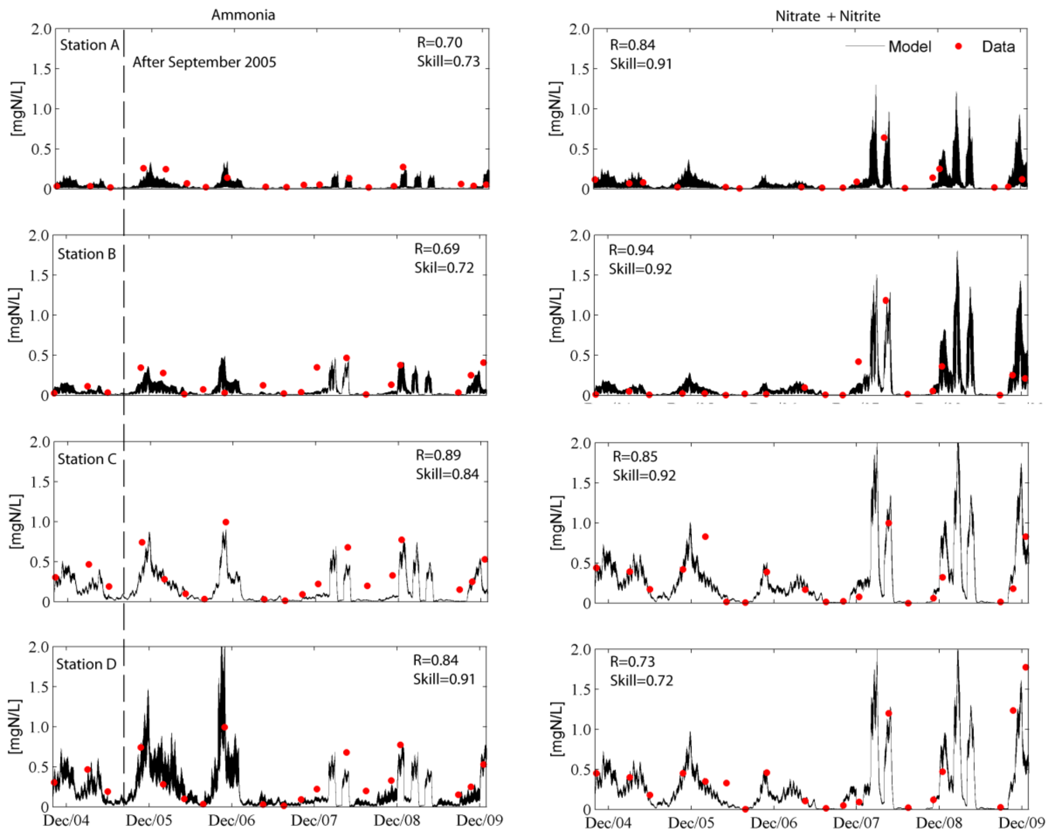


Figure 5.5. Modeled and observed time-series of ammonia and nitrate+nitrite from October, 2004 to December 2009 at A (near the inlet), B (central bay), C (Bom Sucesso Branch) and D (Barrosa Branch) stations.

PO_4^{3-} presents lower correlations in the upper lagoon stations (0.52 in C and 0.40 in D) and higher in the lower lagoon (above 0.65). The lower correlation in the upper lagoon seems to be related with the model failing to reproduce the summer PO_4^{3-} peaks (Figure 5.6) when the river discharges runs dry. A better agreement is also seen for phytoplankton in the lower lagoon, with correlations and skill scores at A of 0.75 and 0.82, respectively; and at B of 0.70 and 0.79, respectively. Correlations (0.63 for C and 0.40 for D) and skill score values (0.66 for C and 0.58 for D) are lower in the upper lagoon. Results suggested that available PO_4^{3-} in the water column could be controlled by other processes since the balance between rivers input and seawater is not enough to explain the seasonal and interannual variability. For that reason PO_4^{3-} and phytoplankton correlations (and skill) seem to be lower in the upper lagoon, particularly in station D (BB area). In fact, with the removal of the three representative PO_4^{3-} summer peaks marked with a circle in station D (see Figure 5.6) and the correspondent for phytoplankton, the predictions adjusted to an R of 0.70 (skill=0.85) and 0.65 (skill=0.70), respectively.

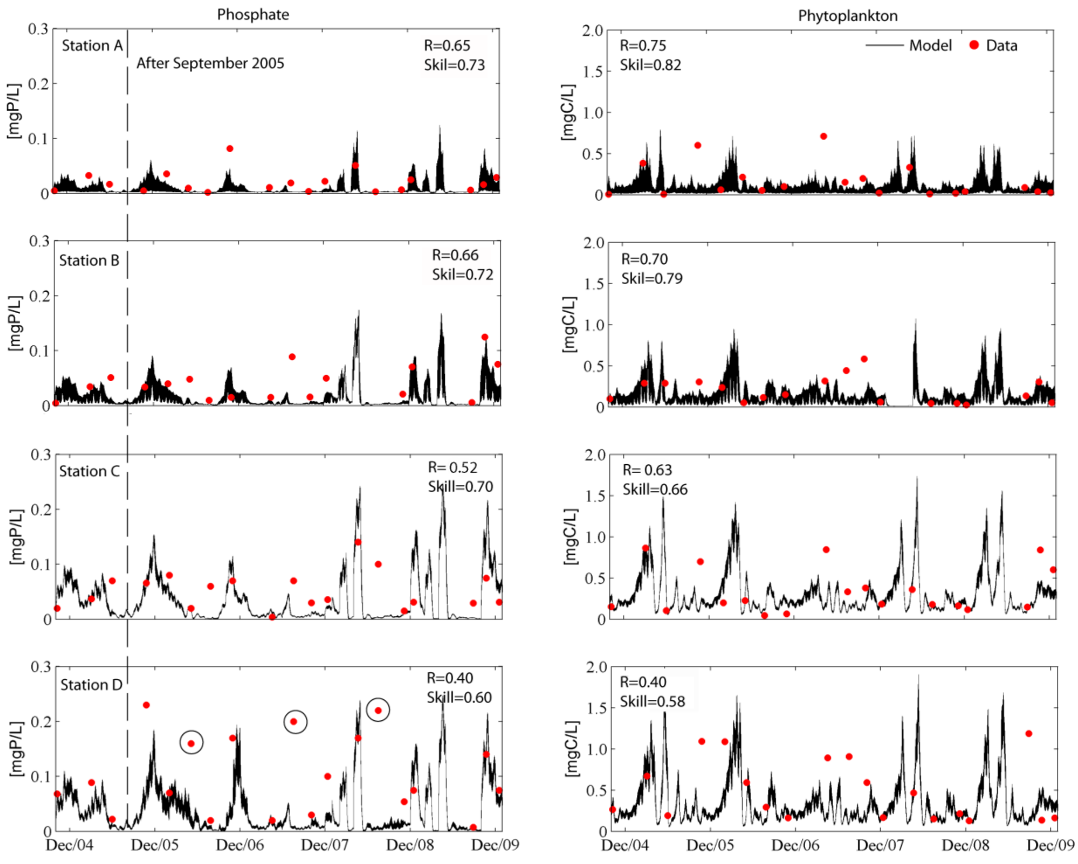
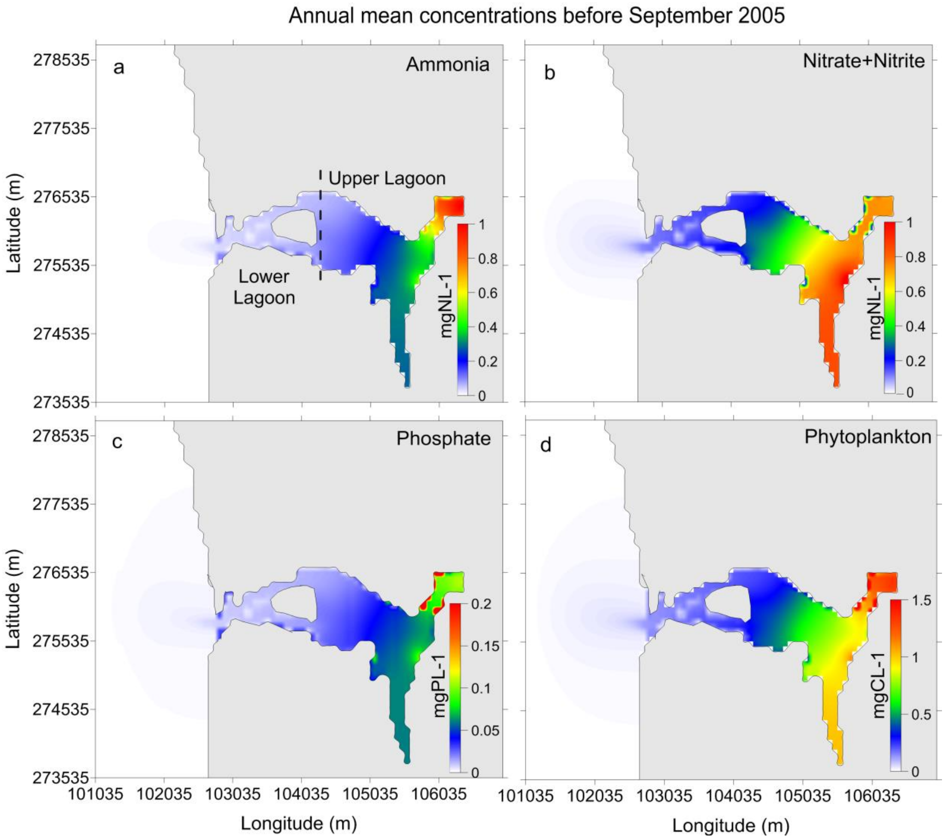


Figure 5.6. Modeled and observed time-series of phosphate and phytoplankton from October, 2004 to December 2008 at A (near the inlet), B (central bay), C (Bom Sucesso Branch) and D (Barrosa Branch) stations. The circles highlight the summer peaks.

5.4.3. Water quality trend before and after removing the urban loads

Figure 5.7 shows annual mean concentrations of nutrients (NO_3^-+NO_2^-, $NH4^+$ and PO_4^{3-}) and phytoplankton biomass generated with model outputs for the period before and after removing the urban loads. Results showed the typical spatial pattern expected in many coastal lagoons with higher nutrient levels and phytoplankton biomass near the catchment areas and lower near ocean influence. The state of water quality reflected the same trend after the suppression of the loads originated in the WWTP effluents: maxima NO_3^-+NO_2^- levels (1.0 mgN l^{-1}) near the Arnóia/Real Rivers delta; and $NH4^+$ (1.0 mgN l^{-1}) and PO_4^{3-} (0.13 mgP l^{-1}) in the confined area of the BB. NO_3^-+NO_2^- concentrations extended to the entire lagoon revealing the dilution effect between outcoming from the Arnóia/Real Rivers and incoming of seawater. Phytoplankton biomass reflected also the conservative mixing between the nutrient-rich freshwater and seawater with maxima reached in the upper lagoon (1.5 mgC l^{-1} ≈ 16.7 μg l^{-1} of Chlorophyll *a* in BB). Contrary, $NH4^+$ and PO_4^{3-} high levels were only pronounced inside BB.



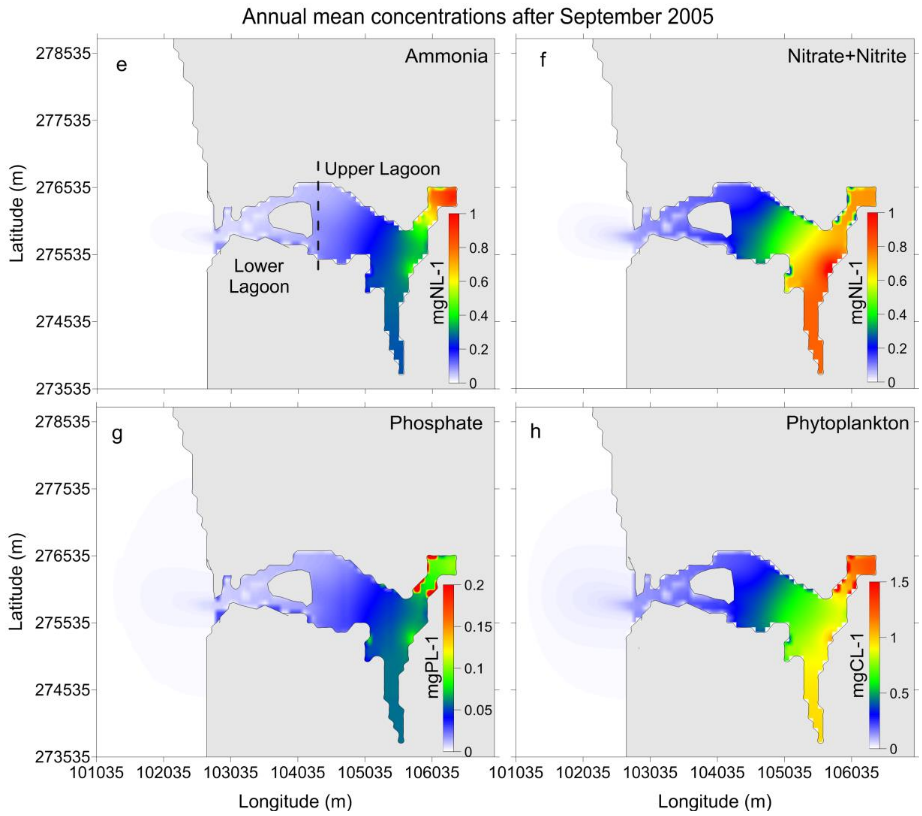


Figure 5.7. Annual mean concentrations of ammonia, nitrate+nitrite, phosphate and phytoplankton for the period before (a to d) and after (e to h) September 2005 performed with model outputs.

A lack of any significant change before and after removing the urban loads is also noticed in the time series for the monitored parameters (Figure 5.5 and Figure 5.6). Interannual variability of NO_3^-+NO_2^- (Figure 5.5, right panel) revealed relatively high concentrations in winter, pointing to a relation between Arnóia/Real Rivers discharge and nutrient availability. Maximum concentrations at all stations were observed over the year of 2008 in April (0.64 mgN l^{-1} in A, 1.8 mgN l^{-1} in B, 1.0 mgN l^{-1} in C, and 1.3 mgN l^{-1} in D stations; in Figure 5.5). Nutrient loads from river runoff were highly variable with large spikes, depending on the wet periods (for instance, in 2006 they peak lower than in 2008 when rainfall was more intense). In fact, 2008 was an atypical year with maximum monthly flows of 7 $m^3 s^{-1}$ in Arnóia/Real Rivers, 2.8 $m^3 s^{-1}$ in Cal River and 1.1 $m^3 s^{-1}$ in Vala do Ameal observed in April. From May to October months the NO_3^-+NO_2^- concentrations decreased to reach their lowest values for summer-fall (0.001 - 0.10 mgN l^{-1}). This was observed at all stations reflecting the dry period and the nutrients depletion due to phytoplankton uptake. Variations of $NH4^+$ (Figure 5.5, left panel) were similar to NO_3^-+NO_2^- trends with higher values during intense freshwater input, and low values in the summer-fall (May to October). Compared to NO_3^-+NO_2^- concentrations, $NH4^+$ maxima were also reached in April 2008 (0.13 mgN l^{-1} at A, 0.41 mgN l^{-1} at B, 0.50 mgN l^{-1} at C and 0.68 mgN l^{-1} at D stations), with the exception of November 2006 at Station D (BB), were the highest value was observed (1.0 mgN l^{-1}; at Station D, Fig. 5). PO_4^{3-} variations (Figure 5.6, left panel) do not follow the same seasonal pattern (e.g., dependent on freshwater discharges) as NO_3^-+NO_2^- and $NH4^+$. The values were high during winter at Station C and D (Figure 5.6, November 2005, November 2006 and December 2008) but PO_4^{3-} peaks was also observed in summer (se circles in Figure 5.6), when the river runoffs are very small or almost dry.

Lowest phytoplankton biomass (Figure 5.6, right panel) were observed in the winter period, mainly due to light limitation. The spring period (March to mid-April) was marked by a rapid increase in phytoplankton biomass production in all stations, with values higher than annual average in all stations (0.12 mgC l^{-1} at A, 0.16 mgC l^{-1} at B, 0.17 mgC l^{-1} at C and 0.33 mgC l^{-1} at D stations). The summer-autumn period was characterized by successive small phytoplankton blooms at all stations: 0.3 mgC l^{-1} at A and B stations; and 0.5 mgC l^{-1} at C and D stations. Even after the implementation of protective measures, the phytoplankton biomass in the 2009 was higher than in 2004/2005 (Figure 5.6, right panel). Phytoplankton biomass annual maximum in 2009 was 1.2 mgC l^{-1}, two times higher than the annual maximum in 2004/2005 (0.7 mgC l^{-1}).

5.4.4. Importance of the urban loads in the basin

Results from the SOA application to the Arnóia/Real Rivers basin (Figure 5.8a and Figure 5.8b) showed that pig farms accounted for 454 tons/year of N and 95 tons/year of P loads. Before the MS urban wastewater and pluvial water loads represented about 46 tons/year of N (9% of the total loads) and 16 tons/year of P (11% of the total loads). After the MS these were reduced to 14 tons/year of N and 3 tons/year of P (Table 5.3) – about 2% in the urban loads in the basin (Figure 5.8c). These results pointed out the pig farms as the most important source of nutrients exported from the basin (73% of the total N and 66% of the total P).

In the Cal River basin the major source of nutrients was the WWTP (Caldas da Rainha and Foz do Arelho) accounting 95% of the total nutrients input (Figure 5.8d and Figure 5.8e).

Estimated N loads before September 2005 were 280 tons/year reduced to 6 tons/year afterwards (~94%, Figure 5.8f); P loads were also reduced after September 2005, from 64 tons/year to 7 tons/year (~85%, Figure 5.8f).

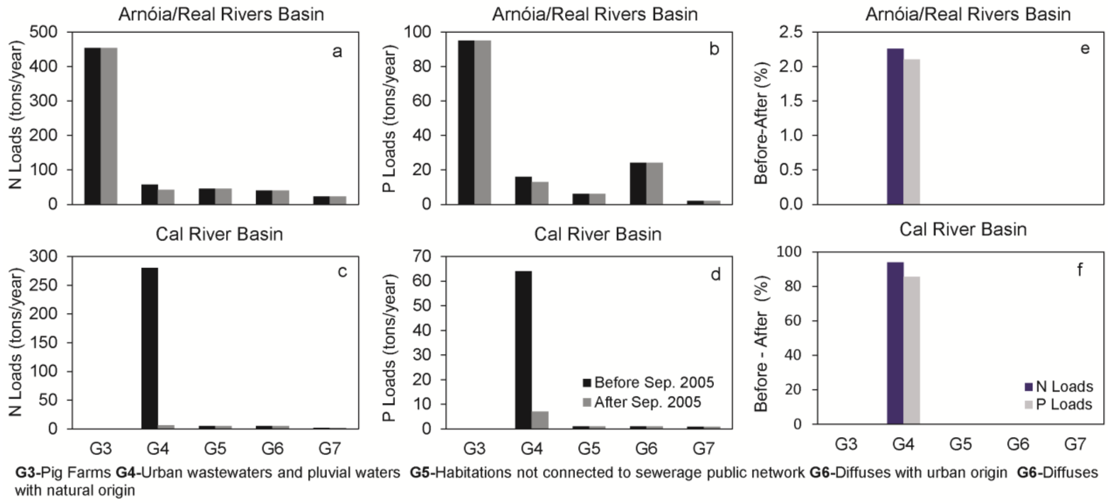


Figure 5.8. Individual sources of nitrogen and phosphorus: Arnóia/Real Rivers basin (a, b) and Cal River basin (d, e). Reductions in nitrogen and phosphorus loads after September 2005 expressed as percentage of the total load in the basin are also depicted for Arnóia/Real Rivers basin (c) and Cal River basin (f).

Table 5.3 shows the loads derived from the sum of sources (SOA) in Arnóia/Real Rivers basin, retention and exported loads (for both approaches – SOA and LOA). The relation between the load-oriented and source-oriented approaches indicated that despite challenges with data completeness, the magnitudes of N and P loadings were the same (see Table 5.3).

The small differences encountered for both approaches, 23 tons/year for N and 11 tons/year for P, could be explained by the capitations used for the estimations of N and P point sources. The retention in Cal River basin (the small one) could not be determined, but the calculus performed for individual sources can be assumed as correct given the small fluctuations achieved by applying both methods in Arnóia/Rivers basin.

Table 5.3. Exported loads from Arnóia/Real Rivers basin obtained with "Source Orientated Approach" and "Load Orientated Approach".

Harmonized Quantification and Reporting Procedures for Nutrients (HARP) Quantification procedures for "Source Orientated Approach" and Load Orientated Approach"				
Exported Loads: Rio Arnóia/Real Rivers Basin	Before Sep. 2005		After Sep. 2005	
	N	P	N	P
	Tons/year			
Total loads derived from SOA: estimated by the sum of all sources	620	143	606	140
Retention in basin area	114	17	114	17
Exported loads derived from LOA: estimated downstream monitoring station	483	115	474	113
Exported loads derived from the difference between SOA and retention	506	126	492	123
Difference between SOA and LOA	**23**	**11**	**18**	**10**

5.4.5. Management scenarios

The average annual export of phytoplankton biomass estimated for each scenario and reference situation (before and after MS) is depicted in Figure 5.9. After urban loads deviation ("Ref - After MS") a reduction of about 12% (scaled to "Ref - Before MS") in annual export was achieved showing that high phytoplankton biomass still occurred in the lagoon. Contrary, by removing the pig farms (major source of nutrients from the basins to the lagoon) a drastic reduction in annual export of phytoplankton biomass was observed (48% less than "Ref - After MS"). As a reflex the mean spatial trend of nutrients (especially in NO_3^-+NO_2^-) and phytoplankton revealed a diminishing in concentrations in the upper lagoon (Figure 5.10).

The suppression of Cal River (scenario 2) did not show a significant difference when compared with annual values obtained for "Ref - After MS". Only a reduction of 9% was obtained in this scenario when scaled to Ref - Before MS.

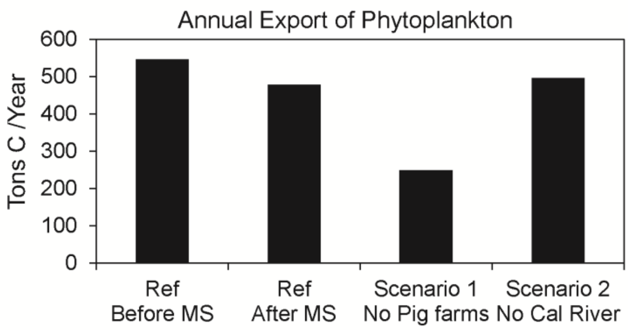


Figure 5.9. Annual export of phytoplankton biomass (tons C/year) for the reference situation before and after management strategies (MS) and simulated scenarios.

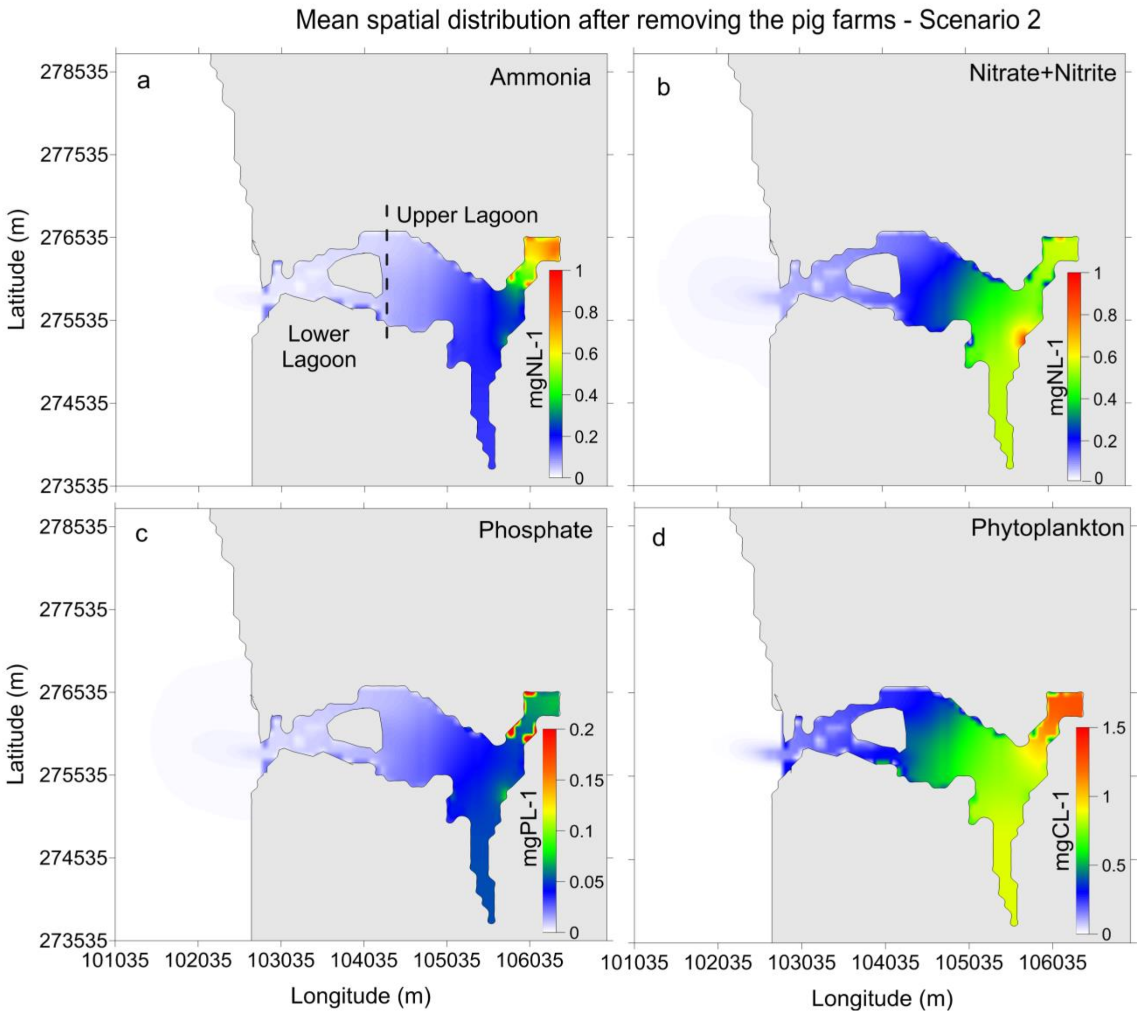


Figure 5.10. Mean spatial trend of ammonia (a), nitrate+nitrite (b), phosphate (c) and phytoplankton (d) after removing the pig farms (scenario 2).

5.5. Discussion

5.5.1. Water quality within lagoon before and after management strategies

A longitudinal trend in nutrient concentrations was observed in the lagoon, despite the small freshwater discharges, with a similar spatial pattern observed in many estuarine systems with an important freshwater input (Cabecadas *et al*. 1999; Lopes *et al*. 2007). In general, freshwater input and the hydrodynamics control the biogeochemical balance in the lagoon (with exception in BB section), and ultimately determine the water quality. The upper part of the lagoon was characterized by significant nutrient loads coming from important rivers, and by high residence time of water in the branches (~3 weeks in BSB and 4 – 12 days in BB). Water renewal is constant in the lower part due to the connection with the inlet, leading to a rapid nutrient exportation to the coastal area, thus inhibiting local phytoplankton growth (Malhadas *et al*. 2010).

The observed nutrient concentrations before MS (from October 2004 to September 2005, Figure 5.7) showed higher values in the upper lagoon (0.1 – 2.5 mgN l^{-1} for NO^{2-}+NO^{3-}, and 0.1 – 0.3 mgP l^{-1} for PO_4^{3-}). A similar distribution has been observed in other Portuguese costal systems, such as the Guadiana estuary (Domingues *et al*. 2005) and the Tagus Estuary (Mateus *et al*. 2012a; Mateus *et al*. 2012c), and also in larger scale systems such as the San Francisco Bay (Cloern 1996), the Chesapeake bay (Ward and Twilley 1986) or the Pearl River estuary (Yin *et al*. 2001). Both BSB (Station C) and BB (Station D) were characterized by particularly high nutrient concentrations, when compared to the observed values in non-polluted coastal systems with absent eutrophication signs such as the Arcachon Bay (Gle *et al*. 2008).

Curiously, field data does not revealed significant improvement in the water quality state of the lagoon after the MS, explaining why high nutrient concentrations and associated eutrophic conditions occurred in the same areas. This is particularly relevant in the problematic area of the BB, where the same polluted conditions persisted after the MS. As seen, significant summer peaks of phytoplankton and phosphate still occurred after 2005 (circles in the Fig. 6 for D stations) in BB, reflecting the pulsed nature of biogeochemical events in this area, as discussed in previous works (Pereira *et al*. 2012b; Pereira *et al*. 2010; Pereira *et al*. 2011; Pereira *et al*. 2009a; Pereira *et al*. 2009b).

Since the most obvious source of nutrient pollution was eliminated (the Caldas da Rainha WWTP), it can be hypothesized that other source of nutrients represented a key input to deteriorate the state of water quality, particularly in summer at BB. The exchanges at the water-sediment interface can be a plausible enrichment mechanism at BB, with the sediments acting as a source of nutrients via organic matter mineralization, as proposed by Pereira *et al*. (2009a).

5.5.2. The modelling approach

The water quality of the Óbidos Lagoon has been the subject of several studies over the past years (e.g., Pereira *et al*. 2012a; Pereira *et al*. 2010; Pereira *et al*. 2011; Pereira *et al*. 2009a; Pereira *et al*. 2009b). These studies, however, were experimental in nature and based on the analysis of measured data. As such, the present work reports the first attempt to use a coupled hydro-ecological model to simulate the water quality of the system, and to test management scenarios of nutrient input reduction. Model results suggest that the main ecological features have been captured by the model, despite some observed discrepancies. NH4$^+$ and NO_3^-+NO_2^- variability is well explained in respect to the balance of nutrients that enter via river discharges and from the seawater. This balance alone is not sufficient to explain PO_4^{3-} variability, explaining the main differences between simulated and observed values. In fact, also phytoplankton concentrations in the upper lagoon can be related with the PO_4^{3-} lower model fit. PO_4^{3-} concentrations are under-estimate by the model in summer, resulting in lower blooms as a consequence of a limitation by this nutrient. The peaks of PO_4^{3-} observed in field data can be related with the pulse of metals (Manganese-Mn and Iron-Fe) from the sediment during the night under anoxic conditions, when Mn^{2+} and Fe^{2+} are released to the water column (Pereira *et al*. 2010). This process is followed with an additional enrichment of PO_4^{3-} coincident with the peaks of these elements.

The actual model formulation of MOHID model, as in many water quality models (Bendoricchio and De Boni 2005, Painting, 2005, Lopes *et al*. 2008, Duarte *et al*. 2008, Azzellino *et al*. 2013), does not connected metals cycle to biogeochemical cycle of nutrients. The absence of chemical cycles (metals and other components) explained the handicap of the model in reproducing the PO_4^{3-} summer peaks and consequently the blooms in the BB. This is in line with the hypothesis advanced previously of considering the internal sources (e.g., nutrient loads from sediments) as an important source of nutrients in this area. Internal sources are only relevant in the specify area of the BB and it seems that they continued to deteriorate the state of water quality in BB after removing WWTP (Caldas da Rainha) loads in the Cal River. However, when considering the entire system, the external sources of nutrients are by far the most important to determine the state of the water quality as discussed in Pereira *et al*. (2009a).

The limitation of the model to achieve a better fit for PO_4^{3-} and phytoplankton in the upper lagoon (particularly in BB) does not compromise its use to simulate the impact of the management strategies and load reduction scenarios. The load of PO_4^{3-} in BB is attributed to specific conditions (only in summer for very dry and anoxic conditions) and does not occurred regularly. In the lower lagoon, where sediments are mainly composed by sand, the regenerated processes near the sediment–water interface are not so significant and thus model performance is better. Moreover, model performance was similar to Azzellino *et al*. (2013) for the Lagoon of Venice, and by Santhi *et al*. (2006) that present skill and R values equal or higher than 0.5. However, it must be stressed that the values must be interpreted under the assumption that there is no sediment-water exchange of nutrients.

5.5.3. Management implications

We have adopted a methodology which helps support reaching the objectives of the WFD, i.e., the implementation and development of integrated approaches to watershed, hydrodynamic and water quality models (EEB 2001). Other studies on coastal lagoons and estuarine management in Europe have focused on the catchment area or in the lagoons/estuaries, without necessarily linking both (Azzellino *et al.* 2013; Duarte *et al*. 2008; Gikas *et al*. 2006; Konstantinou *et al*. 2012; Stybel *et al*. 2009).

Point sources such as WWTP have been proposed as the cause for the LTS. Our results, however, highlight the pig farms as the major contribution to the LTS. Hence, the expected improvement in the LTS did not occurred five years after urban loads diverting, particularly at BB (major receptor of Caldas da Rainha WWTP). Thus, TRIX values (7 and 6.4 before and after MS, see Table 5.4) remained in the "Elevated" level of eutrophication after MS, and the water quality remained with a "Poor" status. Both classifications were based on chlorophyll *a*, DIN and DIP concentrations before and after removing the point sources from the lagoon catchment areas. The consequence of the non-improvement within LTS is that high levels of nutrients are still observed in the same areas after removing the WTTP, particular at the BB, the most impacted area of the lagoon before MS.

Model results combined with in situ data and previous knowledge of the Óbidos Lagoon (Carvalho *et al*. 2005, Carvalho *et al*. 2006, Pereira *et al*. 2012b; Pereira *et al*. 2009a; Pereira *et al.* 2009b) pointed to another source of nutrients, namely the regeneration of nutrients in the sediments of the BB (enriched by organic matter after decades of external nutrient loads) and their efflux to the water column under specific conditions. Removing the Cal River to target the importance of illegal discharges confirmed the internal loads in the BB since PO_4^{3-}concentrations stills high. After years of nutrient accumulation in the lagoon, the release of PO_4^{3-} from bottom-sediments into the water column is another cause of lagoon eutrophication (in particular at BB). This process is further enhanced in the summer period (Cobelo-García *et al.* 2012). Recovery speed is reduced and eutrophic conditions persist despite the reduction of external loading of nutrients within systems influenced by internal loads (Søndergaard *et al.* 1992, Penn 2000, Perkins and Underwood 2000, Peticrea and Arocena 2001, Druschel 2005).

Table 5.4. Trophic state multivariate index (TRIX) scale for the scenarios and reference situation before and after the management strategies (MS).

Scenarios	Scale TRIX	State of water quality	Level of eutrophication
Ref - Before MS	7	Poor	Elevated
Ref - After MS	6	Bad	High
Scenario 1 - No Pig farms	5	Good/Bad	Medium/High
Scenario 2 - No Cal River	6	Bad	High

With respect to the protective measures taken over the last 5 years, they were not effective in reducing the LTS. The results show that the water management actions targeted the most plausible nutrient sources, ignoring less obvious ones, but by no means less important. Penn *et al*. (2000) estimated that internal loading can contribute up to 80% of the PO43- input under specific circumstances (e.g., particularly in summer). Generally, water management studies to improve water quality in European ecosystems have focused on external sources of nutrients (Korfmacher 1998; Jeunesse *et al*. 2002, Gikas *et al*. 2006, Duarte *et al*. 2008, Neto *et al*. 2008, Azzellino *et al*. 2013). Internal loads of nutrients tend to be suppressed in the management studies, as well in the strategy of the WFD (http://ec.europa.eu/environment/water/water-framework/), being considered less representative than external loads, possibly due to the fact that it is easier to act on this sources (e.g., point sources).

The hypothetical management scenario simulated here (removing the pig farms loads) could be a protective action that should be evaluated. With regard to the scenario without the loads from the pig farms, it can be concluded that the impact of the most feasible measures on the annual phytoplankton exportation is very high. This is quite visible in the TRIX values (values of Table 5.4,) and consequently in the mean spatial trend in the upper lagoon (Figure 5.10) .A moderate anthropogenic influence in terms of the loads stress in the upper lagoon reflected the level of eutrophication in this area and conditioned the LTS. Thus a level of eutrophication between “Medium/High” and a state of water quality between “Good/Bad” was obtained by removing the pig farms.

Even with the uncertainty associated to the model scenarios, this case study shows that applicable measures in a correct way within lagoon could help to reach the goal of good water quality, as requested by European WFD. These results showed that a better state of water quality and low level of eutrophication could be achieved in the future if the entities act on the right representative loads.

5.6. Conclusions

Despite the intense study program undertaken in the Óbidos Lagoon over the last years, the use of numerical models to integrate much of the field data has not been developed. As such, this work stands as a first attempt to use numerical tools in the ecological management of this complex ecosystem.

Our results highlight the role of the model in understanding the dynamics of the system, but also its usefulness to test hypothesis on its functioning. The results obtained with the model can be used as a support in the decision-making process by the entities involved in the management of the lagoon. Since this is a pioneer study on the lagoon, several aspects of this study can be improved in the future, namely the inclusion of sediment-water interaction to account for the nutrient upward flux, namely the inclusion of sediment-water interaction to account for the nutrient upward flux.

5.7. Acknowledgements

This work had the financial support of Águas do Oeste S.A, as part of the project “Monitoring and modelling the Óbidos lagoon and Foz do Arelho submarine outfall”.

5.8. References

Amatya, D. M., M. K. Jha, T. M. Williams, A. E. Edwards & D. R. Hitchcock, 2013. SWAT Model Prediction of Phosphorus Loading in a South Carolina Karst Watershed with a Downstream Embayment. Journal of Environmental Protection 4:75-90.

Arnold, J. G., P. M. Allen & G. Bernhardt, 1993. A Comprehensive Surface-Groundwater Flow Model. Journal of Hydrology 142(1-4):47-69 doi:Doi 10.1016/0022-1694(93)90004-S.

Azzellino, A., M. Carpani, S. Çevirgen, C. Giupponi, P. Parati, F. Ragusa & R. Salvetti, 2013. Managing the nutrient loads of the Venice Lagoon Watershed: are the loads external to the watershed relevant under the WFD River Basin District framework? Journal of Coastal Research SI65:25-30.

Bendoricchio, G. & G. De Boni, 2005. A water-quality model for the Lagoon of Venice, Italy. Ecological Modelling 184(1):69-81 doi:DOI 10.1016/j.ecolmodel.2004.11.013.

Borowski, I. & M. Hare, 2007. Exploring the gap between water managers and researchers: Difficulties of model-based tools to support practical water management. Water Resour Manag 21(7):1049-1074 doi:DOI 10.1007/s11269-006-9098-z.

Cabecadas, G., M. Nogueira & M. J. Brogueira, 1999. Nutrient dynamics and productivity in three European estuaries. Marine Pollution Bulletin 38(12):1092-1096 doi:Doi 10.1016/S0025-326x(99)00111-3.

Carvalho, S., A. Moura, M. B. Gaspar, P. Pereira, L. C. da Fonseca, M. Falcao, T. Drago, F. Leitao & J. Regala, 2005. Spatial and inter-annual variability of the macrobenthic communities within a coastal lagoon (Obidos lagoon) and its relationship with environmental parameters. Acta Oecol 27(3):143-159 doi:DOI 10.1016/j.actao.2004.11.004.

Carvalho, S., M. B. Gaspar, A. Moura, C. Vale, P. Antunes, O. Gil, L. C. da Fonseca & M. Falcao, 2006. The use of the marine biotic index AMBI in the assessment of the ecological status of the Obidos lagoon (Portugal). Marine Pollution Bulletin 52(11):1414-1424 doi:DOI 10.1016/j.marpolbul.2006.04.004.

Cloern, J. E., 1996. Phytoplankton bloom dynamics in coastal ecosystems: A review with some general lessons from sustained investigation of San Francisco Bay, California. Rev Geophys 34(2):127-168 doi:Doi 10.1029/96rg00986.

Cloern, J. E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar Ecol-Prog Ser 210:223-253.

Cobelo-Garcia, A., P. Bernardez, M. Leira, D. E. Lopez-Sanchez, J. Santos-Echeandia, R. Prego & M. Perez-Arlucea, 2012. Temporal and diel cycling of nutrients in a barrier-lagoon complex: Implications for phytoplankton abundance and composition. Estuar Coast Shelf S 110:69-76 doi:DOI 10.1016/j.ecss.2012.03.015.

de Kok, J. L., S. Kofalk, J. Berlekamp, B. Hahn & H. Wind, 2009. From Design to Application of a Decision-support System for Integrated River-basin Management. Water Resour Manag 23(9):1781-1811 doi:DOI 10.1007/s11269-008-9352-7.

Domingues, R. B., A. Barbosa & H. Galvao, 2005. Nutrients, light and phytoplankton succession in a temperateestuary (the Guadiana, south-western Iberia). Estuar Coast Shelf S 64(2-3):249-260 doi:DOI 10.1016/j.ecss.2005.02.017.

Druschel., G. K., A. Hartmann, R. Lomonaco & K. Oldrid, 2005. Determination of sediment phosphorus concentrations in St. Albans Bay, Lake Champlain: Assessment of internal loading and seasonal variations of phosphorus sediment-water column cycling. Report to the Vermont Agency of natural resources, 71p.

Duarte, P., B. Azevedo, M. Guerreiro, C. Ribeiro, R. Bandeira, A. Pereira, M. Falcao, D. Serpa & J. Reia, 2008. Biogeochemical modelling of Ria Formosa (South Portugal). Hydrobiologia 611:115-132 doi:DOI 10.1007/s10750-008-9464-3.

EEB, 2001. Handbook on EU Water Policy under the Water Framework Directive. European Environmental Bureau, Brussels.

EPA, 1985. Rates, constants, and kinetics formulations in surface water-quality modeling. US Environmental Protection Agency.

Fohrer, N., S. Haverkamp, K. Eckhardt & H. G. Frede, 2001. Hydrologic response to land use changes on the catchment scale. Phys Chem Earth Pt B 26(7-8):577-582 doi:Doi 10.1016/S1464-1909(01)00052-1.

Fransz, H. G., J. P. Mommaerts & G. Radach, 1991. Ecological Modeling of the North-Sea. Neth J Sea Res 28(1-2):67-140 doi:Doi 10.1016/0077-7579(91)90005-L.

Gikas, G. D., T. Yiannakopoulou & V. A. Tsihrintzis, 2006. Water quality trends in a coastal lagoon impacted by non-point source pollution after implementation of protective measures. Hydrobiologia 563:385-406 doi:DOI 10.1007/s10750-006-0034-2.

Gle, C., Y. Del Amo, B. Sautour, P. Laborde & P. Chardy, 2008. Variability of nutrients and phytoplankton primary production in a shallow macrotidal coastal ecosystem (Arcachon Bay, France). Estuar Coast Shelf S 76(3):642-656 doi:DOI 10.1016/j.ecss.2007.07.043.

Heinz, I., M. Pulido-Velazquez, J. R. Lund & J. Andreu, 2007. Hydro-economic modeling in river basin management: Implications and applications for the European Water Framework Directive. Water Resour Manag 21(7):1103-1125 doi:DOI 10.1007/s11269-006-9101-8.

IST/IPIMAR, 2010. Variação sazonal e inter-annual da qualidade da água na Lagoa de Óbidos, seus afluentes e emissário submarino da Foz do Arelho. Relatório Final: Outubro 2004-Janeiro 2008 (in Portuguese). IST / IPIMAR, Lisboa.

Konstantinou, Z. I., Y. N. Krestenitis, D. Latinopoulos, K. Pagou, S. Galinou-Mitsoudi & Y. Savvidis, 2012. Aspects of Mussel-Farming Activity in Chalastra, Thermaikos Gulf, Greece: An Effort to Untie a Management Gordian Knot. Ecol Soc 17(1) doi:Doi 10.5751/Es-04455-170101.

Korfmacher, K. S., 1998. Water quality modeling for environmental management: Lessons from the policy sciences. Policy Sci 31(1):35-54.

Krause, S., A. L. Heathwaite, F. Miller, P. Hulme & A. Crowe, 2007. Groundwater-dependent wetlands in the UK and Ireland: Controls, functioning and assessing the likelihood of damage from human activities. Water Resour Manag 21(12):2015-2025 doi:DOI 10.1007/s11269-007-9192-x.

La Jeunesse, I., J. M. Deslous-Paoli, M. C. Ximénès, J. P. Cheylan, C. Mende, C. Borrero & L. Scheyer, 2002. Changes in point and non-point sources phosphorus loads in the Thau catchment over 25 years (Mediterranean Sea – France). Hydrobiologia 475-476(1):403-411 doi:10.1023/a:1020351711877.

Le Provost, C., F. Lyard, J. M. Molines, M. L. Genco & F. Rabilloud, 1998. A hydrodynamic ocean tide model improved by assimilating a satellite altimeter-derived data set. J Geophys Res-Oceans 103(C3):5513-5529.

Leitão, P., H. Coelho, A. Santos & R. Neves, 2005. Modelling the main features of the Algarve coastal circulation during July 2004: A downscaling approach. Journal of Atmospheric & Ocean Science 10(4):421-462.

Li, Q. P., P. J. S. Franks, M. R. Landry, R. Goericke & A. G. Taylor, 2010. Modeling phytoplankton growth rates and chlorophyll to carbon ratios in California coastal and pelagic ecosystems. J Geophys Res-Biogeo 115 doi:Artn G04003. Doi 10.1029/2009jg001111.

Lillebo, A. I., J. M. Neto, M. R. Flindt, J. C. Marques & M. A. Pardal, 2004. Phosphorous dynamics in a temperate intertidal estuary. Estuar Coast Shelf S 61(1):101-109 doi:DOI 10.1016/j.ecss.2004.04.007.

Lillebo, A. I., M. Valega, M. Otero, M. A. Pardal, E. Pereira & A. C. Duarte, 2010. Daily and inter-tidal variations of Fe, Mn and Hg in the water column of a contaminated salt marsh: Halophytes effect. Estuar Coast Shelf S 88(1):91-98 doi:DOI 10.1016/j.ecss.2010.03.014.

Lopes, C. B., A. I. Lillebo, J. M. Dias, E. Pereira, C. Vale & A. C. Duarte, 2007. Nutrient dynamics and seasonal succession of phytoplankton assemblages in a Southern European Estuary: Ria de Aveiro, Portugal. Estuar Coast Shelf S 71(3-4):480-490 doi:DOI 10.1016/j.ecss.2006.09.015.

Lopes, J. F., C. I. Silva & A. C. Cardoso, 2008. Validation of a water quality model for the Ria de Aveiro lagoon, Portugal. Environmental Modelling & Software 23(4):479-494 doi:DOI 10.1016/j.envsoft.2007.07.001.

Malhadas, M., R. Neves, P. Leitão & A. Silva, 2010. Influence of tide and waves on water renewal in Óbidos Lagoon, Portugal. Ocean Dynamics 60(1):41-55 doi:10.1007/s10236-009-0240-3.

Malhadas, M. S., P. C. Leitao, A. Silva & R. Neves, 2009a. Effect of coastal waves on sea level in Obidos Lagoon, Portugal. Continental Shelf Research 29(9):1240-1250 doi:DOI 10.1016/j.csr.2009.02.007.

Malhadas, M. S., A. Silva, P. C. Leitao & R. Neves, 2009b. Effect of the Bathymetric Changes on the Hydrodynamic and Residence Time in Obidos Lagoon (Portugal). Journal of Coastal Research:549-553.

Martins, F., P. Leitao, A. Silva & R. Neves, 2001. 3D modelling in the Sado estuary using a new generic vertical discretization approach. Oceanologica Acta 24:S51-S62.

Martins, F., P. Pina, S. Calado, S. Delgado & R. Neves, 2003. A coupled hydrodynamic and ecological model to manage water quality in Ria Formosa coastal lagoon. Adv Ecol Sci 18 and 19:93-100.

Mateus, M., P. C. Leitão, H. de Pablo & R. Neves, 2012a. Is it relevant to explicitly parameterize chlorophyll synthesis in marine ecological models? Journal of Marine Systems 94:S23-S33 doi:10.1016/j.jmarsys.2011.11.007.

Mateus, M., G. Riflet, P. Chambel, L. Fernandes, R. Fernandes, M. Juliano, F. Campuzano, H. de Pablo & R. Neves, 2012b. An operational model for the West Iberian coast: products and services. Ocean Science 8(4):713-732 doi:10.5194/os-8-713-2012.

Mateus, M., N. Vaz & R. Neves, 2012c. A process-oriented model of pelagic biogeochemistry for marine systems. Part II: Application to a mesotidal estuary. Journal of Marine Systems 94, Supplement:S90-S101 doi:10.1016/j.jmarsys.2011.11.009.

Metcalf & Eddy, 2003. Wastewater Engineering: Treatment and Reuse, Fourth Edition edn. McGraw-Hill.

Oliveira, A., A. B. Fortunato & F. E. P. Sancho, 2005. Morphodynamic modeling of the Obidos lagoon. Coastal Engineering 2004, Vols 1-4:2506-2518.

Oliveira, A., A. B. Fortunato & J. R. L. Rego, 2006. Effect of morphological changes on the hydrodynamics and flushing properties of the Obidos lagoon (Portugal). Continental Shelf Research 26(8):917-942 doi:DOI 10.1016/j.csr.2006.02.011.

Painting, S. J., M. J. Devlin, S. J. Malcolm, E. R. Parker, D. K. Mills, C. Mills, P. Tett, A. Wither, J. Burt, R. Jones & K. Winpenny, 2007. Assessing the impact of nutrient enrichment in estuaries: Susceptibility to eutrophication. Marine Pollution Bulletin 55(1-6):74-90 doi:DOI 10.1016/j.marpolbul.2006.08.020.

Penn, M. R., M. T. Auer, S. M. Doerr, C. T. Driscoll, C. M. Brooks & S. W. Effler, 2000. Seasonality in phosphorus release rates from the sediments of a hypereutrophic lake under a matrix of pH and redox conditions. Can J Fish Aquat Sci 57(5):1033-1041 doi:DOI 10.1139/cjfas-57-5-1033.

Pereira, P., M. J. Botelho, M. T. Cabrita, C. Vale, M. T. Moita & C. Goncalves, 2012a. Winter-summer nutrient composition linkage to algae-produced toxins in shellfish at a eutrophic coastal lagoon (Obidos lagoon, Portugal). Estuar Coast Shelf S 112:61-72 doi:DOI 10.1016/j.ecss.2011.07.016.

Pereira, P., S. Carvalho, F. Pereira, H. de Pablo, M. B. Gaspar, M. Pacheco & C. Vale, 2012b. Environmental quality assessment combining sediment metal levels, biomarkers and macrobenthic communities: application to the Obidos coastal lagoon (Portugal). Environ Monit Assess 184(12):7141-51 doi:10.1007/s10661-011-2486-8.

Pereira, P., H. de Pablo, S. Carvalho, C. Vale & M. Pacheco, 2010. Daily availability of nutrients and metals in a eutrophic meso-tidal coastal lagoon (Obidos lagoon, Portugal). Marine Pollution Bulletin 60(10):1868-1872 doi:DOI 10.1016/j.marpolbul.2010.07.021.

Pereira, P., H. de Pablo, M. D. Subida, C. Vale & M. Pacheco, 2011. Bioaccumulation and biochemical markers in feral crab (Carcinus maenas) exposed to moderate environmental contamination--the impact of non-contamination-related variables. Environmental toxicology 26(5):524-40 doi:10.1002/tox.20641.

Pereira, P., H. de Pablo, C. Vale, V. Franco & M. Nogueira, 2009a. Spatial and seasonal variation of water quality in an impacted coastal lagoon (Óbidos Lagoon, Portugal). Environ Monit Assess 153(1-4):281-292 doi:DOI 10.1007/s10661-008-0355-x.

Pereira, P., H. de Pablo, C. Vale, F. Rosa-Santos & R. Cesario, 2009b. Metal and nutrient dynamics in a eutrophic coastal lagoon (Óbidos, Portugal): the importance of observations at different time scales. Environ Monit Assess 158(1-4):405-418 doi:DOI 10.1007/s10661-008-0593-y.

Petticrew, E. L. & J. M. Arocena, 2001. Evaluation of iron-phosphate as a source of internal lake phosphorus loadings. Science of the Total Environment 266(1-3):87-93 doi:Doi 10.1016/S0048-9697(00)00756-7.

Perkins, R. G. & G. J. C. Underwood, 2001. The potential for phosphorus release across the sediment-water interface in an eutrophic reservoir dosed with ferric sulphate. Water research 35(6):1399-1406 doi:Doi 10.1016/S0043-1354(00)00413-9.

Petticrew, E. L. & J. M. Arocena, 2001. Evaluation of iron-phosphate as a source of internal lake phosphorus loadings. Science of the Total Environment 266(1-3):87-93 doi:Doi 10.1016/S0048-9697(00)00756-7.

Pina, P., 2001. An Integrated Approach to Study The Tagus Estuary Water Quallity. M.Sc Thesis, Superior Técnico, Universidade Técnica de Lisboa.

Portela, L. I., 1996. Mathematical modelling of hydrodynamic processes and water quality in Tagus estuary. Ph.D. Thesis, Universidade Técnica de Lisboa, Instituto Superior Técnico.

Reungsang, P., R. Kanwar, M. Jha, P. W. Gassman, K. Ahmad & S. Saleh, 2005. Calibration and Validation of SWAT for the Upper Maquoketa River Watershed - Working Paper 05-WP 396. Center for Agricultural and Rural Development. Iowa State University, Ames, Iowa.

Sanchez-Avila, J., J. Bonet, G. Velasco & S. Lacorte, 2009. Determination and occurrence of phthalates, alkylphenols, bisphenol A, PBDEs, PCBs and PAHs in an industrial sewage grid discharging to a Municipal Wastewater Treatment Plant. Science of the Total Environment 407(13):4157-4167 doi:DOI 10.1016/j.scitotenv.2009.03.016.

Sanchez-Avila, J., R. Tauler & S. Lacorte, 2012. Organic micropollutants in coastal waters from NW Mediterranean Sea: Sources distribution and potential risk. Environ Int 46:50-62 doi:DOI 10.1016/j.envint.2012.04.013.

Santhi, C., R. Srinivasan, J. G. Arnold & J. R. Williams, 2006. A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. Environmental Modelling & Software 21(8):1141-1157 doi:DOI 10.1016/j.envsoft.2005.05.013.

Saraiva, S., P. Pina, F. Martins, M. Santos, F. Braunschweig & R. Neves, 2007. Modelling the influence of nutrient loads on Portuguese estuaries. Hydrobiologia 587:5-18.

Søndergaard, M., P. Kristensen & E. Jeppesen, 1992. Phosphorus release from resuspended sediment in the shallow and wind-exposed Lake Arresø, Denmark. Hydrobiologia 228(1):91-99 doi:10.1007/bf00006480.

Stybel, N., C. Fenske & G. Schernewski, 2009. Mussel Cultivation to Improve Water Quality in the Szczecin Lagoon. Journal of Coastal Research:1459-1463.

Thieu, V., J. Garnier & G. Billen, 2010. Assessing the effect of nutrient mitigation measures in the watersheds of the Southern Bight of the North Sea. Science of the Total Environment 408(6):1245-1255 doi:DOI 10.1016/j.scitotenv.2009.12.031.

Trancoso, A. R., S. Saraiva, L. Fernandes, P. Pina, P. Leitao & R. Neves, 2005. Modelling macroalgae using a 3D hydrodynamic-ecological model in a shallow, temperate estuary. Ecological Modelling 187(2-3):232-246.

Valiela, I., 1995. Marine ecological processes. Springer-Verlag, New York.

Volf, G., N. Atanasova, B. Kompare & N. Ozanic, 2013. Modeling nutrient loads to the northern Adriatic. Journal of Hydrology 504:182-193 doi:DOI 10.1016/j.jhydrol.2013.09.044.

Vollenweider, R. A., F. Giovanardi, G. Montanari & A. Rinaldi, 1998. Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: Proposal for a trophic scale, turbidity and generalized water quality index. Environmetrics 9(3):329-357 doi:Doi 10.1002/(Sici)1099-095x(199805/06)9:3<329::Aid-Env308>3.0.Co;2-9.

Ward, L. G. & R. R. Twilley, 1986. Seasonal Distributions of Suspended Particulate Material and Dissolved Nutrients in a Coastal-Plain Estuary. Estuaries 9(3):156-168 doi:Doi 10.2307/1352127.

Warner, J. C., W. R. Geyer & J. A. Lerczak, 2005. Numerical modeling of an estuary: A comprehensive skill assessment. Journal of Geophysical Research: Oceans 110(C5):C05001 doi:10.1029/2004jc002691.

Willmott, C. J., 1981. On the validation of models. Physical Geography 2:184-194.

Yin, K. D., P. Y. Qian, M. C. S. Wu, J. C. Chen, L. M. Huang, X. Y. Song & W. J. Jian, 2001. Shift from P to N limitation of phytoplankton growth across the Pearl River estuarine plume during summer. Mar Ecol Prog Ser 221:17-28 doi:Doi 10.3354/Meps221017.

Zemlys, P., A. Ertürk & A. Razinkovas, 2008. 2D finite element ecological model for the Curonian lagoon. Hydrobiologia 611(1):167-179 doi:10.1007/s10750-008-9452-7.

6. Summer-winter diel variability in a mesotidal costal lagoon: a focus on biogeochemical and metals cycle in reference and eutrophic sites

Madalena S. Malhadas[a,b], Nuno Vaz[c], Carlos A.F. Marques[c], Susana Nunes[a], João Miguel Dias[c], Marcos[a] Mateus, Ramiro Neves[a]

[a] HIDROMOD, Rua Rui Teles Palhinha, nº4 - 1º, Leião, 2740-278 Porto Salvo, Portugal.
[b] Instituto Superior Técnico, Secção de Ambiente e de Energia, Departamento de Engenharia Mecânica, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.
[c] CESAM, Departamento de Física, Universidade de Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal.

Accepted in: Hydrobiologia (under review), Impact Factor: 2.275

Abstract

The processes controlling the diel variability of physicochemical properties (pH, saturation of dissolved oxygen, salinity, turbidity), chlorophyll *a*, nutrients (silicate, nitrate, ammonium and phosphate) and metals (aluminium, iron, manganese and lead) in a mesotidal coastal lagoon (Óbidos Lagoon, Portugal) was studied both in two sites (eutrophic and reference) covering different seasonal conditions (summer and winter). Principal component analyses (PCAs) were applied to the data (laboratorial sampling and 24-hours real time data cycles) to identify which stations with respect to one another and whether or not associations were consistent between the sampling periods/sites. The summer diel cycle at eutrophic site revealed anoxic conditions in sediment due to the combination of low freshwater inputs and high air temperatures coupled to the elevated primary production and water stagnancy. These leads to maximum concentrations for nutrients and metals at night-time concurrent with the temporal decrease of dissolved oxygen saturation and phytoplankton biomass. The drastic fluctuations in summer diel cycles were not observed in winter mainly due to the prevalent conditions of eutrophic state and consequently anoxic conditions during the dry season. As a consequence the winter diel cycle at same eutrophic site is quite uniform along the 24-hours. Encountered differences are primarily associated to site location (eutrophic or not) but hydrographical (low and high flows) and meteorological conditions (high and low temperatures) exert also a control on the diel cycles in the lagoon. Observed diel changes in summer are affected by the balance between photosynthetic production and heterotrophic respiration which influence the vertical migration of metals and nutrients in the sediment. The oxic conditions and low phytoplankton biomass characteristics of the winter cycle blocked the internal loads. PCAs confirmed the separation between sites and seasons, pointed the internal sources in as the major control in summer diel variability and external in winter. The results obtained here are relevant for other coastal lagoons due to the importance of assessing chemical conditions over diel cycle in eutrophic areas.

Keywords: Diel cycles; nutrients; trace-metals; high-low flows; internal loads; Óbidos Lagoon

6.1. Introduction

Coastal lagoons are ecosystems of ecological and economic importance, constituting areas of high productivity, being especially sensitive to both, anthropogenic and natural variations (Perrila *et al*., 2012). These ecosystems are subjected to human over-exploitation through urban, industrial and agricultural activities in the surrounding areas, which can lead to an increase in chemical (e.g., nutrients and organic matter) and consequent water quality deterioration, as well, highly vulnerable to eutrophication.

Eutrophication often causes hypoxia in estuarine and coastal systems, but the mechanisms that control hypoxic events and affects water quality vary among estuaries and coastal lagoons are often difficult to discern. The primary sources reported as the main cause of nutrient enrichment are the urban loads and agricultural runoff. However it is important to know the dynamics of coupled sediment-water column since a massive amount of nutrients are usually tied up in the sediments (e.g. Druschel *et al*. 2005) and can be released under specific conditions (internal loading), perpetuating the eutrophic state and the presence of cyanobacteria blooms (Smith., 2009).

The hydrodynamics of a coastal lagoon is often controlled by the complex interaction between tidal propagation through its mouth and freshwater discharge from its main tributaries (Vaz and Dias, 2008) and also by surface wave set-up (Malhadas *et al*., 2009). On the other hand, the variability in the water quality are mainly explained by changing conditions (weather, seasonal, annual), episodic events (rainfall, runoff), anthropogenic activity (WTTP effluent, reservoir release for power generation, irrigation withdrawal) and diel biogeochemical cycle. Together, all these processes affect the nutrient cycling and lead to a complex scenario involving various stressors to pelagic organisms and benthic fauna affecting the distribution of estuarine species (Génio *et al*., 2008).

Nutrient cycling reflects not just agricultural and urban runoff (external loading) but also the amounts released from the sediments to the water column throughout internal loading processes controlled by redox conditions, pH, temperature, light, and physical disturbances (e.g. Ryding, 1985; Andersen and Jensen, 1992; Søndergaard, 2003). Fundamental processes that affect internal nutrient loading are largely dependent on nutrients-metals association under specific conditions. Internal loading occurs when conditions within sediments allow for phosphorus (P) and nitrogen (N) release into the water column, thereby increasing the total phosphorus (TP, specifically available or reactive P) of the water column.

Seasonal or monthly monitoring tends to underestimate the benthic processes and our percept of sharp variability occurred in a 24-hours cycle (e.g., internal loads at night). The knowledge of day-night variations in coastal lagoons is a present and challenging issue since could be included in surveillance monitoring.

Only a few studies about diel cycles in coastal ecosystems were performed in the Iberian Peninsula: Ria Formosa coastal lagoon by Ribeiro *et al*. (2006), Mondego estuary by Lillebo *et al*. (2002, 2004, 2010), Óbidos lagoon by Pereira et al. (2010) and Louro lagoon by Cobelo-García *et al.* (2012).

In Óbidos Lagoon the work addressed by Pereira *et al*. (2009a, 2010) relate the bottom water anoxia (e.g., Carignan and Lean, 1991; Andersen and Jensen, 1992; Olila and Reddy, 1997) with metals and nutrients variability but does not explore the balance between photosynthetic production and heterotrophic respiration in the influence of metals and nutrients vertical migration in sediment. The novelty of our approach compared to previously studies in Óbidos coastal lagoon (Pereira *et al*., 2009a, Pereira *et al*., 2009a 2010) and other works (Ribeiro *et al.* 2006, Lillebo *et al*. 2002, Lillebo *et al*. 2004, Lillebo *et al*. 2010, Cobelo-García *et al*., 2012) explores the balance between photosynthetic production and heterotrophic respiration in the influence of the vertical migration in sediment, and uses data from both, laboratory samplings and 24-hours cycles in real time. Additionally, we try also to combine the diel variability observed in the Óbidos Lagon water column with meteorological and hydrological forcing.

Diel fluctuations as presented in this study have not been documented at this scale before in coastal lagoons. This study addresses aspects of physicochemical, chlorophyll a, nutrients and metals diel cycle in a mesotidal coastal lagoon in the west coast of Portugal (Óbidos Lagoon) subject to anthropogenic nutrient loading, eutrophication and hypoxia. Our goal was to identify which factors most influence the diel variability in impacted and reference sites for two seasonal conditions with a combination of: 1) high solar radiation and low freshwater discharges (e.g., summer), and 2) low solar radiation and increased freshwater discharges (e.g., winter). To accomplish these goals statistical analysis (Pearson correlation and principal component analysis) were applied to the data (24-hours cycles in real time versus to laboratory samplings). Data included as key parameters the physicochemical properties of water (salinity, pH, and dissolved oxygen-DO), chlorophyll *a* (Chl *a*), nutrients (nitrate-NO_3^-, nitrite-NO_2^-, ammonium-NH_4^+, phosphate-PO_4^{3-} and silicate-Si) and metals (aluminum-Al, iron-Fe, manganese-Mn and lead-Pb).

6.2. Material and methods

6.2.1. Study site

Óbidos Lagoon (39º24´N, 9º17’W) is a shallow (~2 m average depth) coastal lagoon of 7 km^2 (wet area) on the northwest coast of Portugal (Figure 6.1), connected to the Atlantic Ocean by a narrow mobile inlet (100 m wide); the position of the inlet has changed naturally during the last decades (Oliveira et al 2006).

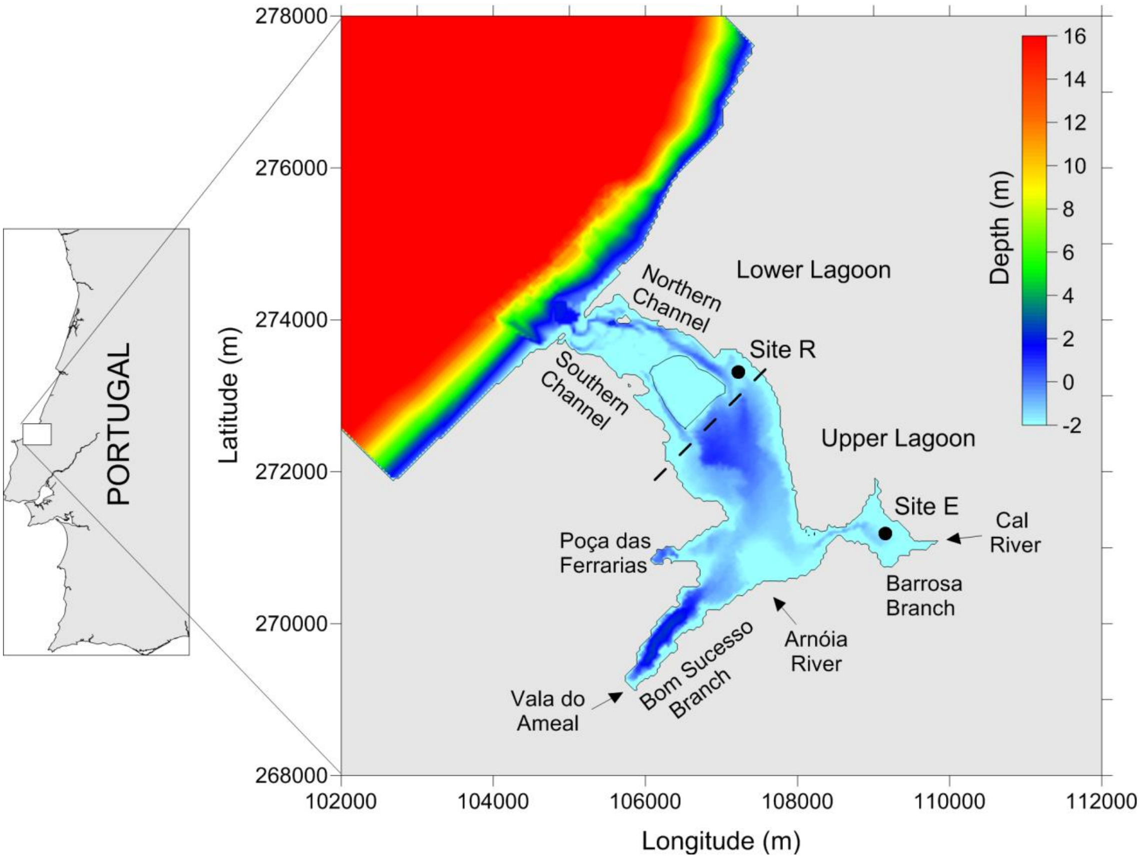


Figure 6.1. Geographical location of Óbidos Lagoon. Location of sites (R-Reference and E-Eutrophic) are marked. Main river discharges are also marked.

The main freshwater inputs comes from two small streams (Arnóia and Cal rivers; 3 m^3s^{-1} and 0.14 m^3s^{-1} annual average flows), and one drainage creek (Vala do Ameal; 0.08 m^3s^{-1} annual average flow) usually dry during summer (Vão, 1991).

The oceanic influence from the Atlantic and the freshwater inputs lead to clearly distinct geographical areas in the lagoon according to hydrological parameters: (1) the lower reaches, directly influenced by the oceanic waters and composed by sand banks and narrow channels (northern and south channels); (2) the upper reaches, particularly influenced by land inputs with a large shallow basin, two elongated branches (Bom Sucesso and Barrosa) and a small embayment on the southern margin (Poça das Ferrarias; Oliveira *et al*., 2006).

This shallow lagoon is well-mixed, subjected to semidiurnal and mesotidal tides (0.5 m to 3.5 m; Bertin *et al*., 2013) and in a small extension to storm waves (wave height values ranging between 3 and 7 m; Malhadas *et al*., 2010) enabling important water exchanges with the adjacent oceanic waters. These have been estimated around 6×10^6 m^3 for an average neap tide and 10^7 m^3 for a spring tide (Malhadas *et al*., 2009). Freshwater inputs are less than 5% of the average tidal prism scaled by the M2 period (Rego, 2004).

The water in the lower reaches flows mainly along the northern channel with strongest velocities (~1.0-1.5 ms^{-1}) during flood circulation (Figure 6.2a and Figure 6.2b).In the upper part the velocities often exceed 0.4 ms^{-1}, but still range 30% less than in the lower part (Figure 6.2c and Figure 6.2d). According to Malhadas *et al*. (2009) the laggon is flood-dominated,with ebb periods (~6h) longer than flood periods (~4h).

Mean water renewal is typically between 1-2 days in the near-ocean areas, 4-7 days in the middle reaches and 10-26 days in the inner branches - Barrosa and Bom Sucesso (Malhadas *et al*., 2010). These values can increase from 10% to 50% during storm wave periods (Malhadas *et al*., 2010).

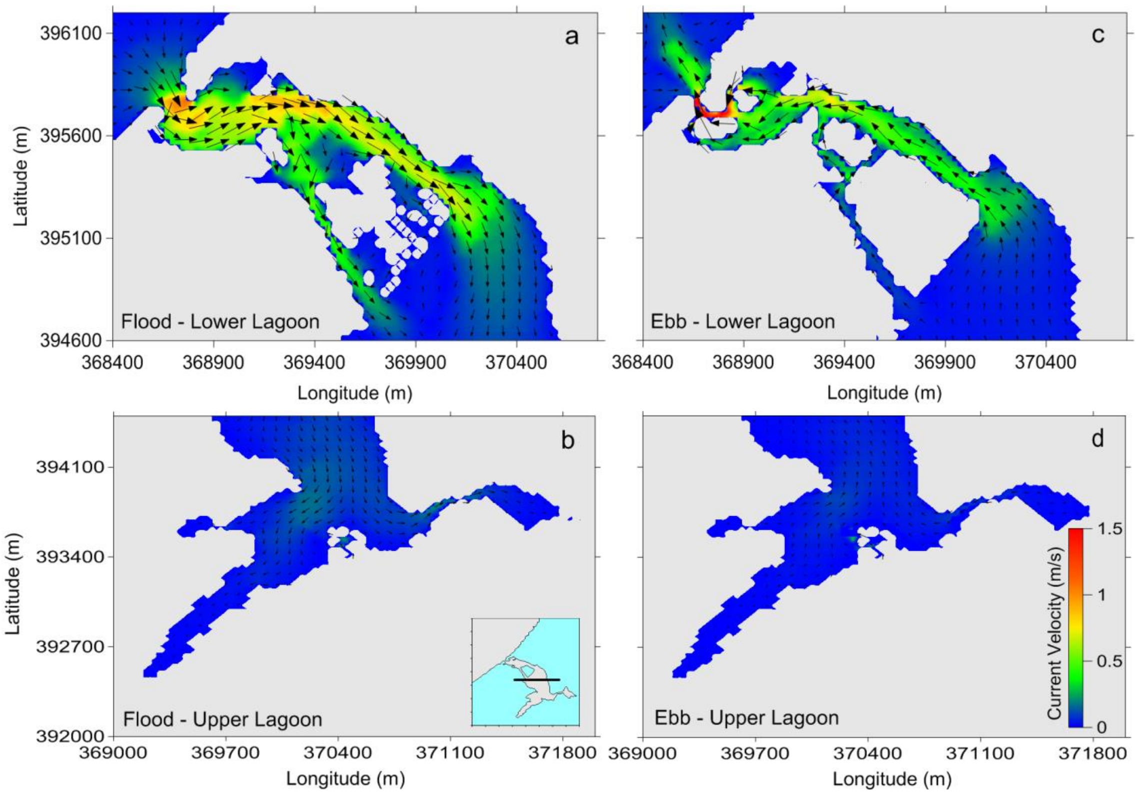


Figure 6.2. Flood (a,b) and ebb circulation (c,d) in the lower lagoon and upper lagoon.

The lagoon is therefore a heterogeneous ecosystem regarding both its morphologic and hydrodynamic characteristics. These lead to significant differences from the lower to the upper reaches in terms of water quality and sediment characteristics. High chlorophyll *a* concentrations (~20 µg L^{-1}) associated to enriched nutrient waters (85 µM for NH_4^+, 120 µM for NO_3^-+NO_2^-, 55 µM for Si and 20 µM for PO_4^{3-}, Pereira *et al.*, 2009b) are usually observed in the upper reaches (mainly in the branches). In addition, high affinities for metals in muddy bottom sediments are also common in this part of the lagoon (Carvalho *et al*., 2006; Pereira *et al*., 2009b). In fact, the most problematic area is Barrosa branch, classified as eutrophic to polytrophic, according to several trophic classification methods (Pereira *et al.*, 2009b). Opportunistic macroinvertebrate species found in Barrosa corroborates the eutrophic condition in the branches (Carvalho *et al*. 2005, 2006).

The extreme deterioration conditions in that branch are presumably related with the urban effluents from the town "Caldas da Rainha". During the past decades effluents enter in the branch via Cal River. From September 2005, urban effluents are deviated to a sewage collector, but Cal

River continued to deteriorated water quality conditions according to the Portuguese classification of freshwater systems (IST/IPIMAR, 2008). Monthly campaigns carried out in Cal River after loads deviation showed a mean flow of 0.20 $m^3\ s^{-1}$ with elevated levels of NH_4^+ (136–850 µM), NO_3^- (12–286 µM) and PO_4^{3-} (36–214 µM; IST/IPIMAR, 2010).

The confined area of Barrosa branch presents particular characteristics, compared with the rest of the lagoon, which should be on surveillance: it is an enclosed embayment with lower velocities and relatively high residence times where phytoplankton growth and macroalgal cover (*Ulva* and *Enteromorpha*) is favored. Moreover, in such ecosystems, the release of phosphate from sediments as oxidation of organic matter, could sustain the high summer phosphate levels as already shown by temporal cycling of nutrients (Pereira *et al.*, 2009a, 2010).

6.2.2. Field sampling

6.2.2.1. Sites location and field conditions

Three sampling campaigns were carried out in summer (high temperatures and low flows) and winter (low temperatures and high flows) at two sites (R and E, Figure 6.1) covering a complete 24-hours cycle. Site E was surveyed on 19th and 20th September 2008 (summer) and 3rd and 4th December 2008 (winter). Site R was not sampled during winter since they were not expected variations in results, considering physical factors and the biogeochemical knowledge of the system (Malhadas *et al*., 2010; Pereira *et al*., 2009b). Site R was chosen as reference station due to marine dependence; and site E (Barrosa branch) as a eutrophic site due to strong anthropogenic loads influence and eutrophication symptoms. In addition, surface sediments from the two sites differed in nature and physicochemical characteristics (Table 6.1, IST/IPIMAR, 2010). Sediments from site E are more reductive (Eh) presenting higher organic matter (OM) and content of metals (Al, Fe, Mn and Pb) than those from site E.

Table 6.1. Characteristics of surface sediments (IST/IPIMAR, 2010): values of pH, reduction potential (Eh), fraction of fine particles (d<65 µm), organic matter (OM) and metals (Al, Fe, Mn and Pb) determined in Site R (Reference) and E (Eutrophic). Sediment type is also indicated.

Sites	pH	Eh (mV)	Fraction of fine particles (%)	OM (%)	Al (%)	Fe (%)	Mn (µg g^{-1})	Pb (µg g^{-1})	Sediment Type
R - Reference	7.5	162	0	1	0.41	0.09	33	2.9	Sand
E - Eutrophic	8.7	-391	86.5	6.2	9.2	4.6	287	22	Mud

Daily average flows with StreamPro ADCP (http://www.rdinstruments.com) at the three freshwater river discharges (Arnóia and Cal Rivers, and Vala do Ameal) were measured. Meteorological (air temperature, precipitation and solar radiation) conditions measured at Óbidos automatic station (INAG, www.inag.pt: code 17C/07C) during the sampling period are shown in Figure 6.3.

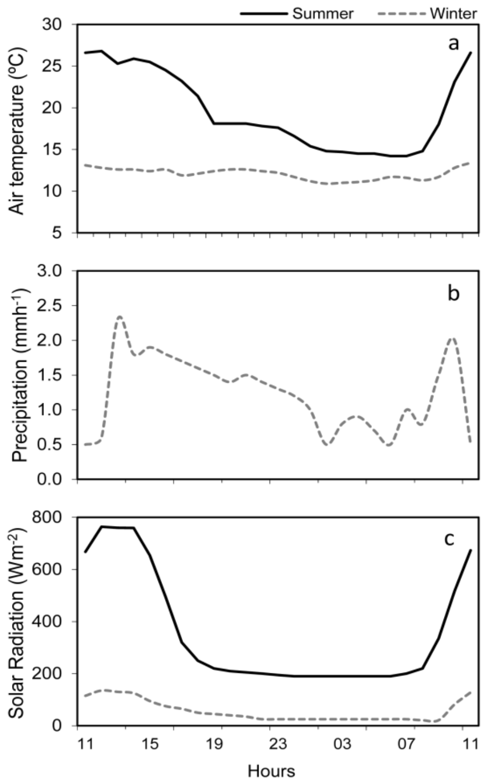


Figure 6.3. Meteorological conditions (a-air temperature, b-precipitation and c-solar radiation) during sampling periods: summer (19th-20th, September 2008, solid line) and winter (3rd-4th, December 2008, dash line).

Information about tidal cycle (LW-Low Waters and HW-High Waters) for the surveyed periods is presented in Table 6.2. Information was provided from hydrodynamic model of the lagoon implemented and validated by Malhadas *et al.* (2009, 2010). The monitoring strategy includes *in situ* data acquisition and laboratory analyses described in the next sections.

Table 6.2. Tidal information (LW-Low Waters and HW-High Waters) during sampling periods: summer (19th-20th, September 2008) and winter (3rd-4th, December 2008).

Hours	12h00	18h00	00h00	04h00	10h00	14h00
19th-20th, September 2008	HW	LW	HW	LW	HW	LW
Hours	11h00	15h00	21h00	01h00	07h00	11h00
3rd-4th, December 2008	LW	HW	LW	HW	LW	HW

6.2.2.2. In situ data

On each site a multi-parameter probe (YSI 6600-V2; www.easy.com) and an automatic nutrient analyzer (DPA, Deep-sea Probe Analyzer) were deployed. Instruments were calibrated in laboratory according to manufacturer specifications before fieldwork.

The probe consists on a multi-parameter water quality data collection system. Measurements of temperature (ºC), salinity, pH, and turbidity (NTU) were acquired with a data accuracy of ± 0.15 ºC for temperature, ±1% for salinity, ±0.2 for pH and ±5% for turbidity. No levels of accuracy are specified for DO and Chl *a*. Sampling rate was set to 10-minutes interval.

DPA is an *in situ* probe analyzer from Systea (www.systea.it) able to measure automatically NO_3^-, NO_2^-, NH_4^+ and PO_4^{3-} in surface, transition waters and seawater according to the following detection limits: 0.1 µM NH_4^+, 0.01 µM PO_4^{3-}, 0.03 µM NO_3^- and 0.01 µM NO_2^-.

6.2.2.3. Laboratorial sampling

Water was sampled to various bottles according to the analytical specifications and transported to a field laboratory for filtration and preservation of the samples. Samplings were performed to cover a complete diel cycle with 2-hour intervals during the day and 4-hour intervals at night for quantitation of dissolved inorganic nutrients (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-} and Si) and metals (Al, Pb, Mn and Fe) in particulate fraction.

Samples for the determination of dissolved inorganic nutrients were filtered through MSI Acetate Plus filters, and analysis carried out using an AutoAnalyser TRAACS 2000 (Bran + Luebbe). Certified standards (Wako, CSK Standard Solution) were used to ensure the accuracy of the procedures and precision was found to be ±1.0% for NO_3^-, ±2.0% for NH_4^+, ±1.9% for PO_4^{3-} and ±1.1% for Si.

The concentrations of Pb and Mn were determined by inductively coupled plasma mass spectrometry (ICP-MS e Thermo Elemental, X-Series) and the levels of Al and Fe by atomic absorption spectrometry (AAS e Perkin Elmer, AAnalyst 600). Metal levels obtained in the reference materials were consistently within the ranges of certified values (Fe 0.568 µg l^{-1}, Mn 1.61 µg l^{-1}, Pb 0.0090 µg l^{-1} and indicative values for Al).

6.2.3. Data Analysis

Statistical software (Statistica 6.1 and MATLAB) was applied to the data. Statistica 6.1 was used to perform ANOVA analysis and MATLAB to execute Principal Component Analysis (PCAs).

By applying ANOVA to the data Tukey test was used for post hoc comparison in sampling sites (Zar, 1996). Differences between means were considered significant when $p<0.05$. A Pearson correlation (r) was performed to evaluate the degree of relationship between the parameters.

MATLAB was used to extract composite variables from the original data and assess the underlying patterns in the distribution of the measured parameters (Boyer *et al*. 1997). Raw data was log-transformed to scale down high scores among variables (Sokal and Rohlf, 1995). The PCAs solution was rotated (using Varimax normalized) to optimize statistical results and the composition of each principal component (*Sañudo*-Wilhelmy, 2001). The factor scores were saved and plotted to identify which stations with respect to one another and whether or not associations were consistent between the sampling periods/sites.

6.3. Results

6.3.1. River fluxes

The summer (September 2008) campaign was characterized by low river flow conditions with the flux of the Arnóia and Cal rivers being measured as 0.6 and 0.02 m^3s^{-1} which is 20% and 14% of the annual average (see study site description). In contrast, winter (December 2008) was characterized by high discharge conditions with the flux of the Arnóia and Cal rivers (4.5 m^3s^{-1} and 0.3 m^3s^{-1}, respectively) being 150% and 214% of the annual average. Vala do Ameal run dry in summer and in winter was measured 0.1 m^3s^{-1}which is 125% of the annual average.

6.3.2. Summer diel cycles at reference and eutrophic sites

Summer (e.g., high temperatures and no precipitation – Figure 6.3a and Figure 6.3b) diel cycles of physicochemical properties (water temperature, salinity, turbidity, pH and DO saturation), Chl *a*, nutrients (NH_4^+, PO_4^{3-}, Si, NO_3^-+NO_2^-) and metals (Fe/Al, Mn/Al and Pb/Al) at reference (site R) and eutrophic (site E) sites are depicted in Figure 6.4, Figure 6.5 and Figure 6.6, respectively.

6.3.2.1. Physicochemical properties and chlorophyll a

Water temperature (Figure 6.4a) in both sites followed the solar radiation diurnal cycle (Figure 6.3c) with higher values during the daytime and lower in the nighttime. The grand medians ranged from 19.29 ºC at reference to 23.20 ºC at eutrophic. Temperatures were lower in the reference (R) and higher in the eutrophic (E) stations. The maximum value during the 24-hours cycle was 25.45 ºC and the minimum 18.05 ºC, at E and R, respectively.

Salinity (Figure 6.4b) reflected the expected variation along the tidal cycle (see hours of LW and HW in Table 6.1) with minimum values typically observed in LW (35.0 at site R and 31.4 at site E) and maximum in HW (36.3 at R and 35.2 at E). It is also observed a gradient increasing from the reference to the eutrophic site because it is influenced by the freshwater runoff from the Cal River (Figure 6.1). Lower salinities were found near the Barrosa branch (E) and higher salinities were found near the coastal station (R). The grand medians ranged from 35.9 (R) to 33.3 (E).

Turbidity (Figure 6.4c) measured in site E was larger than measurements in site R. The grand medians ranged from 2.2 (R) to 10.53 (E) and the maximums from 5.4 (R) to 17.2 (E).

The diel amplitude observed in pH (Figure 6.4d), DO saturation (Figure 6.4e) and Chl *a* (Figure 6.4f) at reference (R) is much weaker and, as expected no remarkable peaks were observed during the 24-hours measurements. Contrary at eutrophic site (E), substantial diel cycles with high levels during the daytime and low levels at nighttime were observed. The rise in concentrations during daytime corresponded to maximum hours of solar radiation (Figure 6.3c) during the 24-hours cycle. Minimum values (pH-7.77, DO saturation-40%, chlorophyll *a*-10 μg L^{-1} – site E) were typically observed between 23h00 and 07h00 local time (LT), and maximums (pH-8.35, DO saturation-219%, Chl *a*-33 μg L^{-1} – site E) occurred between 14h00 and 17h00 LT. Site E experienced a phytoplankton bloom (Chl *a* of 30 μg L^{-1}, Figure 6.4f) at same hours of maximum solar radiation (from 13h00-16h00 LT, Figure 6.3c), and the diel DO variation was pronounced (>200% saturated decreased to complete state of anoxia from 23h till 07h00 LT; Figure 6.4e).

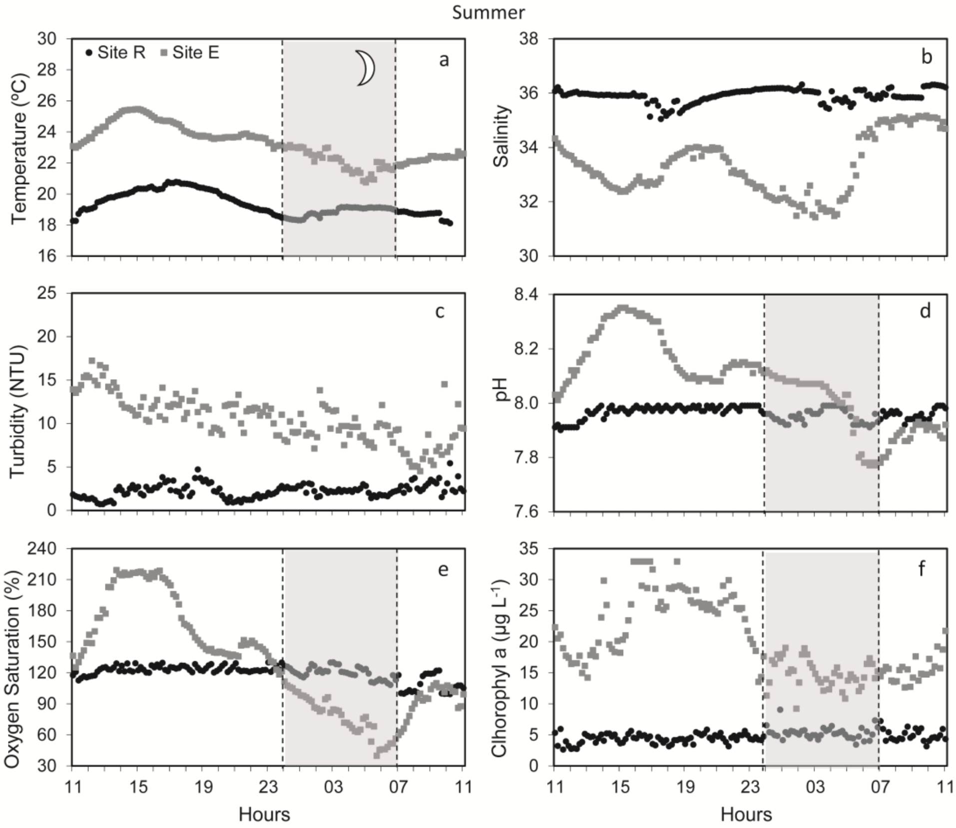


Figure 6.4. Diel variations of surface temperature (°C), salinity, pH, turbidity (NTU), oxygen saturation (%) and Chlorophyll *a* ($\mu g l^{-1}$) at reference (site R) and eutrophic (site E) sites in summer.

6.3.2.2. Nutrients

It is notable the difference observed between nutrients diel cycle at site R (Figure 6.5 panel one) compared to site E (Figure 6.5 panel two), except for NO_3^-+NO_2^-.

Strong diel patterns of NH_4^+, PO_4^3 and Si (Figure 6.5b to Figure 6.5f) were observed during the series of measurements at site E. Measurements at site E captured the relationship between DO and NH_4^+, PO_4^{3-} and Si concentrations, specifically, when the DO levels decreased the NH_4^+, PO_4^{3-} and Si concentrations increased simultaneously. NH_4^+, PO_4^{3-} and Si cycles follow more stable concentrations from 11h00 – 23h00 LT, decreasing DO concentrations with increasing NH_4^+, PO_4^{3-} and Si concentrations from 23h00 to 07h00 LT.

The values of the nocturnal peaks coincident with low oxygen were: NH_4^+ 15 µM, PO_4^{3-} 3 µM and Si 20 µM. Moreover, the peaks also corresponded to the periods of shallower water column (e.g., LW times – Table 6.1). The high concentrations are not influenced by the loading of the Cal River in this zone. Discharge data from the Cal River revealed flow conditions of a dried river run-off during the monitoring period. The peaks of PO_4^{3-} during low oxygen conditions at site E could be associated to the release of Mn and Fe from sediments (further discussed).

NO_3^-+NO_2^- and NH_4^+ concentrations at site R (Figure 6.5g) showed two peaks with values higher than 1 µM and 5 µM, respectively: the first one was reached during the day at 15h00-17h00 LT and the second during night at 03h00-06h00 LT. Encountered variability are not believed to be diel cycle because is in agreement with the times of ebb: the first one occurred from 15h00 till 21h00 LT and the second from 01h00 to 07h00 LT (Table 6.1). Si diel cycle showed a pronounced peak during the daytime peak; it reached 8 µM and is concurrent with LW (Table 6.1). PO_4^{3-} cycle was quite uniform and without a diel pattern showing average values of 0.2 µM.

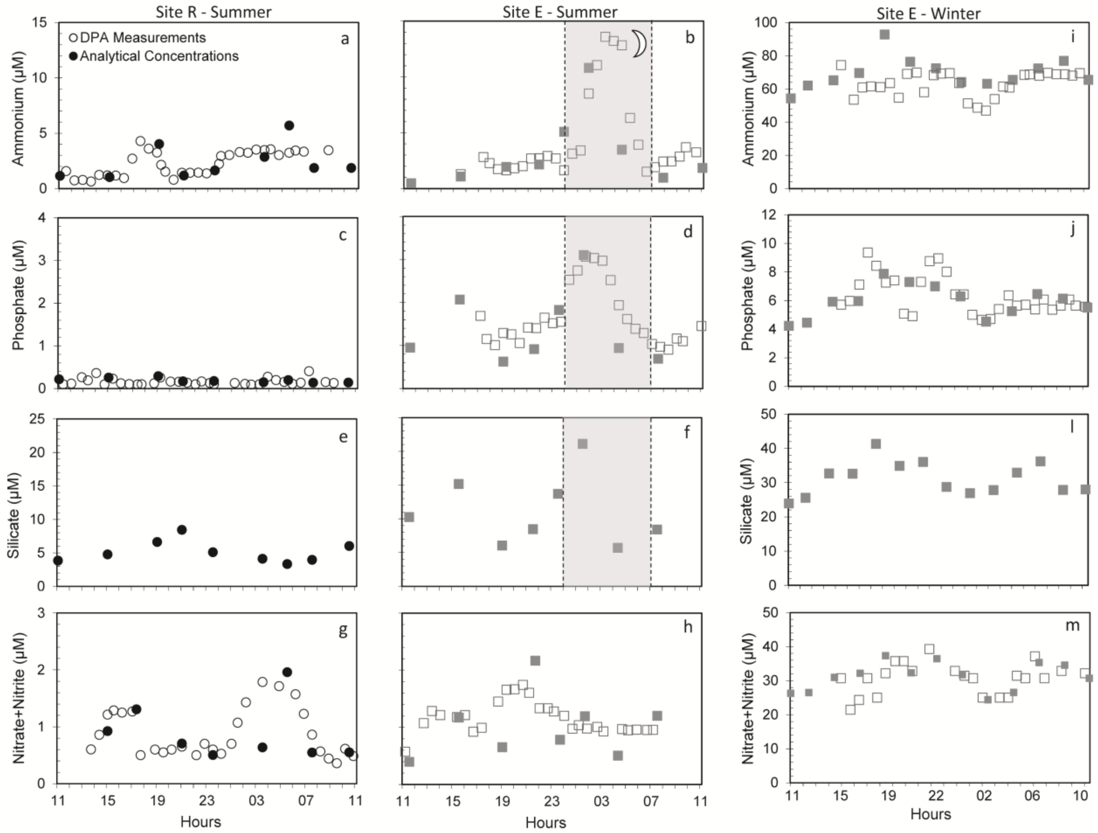


Figure 6.5. Diel trends of surface nutrients (ammonium, nitrate+nitrite, phosphate and silicate in µM) at reference (site R - column one) and eutrophic (site E - column two) sites in summer. Diel variations in winter at Site E are also presented (column three). The data includes analytical concentrations with DPA measurements with exception for silicate.

6.3.2.3. Metals

Data collected in summer at site E for Fe/Al (Figure 6.6a), Mn/Al (Figure 6.6b) and Pb/Al (Figure 6.6c) revealed a similar diel cycle as seen in the nutrients data – maximum concentrations (Fe/Al 0.7, Mn/Al 800×10^{-4} and Pb/Al 10 ×10^{-4}) in nighttime from 23h00 to 07h00 LT and temporal decrease with DO saturation.

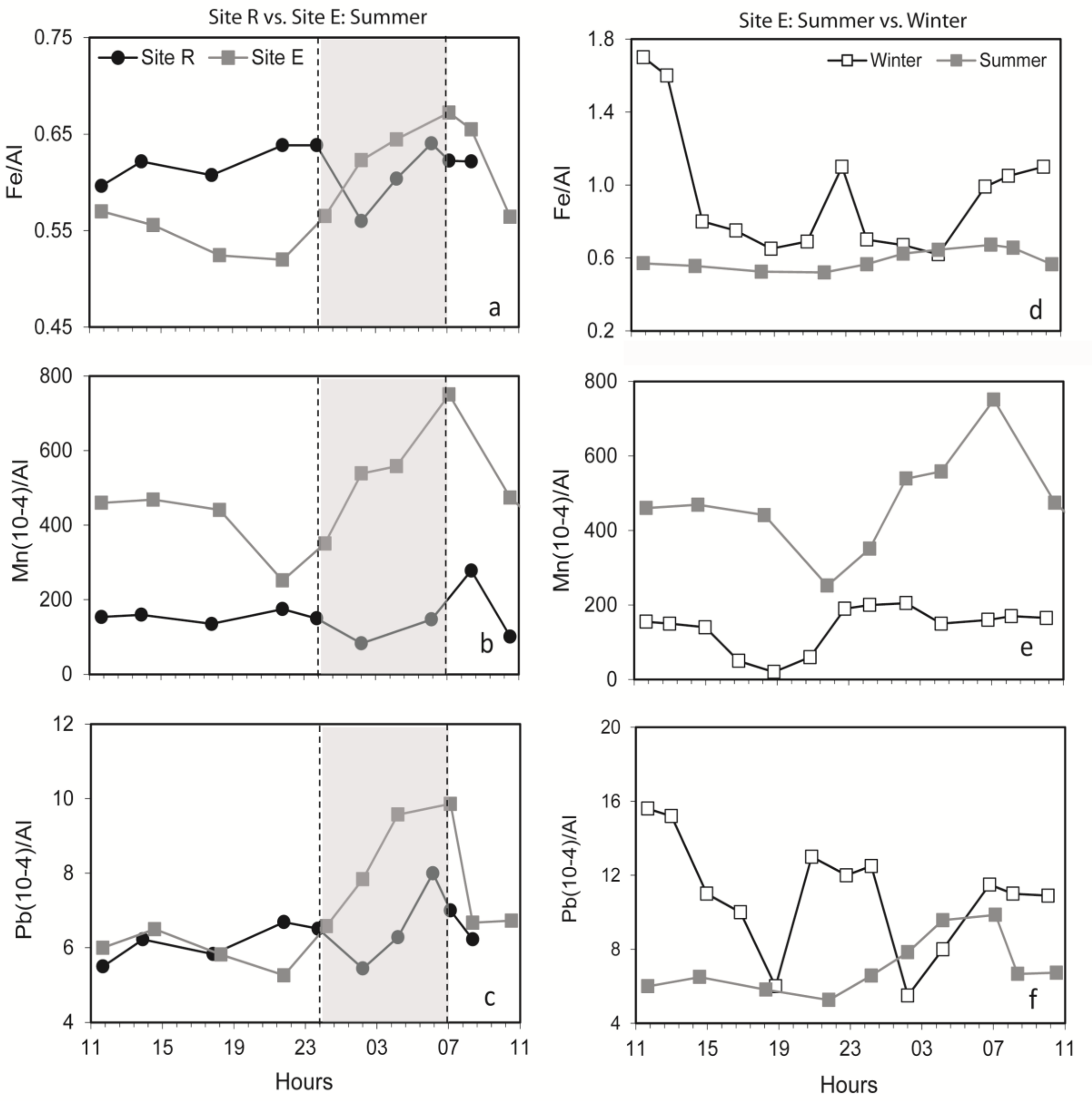


Figure 6.6. Diel variations of Fe/Al, Mn(10^{-4})/Al and Pb(10^{-4})/Al in suspended particulate matter collected at reference (site R) and eutrophic (site E) sites along a 24-h surveys (column a). Diel variations in winter at Site E are also presented (column b).

Observed spikes occurred at the same time as the minimum of DO saturation (~40%, Figure 6.4e) and two hours after the peak of PO_4^{3-}. The enhancement of particulate Fe, Mn and Pb in the ratios to Al could represent a nocturnal enrichment of these elements from the sediments after the peak of PO_4^{3-} as further discussed. The maximums were also observed during lower water column depths (LW, Table 1) diminishing the dilution of particulate matter.

Metal levels (in particular for Mn/Al and Pb/Al ratios, Figure 6.6b and Figure 6.6c) at reference (R) revealed a similar patter recorded for NO_3^-+NO_2^- at same site (Figure 6.5g). Maxima of Mn/Al and Pb/Al ratios (Mn/Al 200×10^{-4} and Pb/Al 8×10^{-4}) were recorded during the ebb times and were concurrent with lower salinity values recorded close to the lagoon's mouth at this site (Figure 6.4b).

6.3.3. Summer and winter diel cycles at eutrophic site

Summer (e.g., high temperatures and no precipitation – Figure 6.3a and Figure 6.3b) and winter (e.g., low temperatures and rainy period – Figure 6.3a and Figure 6.3b) diel cycles of nutrients (NH_4^+, PO_4^{3-}, Si, NO_3^-+NO_2^-) and metals (Fe/Al, Mn/Al and Pb/Al) at eutrophic (E) sites are depicted in Figure 6.5 and Figure 6.6, respectively. Physicochemical properties (water temperature, salinity, turbidity, pH and DO saturation) and Chl *a* are showed in Figure 6.7.

6.3.3.1. Physicochemical properties and Chlorophyll a

Seasonal differences in surface temperature, salinity, pH, turbidity, oxygen saturation and Chl *a* at site E were observed by comparing the concentrations measured in summer under low (no precipitation, Figure 6.3a) and in winter under high (mean precipitation of about 2 mm h^{-1}, Figure 6.3a) flow conditions. Water temperature ranged between 10.6 - 12.9°C (winter) and 19-26°C (summer). Salinity decreased about 23% (scaled to summer median values) in high flow conditions reflecting the freshwater discharges of Cal River in the Barrosa branch near site E (the plume of Arnóia/Real rivers in rainy periods also achieves the branch close to site E). In winter cycle no evident diel trends in DO saturation were observed. pH median values for both periods are approximately 8.1, however in summer cycle there was a clear day-night variation. Average turbidity (20 NTU) was higher during the winter cycle than the mean measured under low flow conditions (10 NTU). During the winter cycle average Chl *a* was 2.9 μg L^{-1} contrasting with the average obtained in summer cycle (20 μg L^{-1}).

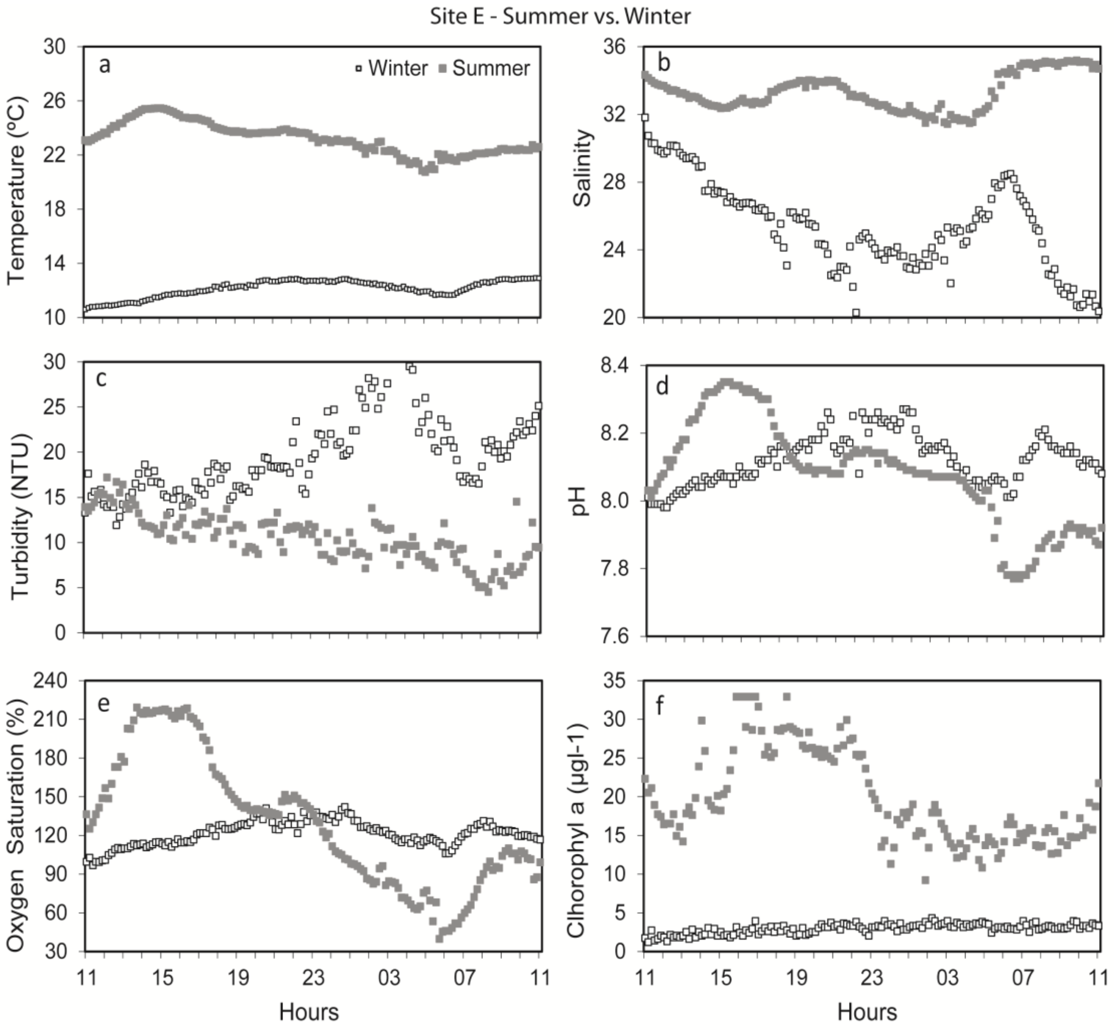


Figure 6.7. Diel variations of surface temperature (ºC), salinity, pH, turbidity (NTU), oxygen saturation (%) and Chlorophyll *a* (μgl^{-1}) at eutrophic (site E) site in summer and winter.

6.3.3.2. Nutrients

Measured concentrations in high flow conditions reflected the input of nutrients from rivers runoff with an increasing of median values: 3-NH_4^+, 1-NO_3^-+NO_2^-, 1.4-PO_4^{3-} and 11-Si in summer; 64-NH_4^+, 29-NO_3^-+NO_2^-, 3.2-PO_4^{3-} and 31-Si in winter. Under such conditions the magnitude of the internal input was far below the external input. In fact, diel variability in winter cycle was hidden by higher concentrations. Moreover, low water temperatures in winter also influenced the differences between day and night over a 24-hours cycle.

6.3.3.3. Metals

Average levels of Mn(10^{-4})/Al were almost three times higher during low flow conditions (462) when compared to high flow conditions (140), while levels of Fe and Pb were higher during high flow conditions (1-Fe/Al and 11-Pb(10^{-4})/Al) when compared to low flow conditions (0.6-Fe/Al and 7-Pb(10^{-4})/Al). The summer cycle of Mn(10^{-4})/Al seems to be dependent of nocturnal variations since diel cycle superimposed the winter cycle.

6.3.4. Molar ratios

Figure 6.8 shows the molar ratios of dissolved inorganic nitrogen (DIN=NH_4^++NO_3^-+NO_2) and dissolved inorganic phosphorus (herein after P to simplify); and DIN:Si for summer and winter at both sites (R and E). At site R the DIN:P ratio based on summer DIN and P concentrations (Figure 6.8a) was ~22. At site E significant deviations from 16 at low DIN:P ratios (Figure 6.8a) were observed in summer cycle and at high DIN:P ratios (Figure 6.8b) in winter cycle. Low Si:N and Si:P ratios in summer and winter were observed at site E.

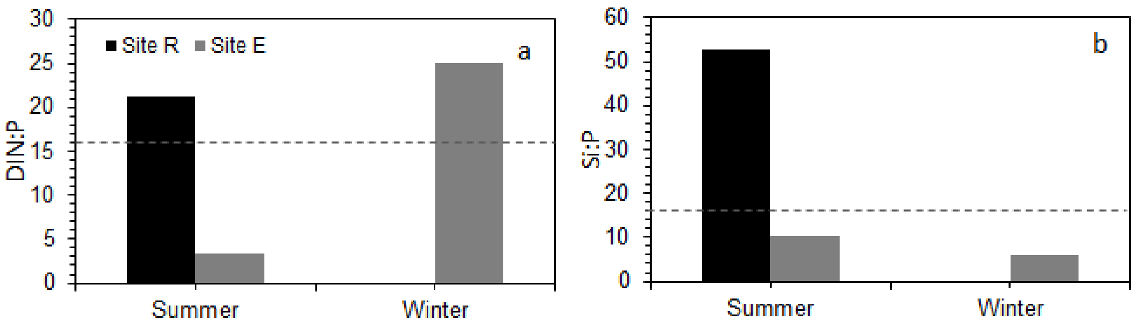


Figure 6.8. DIN:P and Si:P ratios in the sampling sites R (Reference) and E (Eutrophic) for summer and winter.

6.3.5. Principal component analysis

Principal component analysis were applied to metal and nutrient data at sites R and E in order to identify significant relationships among surveyed data in winter and summer diel cycle. Salinity, DO, NH_4^+, PO_4^{3-} and Mn/Al, Pb/Al, Fe/Al ratios were the key variables used to identify the principal mechanisms influencing the variability in summer and winter at both sites.

6.3.5.1. Summer diel cycles at reference and eutrophic sites

Figure 6.9 shows PCAs biplot based on normalized data for the samples collected in summer at sites R and E for the six variables (DO, NH_4^+, PO_4^{3-}, Mn/Al, Fe/Al, Pb/Al). The first component, which accounts for 45% of the variance within the system, is characterized by high positive loadings of Pb/Al, Mn/Al and Fe/Al (0.54, 0.46, and 0.41, respectively) and high negative loadings of DO and PO_4^{3-} (-0.40 and -0.36). It means that observations that have high values for variables Pb/Al, Mn/Al and Fe/Al and low values for variables DO and PO_4^{3-} are distinguished in component 1 from observations that have low values for variables Pb/Al, Mn/Al and Fe/Al and high values for variables DO and PO_4^{3-}.

The second component accounts for 31% of the variance within the system, and is most strongly influenced positively by PO_4^{3-} (0.53), NH_4^+ (0.48) and Fe/Al (0.45), and negatively by DO (-0.45) and Mn/Al (-0.27), with the remaining variable Pb/Al having low magnitude loadings (0.1). Second component distinguishes observations that have high values for PO_4^{3-}, NH_4^+ and Fe/Al and low values for DO and Mn/Al, from observations with low values for PO_4^{3-}, NH_4^+ and Fe/Al and high values for DO and Mn/Al.

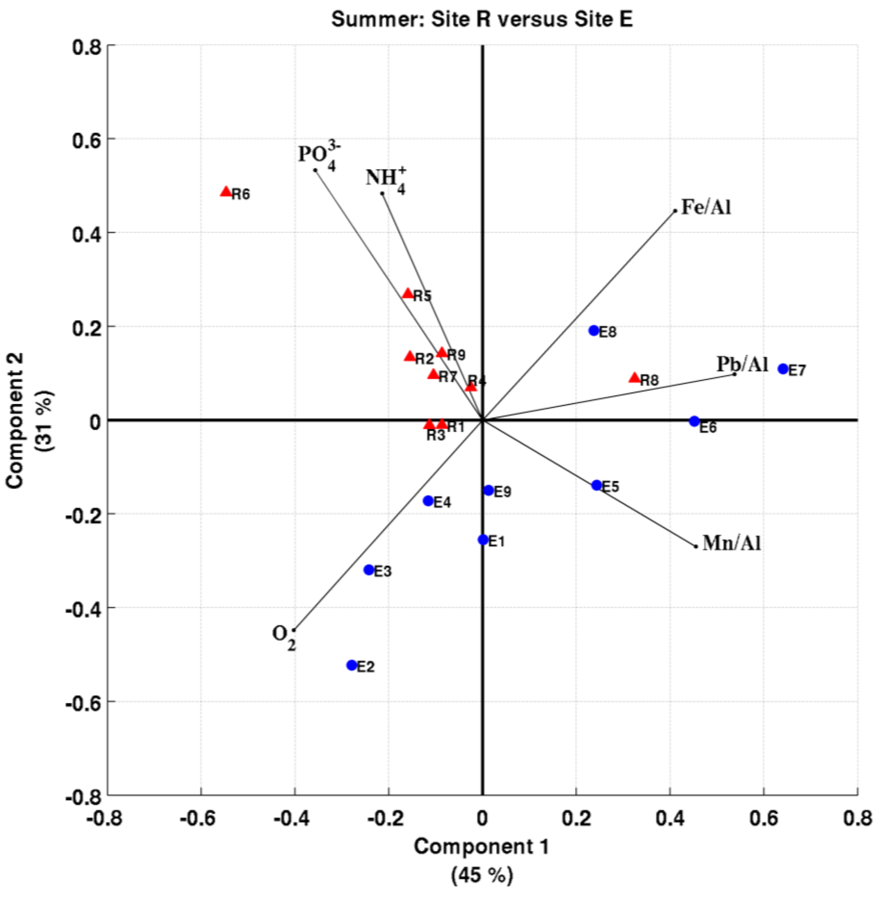


Figure 6.9. PCA biplot based on normalized data of the samples collected during a 24-hours cycle in sites R (▲) and E (•) for the six variables (O_2, NH_4^+, PO_4^{3-} ,Mn/Al, Fe/Al, Pb/Al) in summer. Component 1 accounts for 45 % of the total variance and component 2 for 31 %.

6.3.5.2. Summer and winter diel cycles at eutrophic site

Figure 6.10 shows PCAs biplot based on samples collected at Site E in summer and winter diel cycles for the six variables (salinity, NH_4^+, PO_4^{3-}, Mn/Al, Fe/Al, Pb/Al). First component accounts for 73% of the variance within the system and is characterized by high positive loadings of PO_4^{3-}, NH_4^+, Fe/Al and Pb/Al (0.47, 0.46, 0.36 and 0.31, respectively) and high negative loadings of salinity and Mn/Al (-0.44 and 0.38). First component distinguishes observations that have high values for variables PO_4^{3-}, NH_4^+, Fe/Al and Pb/Al and low values for variables salinity and Mn/Al, from observations that have high values for salinity and Mn/Al and low values for PO_4^{3-}, NH_4^+, Fe/Al and Pb/Al.

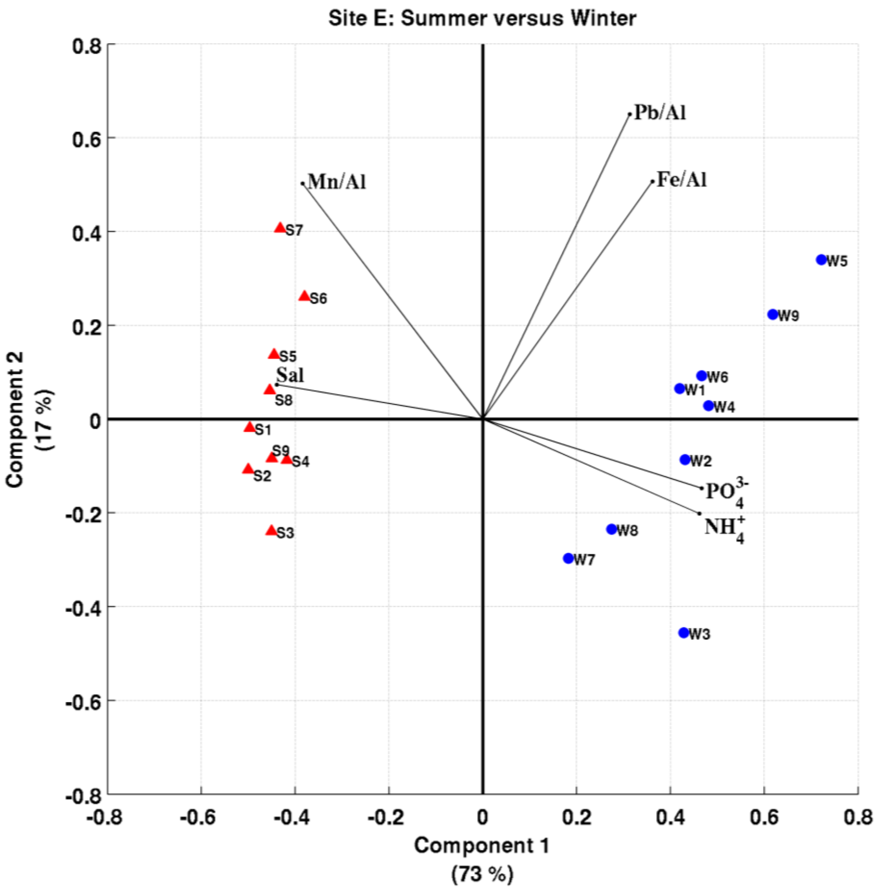


Figure 6.10. PCA biplot based on normalized data of the samples collected during a 24-hours cycle at site E in summer (▲) and winter (•) for the six variables (salinity, NH_4^+, PO_4^{3-} ,Mn/Al, Fe/Al, Pb/Al). Component 1 accounts for 73 % of the total variance and component 2 for 17 %.

6.4. Discussion

The present study investigated the influence of seasonal conditions (summer-winter) and study sites (eutrophic and reference) in the physicochemical, Chla *a*, nutrients and metals diel cycle. The current findings showed that day-night variability of physicochemical, nutrients and metals over 24-hours cycle varied considerably with seasonal conditions and sites.

6.4.1. Site differences

A noticeably different diel trend in cycles was observed between the two sites. No trend was visible in R (Figure 6.5, panel one), while E (Figure 6.5, panel two) demonstrated high variation in the water column with nocturnal peaks. Measured data at site E were significantly ($p<0.05$) different from those observed in site R.

Encountered differences are primarily associated to site location (eutrophic-E and reference-R). The average Chl *a* at site E (20 μg L^{-1}, eutrophic state) contrasts with that obtained at R (4.7 μg L^{-1}). In fact, Pereira *et al*. (2010) classified the Barrosa Branch as an eutrophic area according to Wasmund (2001) eutrophication criteria; and values around 2-3 μg L^{-1} were found by Newton *et al*. (2003) in Ria Formosa (Portugal), a coastal lagoon sufficiently diluted and flushed by the tides to limit the effects of eutrophication. Moreover, specificity of summer conditions (e.g., high solar radiation and low flows) also highlights encountered day-night variability at site E, where both phytoplankton biomass and water temperature were highest.

Phytoplankton biomass diel cycle at E (observed in terms of Chl *a*, Figure 6.4f) is controlled by the dynamics between photosynthesis/respiration cycles (Cobelo-García *et al*., 2012). The bloom recorded during daytime is due to photosynthesis (enhanced by solar radiation maxima, Figure 6.3c). At nighttime, with the cessation of photosynthesis, the respiration explains the decrease observed in concentrations. Similar processes have been observed in other estuarine systems where high photosynthetic and algae respiratory activity occurred in intertidal marshes (e.g., Cai *et al*., 1999; Sanderson and Taylor, 2003). The balance between primary productivity and respiration was also the predominant process affecting the diel shifts in DO 24-hours cycle at same site - maximum DO concentrations were measured in late afternoon during peak photosynthesis and suboxic conditions prevailed in the early morning caused by respiration and decomposition of organic matter. DO diel cycle is like a net oxygen sink resulting in low DO when algae consumed more oxygen than they produced (e.g., D'Avanzo and Kremer, 1994). pH diel variability was explained by the CO_2 consumption during the day due to photosynthesis and release at night due to respiration. The Si diel cycle observed at site E is also superimposed by photosynthesis/respiration cycle were the decrease in nutrients concentrations was attributed to uptake and assimilation during the hours of net primary production in addition to increase in water column DO. In the evening, with the cessation of photosynthesis, the decrease in DO concentrations is followed by an increase in Si (e.g., respiration period).

Rivers runs almost dry (in particular the one discharging in the Barrosa branch; Cal River) and the overall trend of NH_4^+, PO_4^{3-}, Fe/Al, Pb/Al and Mn/Al data at site E showed an increase in concentrations for low DO levels. Increase of ratios to Al of particulate Mn, Fe and Pb during the nighttime of metals diel cycle confirmed an additional enrichment of these elements to the suspended particulate matter, since Al varied within a narrow interval (mean values 4.9–5.0%). A plausible explanation for the nocturnal increased could be the release of metals and nutrients from sediments (e.g., internal loads). The increase of nutrients and metals at low oxygen levels was also previously observed in other coastal ecosystems (e.g. Escaravage, 1990; Carignan and Lean, 1991; Lillebø *et al*., 2002; Lillebø *et al*., 2004; Lillebø *et al*., 2010; *Sañudo*-Wilhelmy, 2001; Smith, 2009;).

Chemical characteristics of sediments (pH=8.7 and Eh=-391 mV) in addition to DO fluctuations (e.g., phytoplankton day-night cycle) are the primary chemical controls of NH_4^+, PO_4^{3-}, Fe/Al, Pb/Al and Mn/Al diel cycles within water column at site E. Christophoridis and Fytianos (2006) found that nutrients release (in particularly P) was most favorable under extremely reductive conditions (-200 mV) and at high pH values (~9). Phytoplankton bloom and stagnant waters (e.g., residence time up to 10 days; Malhadas *et al*., 2010) at site E contributed to sediment anoxia through respiration at night in addition to increased sediment heterotrophic activity augmented by microbial decomposition of cyanobacteria dying and raining to the bottom (Valiela *et al*., 1997; Smith, 2009). According to (Spears *et al*. 2008), temperature and light may be included as a physical control in the release of nutrients and metals from the sediment, however the nutrients release (particularly P) is mostly due to regulation of biological activity.

The transition between late night – early morning time period from oxic conditions to anoxic conditions at site E explains the peaks of NH_4^+, PO_4^{3-}, Fe/Al, Pb/Al and Mn/Al recorded in the daylight period. The strongest correlations found between NH_4^+, PO_4^{3-}, Fe/Al, Pb/Al and Mn/Al and DO (-0.70, -0.78, -0.90, -0.80 and -0.73, respectively) corroborates the release of nutrients and metals from sediment. The maintenance of high oxygenation in the water column at site R during the night (minimum of DO saturation 90%) is associated to low primary production; and the positive Eh (Table 6.1) of surface sediments suggest that P sorption does not occurred in the sandy sediments of these site. Additionally, the low content of organic matter in sediments (six times less than site E, Table 6.1) and e pH equilibrium are relevant to avoid internal loads of nutrients. Thus diel cycles in this site are mainly explained by the balance between freshwater discharges (however with small fluxes in summer) and sea-water exchanges. The peaks observed in NO_3^-+NO_2^-, NH_4^+ and Si (Figure 6.5, panel one) concentrations during LW are not correlated with biogeochemical in water column or/and reductive processes in sediment, but presumably associated to the tidal cycle. The strong correlations found with salinity (0.86, 0.71, 0.69, respectively) further confirms that exchanges between lagoon and sea-water is the most probable control of the diel variability.

The PCAs analysis (Figure 6.9) confirmed the separation between both sites (eutrophic and reference) mainly due to by PO_4^{3-} concentrations and Mn/Al ratios (both higher in site E). The projection of Mn/Al and PO_4^{3-} in the opposite quadrant to site R samples indicated that different processes controlled the observed diel variability of D (high in site E). The projection of site R samples in a single quadrant (left upper) of the ordination diagram reflects the low variability of the analyzed parameters over the 24-h cycle (in summer). This was mainly determined by DO high variability (in site E), as well as PO_4^{3-} concentrations and Mn/Al ratios (both lower in site R). The existence of less variable conditions supports the previous findings of more structured and rich benthic communities within this area (Carvalho *et al*., 2005). On the other hand, the high dispersion of the samples from site E agrees with the high diel variability of the measured parameters during the surveyed cycle in summer and reinforces the importance of the supply of nutrients from sediment in this area of the lagoon.

6.4.2. Seasonal differences

The seasonal differences (summer and winter) in diel cycles at site E (eutrophic) were consistent with the findings of other studies in the Óbidos Lagoon (Patricia *et al*., 2009a, 2009b), and elsewhere in estuaries and other temperate shallow habitats (e.g., Beck and Brunland 2000; Ribeiro *et al*., 2006; Cobelo-García *et al*., 2012) which showed the same trends subject to extreme diel variations in summer. Diel fluctuations are normally higher in summer when biological productivity is highest (Nimick *et al*., 2011) and the surface sediments concentration is lower. Increasingly reduced conditions at the sediment-water interface throughout summer diel cycles have been observed in other ecosystems as result of increased heterotrophic oxygen consumption in the water column during the summer months (e.g., Carignan and Lean, 1991; Scholefield *et al*., 2005; Smith, 2009; Cobelo-García *et al*., 2012; Sañudo-Wilhelmy *et al*., 2011).

The drastic fluctuations in summer DO, pH and Chl *a* diel cycles were not observed in winter mainly due to the prevalent conditions of eutrophic state during the dry season. In fact, during the winter diel cycle average Chl *a* was 2.9 μg L^{-1} contrasting with the average obtained in summer cycle (20 μg L^{-1}); it moves from eutrophic to oligotrophic conditions between summer and winter diel cycle. The fact is that phytoplankton bloom does not occurred in winter diel cycle suggesting that a portion of the PO_4^{3-} needed to fuel a bloom was not consumed. Contrary, the bloom observed in summer diel cycle suggested that a large amount of PO_4^{3-} would have to be incorporated into biomass during daytime. It is plausible that if dissolved PO_4^{3-} in the water column becomes exhausted, PO_4^{3-} in the sediments will become an important source for aquatic organisms. During winter diel cycle the main fluvial source of nutrients appears to shift from the Cal River to the Arnóia River, since the plume of these reached the Barrosa branch in high flows (Malhadas *et al*, 2010). Compared to the Cal River, the Arnóia River supplies the branch with a much greater volume of water (an order of magnitude greater) during high discharge conditions.

As a result, the Arnóia River is the most influential fluvial source of nutrients to the branch (site E).

Further evidence of this can be seen by observing DIN:P and DIN:Si ratios during high/low flow conditions (Figure 6.8). Typical values of atomic DIN:P ratios for aquatic plants roughly range from about 10 to 45 (Duarte, 1992) whereas the generalized Redfield ratio is 16. The increased DIN:P ratio during high flows (winter, Figure 6.8a) is the result of increased runoff and higher terrestrial inputs. Thus, the prevalence of the excessive anthropogenic N loading led to P limited conditions (Dortch and Whitledge, 1992; Justic *et al*., 1993). Contrary, the low DIN:P in summer (low flows, Figure 6.8a) indicated an excess of P prevailing the N limited conditions.

This suggests that external sources (i.e. sewage or fluvial inputs) could be the mechanism controlling the winter diel cycles and internal loads the summer variability. The low Si:P both for winter and summer diel cycles favor the appearance of toxic species and consequently a bloom. Pagou *et al*. (2001) reported Dinophysis acuminata blooms in Thermaikos Gulf (Greece) when N/P and Si/N ratios were very low (in summer). These results are in agreement with previous studies (e.g. Rozan *et al*., 2002) stating that the release of phosphate and ammonium from sediments under hypoxic/anoxic conditions may lead to algae bloom due to the increase in the availability of N or P relative to silicate or changes in the N:P ratios (Anderson *et al*., 2002; Ma *et al*., 2006).

Although river runoff functioned as important source of nutrients to site E it also increased the water turbidity as well total suspended solids. Turbidity and water temperature as well light penetration (e.g., limited by suspended solids in water) control the phytoplankton biomass winter diel cycle. The summer bloom is not replicated in winter diel cycle explaining the absence of nutrient (NH_4^+ PO_4^{3-}) peaks along the 24-hours cycle. For that reason the intense fluctuation observed in Fe/Al, Pb/Al and Mn/Al summer diel cycle was not repeated in winter diel cycle. The correlation between DO during low flows (summer diel cycle) contrasting with the obtained between salinity (NO_3^-+NO_2^-=0.79, NH_4^+ = 0.69, PO_4^{3-} = 0.80, Si=0.68, Mn/Al = 0.68, Fe/Al = 0.64 and Pb/Al = 0.67) in high flows (winter die cycle) reinforce that two different sources play an important role regarding its concentrations in diel cycles. These results are in line with several works (e.g., Sundby *et al*., 1992; Slomp *et al*., 1998; Aller and Benninger, 1981; Sañudo-Wilhelmy *et al*., 2011) that found a relationship between phosphorus availability at the bottom layers and the Fe^2/Fe^3 cycle in summer conditions. They reported also low influence of the effluxes from the sediments when the temperature decreased and the runoff is intense.

The equilibrium between summer hypoxic and phosphate dominance is broken when meteorological and hydrological conditions changed (e.g., winter oxic and nutrients rich waters conditions). Furthermore, PCAs indicated that sources of nutrients and processes affecting the diel cycles in the Óbidos Lagoon were very different between the two seasons (winter and summer). Principal component explained 45% of the summer diel cycle variance (Figure 6.9) and 73% of the winter (Figure 6.10). Summer and winter diel cycle data, are clearly separated, especially by the variables that contribute most to the first component (salinity, DO) and (to a lesser extent) Mn/Al ratios (both lower in winter and higher in summer), as well as PO_4^{3-} and NH_4^+ (both higher in winter and lower in summer). The relatively high contribution for first component reflects the importance of external sources in winter diel cycles and internal sources in summer diel cycles.

Environmental processes as internal loads and rivers runoff (external loads) represent exogenous inputs of nutrients and metals and strongly determine the diel behavior of the 24-hours cycle observed in site E in summer and winter.

6.5. Conclusions

This study provides a database of physicochemical properties, Chl *a*, nutrients and metals in two seasons (summer and winter) over 24-hours cycles at reference and eutrophic sites in the Óbidos Lagoon. The data obtained from this study confirmed the variability of such compounds over small temporal timescales.

Current results demonstrated that diel cycles are seasonally influenced by the meteorological (solar radiation) and hydrological conditions (low and high flows) and site location (eutrophic and non-eutrophic). The study exposed the multifaceted relationships between redox conditions promoted by seasonally, and biological factors associated with phosphorus cycling in sediments. The internal loads of nutrients and metals from sediments are the controlling processes of the diel cycle at eutrophic site in summer. A different situation occurs in winter when the diel cycle variability is superimposed by external loads as well the transition of eutrophic to oligotrophic conditions due to meteorological and hydrological characteristics. At site R (reference), daily variability of nutrients and trace-metal is balanced between sea-water exchanges and freshwater discharges.

The results obtained in this study highlight the importance of assessing chemical conditions over diel cycle in eutrophic areas of coastal lagoons, thus advancing the knowledge on these processes on a short temporal scale. In this context, nutrients could induce toxicity in aquatic organisms (Lima *et al*., 2006) and the broad fluctuation of physicochemical properties (particularly DO) between day and night represents a challenging condition for the organisms to adapt (Fradette *et al*., 2007). Given the implementation of the Water Framework Directive (WFD) in a large number of impacted coastal lagoons in Europe, it may be important to include in the monitoring programs the day-night fluctuations in water column (particularly in summer).

6.6. Acknowledgments

M. S. Malhadas would like to acknowledge Águas do Oeste, SA (AdO) for the financial support of the project. N. Vaz is supported by the Ciência 2008 program. C. A. F. Marques was supported by the Portuguese Foundation for Science and Technology (FCT) under grant SFRH/BPD/76232/2011.

6.7. References

Aller, R.C., and Benniger, L.K. 1981. Spatial and temporal patterns of dissolved ammonium, maganese, and silica fluxes from the bottom sediments of Long Island Sound, USA. *Journal of Marine Research* **39**:295-314.

Andersen, F. O. and Jensen, H. S., 1992. Regeneration of inorganic phosphorus and nitrogen from decomposition of seston in a fresh-water sediment. *Hydrobiologia*, **228**(1), 71-81.

Anderson, D.M., Glibert, P.M., Burkholder, J.M., 2002. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. *Estuaries*, **25**, 704-726.

Beck, N. G., and Bruland, K.W., 2000. Diel biogeochemical cycling in a hyperventilating shallow estuarine environment. *Estuaries*, **23**(2), 177-187.

Bertin, X., Dodet G., Fortunato, A.B., and Bruneau N., 2013. A review of the processes controlling the dynamics of wave-dominated inlets. Coastal Dynamics 2013.

Boyer, J.N., Fourqurean, J.W., Jones, R.D., 1997. Spatial characterization of water quality in Florida Bay and Whitewater Bay by principal component and cluster analyses: zones of similar influence (ZSI). *Estuaries*, **20**, 743–758.

Bostrom, B., Andersen, J.M., Fleischer, S., and Jansson, M., 1988. Exchange of phosphorus Across the sediment – Water Interface. *Hydrobiologia*, **170**, 229-244.

Cai, W.-J., Pomeroy, L.R., Moran, M.A., Wang, Y., 1999. Oxygen and carbon dioxide mass balance for the estuarine–intertidal marsh complex of five rivers in the southeastern U.S. *Limnology and Oceanography*, **44**, 639–649.

Cainfield, D.E., Kristensen, E., and Thamdrup, B., 2005. Aquatic Geomicrobiology. Amsterdam: Elsevier.

Carignan, R., and Lean, D.R.S., 1991. Regeneration of dissolved substances in a seasonally anoxic lake - the relative importance of processes occurring in the water column and in the sediments. *Limnology and Oceanography*, **36**(4), 683-707.

Carvalho, S., Moura, A., Gaspar, M.B., Pereira, P., Cancela da Fonseca, L., Falcão, M., Drago, T., Leitão, F., Regala, J., 2005. Spatial and inter-annual variability of the macrobenthic communities within a coastal lagoon (Óbidos lagoon) and its relationship with environmental parameters. *Acta Oecol*., **27**, 143–159.

Carvalho, S., Gaspar, M.B., Moura, A., Vale, C., Antunes, P., Gil, O., Cancela da Fonseca, L., Falcão, M., 2006. The use of the marine biotic index AMBI in the assessment of the ecological status of the Óbidos lagoon (Portugal). *Mar. Pollut. Bull*., **52**,1414–1424.

Cobelo-García A., Bernárdez P., Leira M,. López-Sánchez D.E., Santos-Echeandía J.,Prego R., Pérez-Arlucea M., 2012. Temporal and diel cycling of nutrients in a barrier lagoon complex: Implications for phytoplankton abundance and composition. *Estuarine, Coastal and Shelf Science*, **110**, 69-76.

Christophoridis, C., and Fytianos, K., 2006. Conditions affecting the release of phosphorus from surface lake sediments. *Journal of Environmental Quality*, **35**(4), 1181-1192.

D’Avanzo, C., Kremer, J.N., 1994. Diel oxygen dynamics and anoxic events in an eutrophic estuary of Waquoit Bay, Massachusetts. *Estuaries*, **17**, 131–139.

Dortch Q., Whitledge TE (1992) Does nitrogen or silicon limit phytoplankton production in the Mississippi River plume and nearby regions? *Cont. Shelf Res*., **12**: 1293−1309.

Duarte, C.M., 1992. Nutrient concentration of aquatic plants: patterns across species. Limnology and Oceanography 37, 882e889.

Druschel, G. K. H., A., Lomonaco R. and Oldrid, K. (2005). *Determination of sediment phosphorus concentrations in St. Albans Bay, Lake Champlain: Assessment of internal loading and seasonal variations of phosphorus sediment-water column cycling.*

Escaravage, V., 1990. Daily cycles of dissolved oxygen and nutrient content in a shallow fishpond: the impact of water renewal. *Hydrobiologia*, **207**, 131–136.

Fradette, C., Batonga, J., Teng, S., Piquette-Miller, M., du Souich, P., 2007. Animal models of acute moderate hypoxia are associated with a down regulation of CYP1A1, 1A2, 2B4, 2C5, and 2C16 and up-regulation of CYP3A6 and Pglycoprotein in liver. *Drug Metab. Dispos*., **35** (5), 765–771.

Génio L., Sousa A., Vaz N., Dias J.M., Barroso C.M., 2008. Effect of low salinity on the survival of recently hatched veliger of Nassarius reticulatus (L.) in estuarine habitats: a case study of Ria de Aveiro. *Journal of Sea Research.*, **59**, 3, 133-143.

IST/IPIMAR., 2008. Variação sazonal e inter-annual da qualidade da água na Lagoa de Óbidos, seus afluentes e emissário submarino da Foz do Arelho. Relatório Final: Outubro 2004- Janeiro 2008 (in Portuguese).

IST/IPIMAR., 2010. Variação sazonal e inter-annual da qualidade da água na Lagoa de Óbidos, seus afluentes e emissário submarino da Foz do Arelho. Relatório Final: Outubro 2004- Janeiro 2010 (in Portuguese).

Justic D, Rabalais NN, Turner RE, Wiseman WJ Jr (1993) Seasonal coupling between river borne nutrients, net productivity and hypoxia. *Mar. Pollut. Bull*., **26**: 184−189.

Koski-Vahala, J., and Hartikainen, H., 2001. Assessment of the risk of phosphorus loading due to resuspended sediment. *Journal of Environmental Quality*, **3***0*(3), 960-966.

Lijklema, L., 1980. Interaction of orthophosphate with iron(III) and aluminum hydroxides. *Environmental Science and Technology*, **14**(5), 537-541.

Lillebø, A. I., Flindt, M. R., Pardal, M. A., Martins, I., Neto, J. M., & Marques, J. C., 2002. Nutrient dynamics in the intertidal pools of the Mondego Estuary. II—seasonal efflux of PO4-P and NH4-N in bare bottom and vegetated pools. In *Aquatic ecology of the Mondego River Basin. Global importance of local experience* (pp. 257–272). Imprensa da Universidade Coimbra.

Lillebø, A.I., Neto, J.M., Flindt, M.R., Marques, J.C., Pardal, M.A., 2004. Phosphorous dynamics in a temperate intertidal estuary. *Estuar. Coast. Shelf Sci.*, **61**, 101–109.

Lillebø, A.I., Válega, M., Otero, M., Pardal, M., Eduarda, P., Duarte, A.C., 2010. Daily and inter-tidal variations of Fe, Mn and Hg in the water column of a contaminated salt marsh: halophytes effect. Estuar. *Coast. Shelf Sci*., **88**, 91–98.

Lima, I., Moreira, S.M., Osten, J.R., Soares, A.M.V.M., Guilhermino, L., 2006. Biochemical responses of the marine mussel Mytilusgallo provincialis to petrochemical environmental contamination along the North-western coast of Portugal. *Chemosphere*, **66** (7), 1230–1242.

Ma, S., Whereat, E.B., Luther, G.W., 2006. Shift of algal community structure in dead end lagoons of the Delaware Inland Bays during seasonal anoxia. *Aquatic Microbial Ecology*, **44**, 279-290.

Malhadas, M.S., Leitão, P.C., Silva, A., Neves, R., 2009. Effect of coastal waves on sea level in Óbidos Lagoon. *Continental Shelf Research*, **29** (9), 1240-1250.

Malhadas, M.S., Neves, R., Leitão, P.C., Silva, A., 2010. Influence of tide and waves on water renewal in Óbidos Lagoon, Portugal. *Ocean Dynamics*, **60**:41–55. DOI 10.1007/s10236-009-0240-3.

Middelburg, J.J., Levin, L.A., 2009. Coastal hypoxia and sediment biogeochemistry. Biogeosciences 6, 1273-1293.

Mortimer, C.H., 1941. The exchange of dissolved substances between mud and water in lakes. *J. Ecol.*, **29**, 280-329.

Newton. A, Icely, J.D., Falcao. M,, Nobre A., Nunes J.P., Ferreira J.G and Vale C., 2003. Evaluation of eutrophication in the Ria Formosa coastal lagoon, Portugal. Continental Shelf Research 23, 1945–1961. DOI: 10.1016/j.csr.2003.06.008 ISSN: 0278-4343.

Nimick, D.A., Gammons, C.H., Parker, S.R., 2011. Diel biogeochemical processes and their effect on the aqueous chemistry of streams: a review. *Chemical Geology*, **283**, 3e17.

Olila, O.G., and Reddy, K.R., 1997. Influence of redox potential on phosphate-uptake by sediments in two sub-tropical eutrophic lakes. *Hydrobiologia*, **345**, 45-57.

Pagou K., Pavlidou A., Assimakopoulou G., 2012. The impact of N/P/Si ratio shifts on phytoplankton structure and biomass in two Greek gulfs influenced by anthropogenic activities. Hellenic Centre for Marine Research,. Institute of Oceanography, Greece.

Perkins, R.G., and Underwood, G.J.C., 2001. The potential for phosphorus release across the sediment-water interface in an eutrophic reservoir dosed with ferric sulphate. *Water Research*, **35**(6), 1399-1406.

Oliveira, A., Fortunato ,André B., Rego João, R. L., 2006. Effect of morphological changes on the hydrodynamics and flushing properties of the Óbidos lagoon (Portugal). *Continental Shelf Research*, **26**, 917-942.

Pereira , P., de Pablo, H., Carvalho, S., Vale, C., Pacheco, M, 2010. Daily availability of nutrients and metal in eutrophic meso-tidal coastal lagoon (Óbidos lagoon, Portugal. Marine Pollution Bulletin, 60, 1868-1872.)

Pereira, P., de Pablo, H., Vale, C., Rosa-Santos, F., Cesário, R., 2009a. Metal and nutrient dynamics in a eutrophic coastal lagoon (Óbidos, Portugal): the importance of observations at different time scales. Environ. Monit. Assess. 158, 405–418.

Pereira, P., de Pablo, H., Vale, C., Nogueira, M., Franco, V., 2009b. Spatial and seasonal variation of water quality in an impacted coastal lagoon (Óbidos lagoon, Portugal). *Environmental Monitoring and Assessment*., **153**(1-4): 281-92.

Perilla, O.L.U., Gómez A.G., Gómez A.G., Díaz, C.A., Cortezón, J.A.R., 2012. Methodology to assess sustainable management of water resources in coastal lagoons with agricultural uses:

An application to the Albufera lagoon of Valencia (Eastern Spain). *Ecological Indicators*, **13**, 129- 143.

Rego, J., 2004. Hidrodinâmica da Lagoa de Óbidos. B.Sc. Thesis for the B.Sc. degree in Geophysical Sciences—Oceanography, Faculdade de Ciências da Universidade de Lisboa, published (in Portuguese).

Ryding, S. O., 1985. Chemical and microbiological processes as regulators of the exchange of substances between sediments and water in shallow eutrophic lakes. *Internationale Revue Der Gesamten Hydrobiologie,* **70**(5), 657-702.

Ribeiro, J., Bentes, L., Coelho, R., Gonçalves, J:M.S., Lino, P.G., Monteiro, P. Erzini, K., 2006. Seasonal, tidal and diurnal changes in fish assemblages in the Ria Formosa lagoon (Portugal). Estuarine, *Coastal and Shelf Science*, **67** (2006) 461-474.

Roden, E. E. a. E., J.W., 1997. Phosphate mobilization in iron-rich anaerobic sediments: microbial Fe(III) oxide reduction versus iron-sulfide formation. *Arch. Hydrobiol.*, **139**(3), 347-378.

Rozan, T.F., Taillefert, M., Trouwborst, R.E., Glazer, B.T., Ma, S., Herzage, J., Valdes, L.M., Price, K.S., Luther, G.W., 2002. Iron-sulfur-phosphorus cycling in the sediments of a shallow coastal bay: implications for sediment nutrient release and benthic macroalgal blooms. *Limnology and Oceanography*, **47**, 1346-1354.

Sanderson, P.G., Taylor, D.M., 2003. Short-term water quality variability in two tropical estuaries, central Sumatra. *Estuaries*, **26**, 156–165.

Sañudo-Wilhelmy S., 2011; Report. Grant X982277-01. *Trace Metals*, Organic Carbon, and Inorganic Nutrients in Surface *Waters* of the. *Long Island* Sound: Sources, Cycling and Effects on Phytoplankton Growth. pp.65, Marine Sciences Research Center Final.

Slomp, C. P., Malschaert, J. F., & Van Raaphorst, W., 1998. The role of absorption in sediment-water exchange of phosphate in North Sea continental margin sediments. *Limnology and Oceanography*, **43**(5), 832–846.

Smith, L.G., 2009. Missisquoy Bay Sediment Phosphorus Cycling: The role of Organic Phosphorus and Seasonal Redox Fluctuations. Msc. Thesis for the for the Degree of Master of Science Specializing in Geology. University of Vermont, pp. 141 (in English), published.

Sokal, R. and Rohlf., F. J., 1995 Biometry: The principles and practice of statistics in biological research. W. H. Freeman, 3rd edition, 1995.

Søndergaard, M., Jensen, J.P., and Jeppesen, E., 2003. *Role of sediment and internal loading of phosphorus in shallow lakes*.

Spears, B.M., Carvalho, L., Perkins, R., and Paterson, D.M., 2008. Effects of light on sediment nutrient flux and water column nutrient stoichiometry in a shallow lake. *Water Research,* **42**(4-5), 977-986.

Sundby, B., Gobeil, C., Silverberg, N., and Mucci, A., 1992. The phosphorous cycle in coastal marine sediments. *Limnology and Oceanography,* **37**(6), 1129–1145.

Sundby, B., 2006. Transient state diagenesis in continental margin muds. *Mar. Chem*., **102**, 2–12.

Van der Zee, C., Roberts, D.R., Rancourt, D.G., and Slomp, C.P., 2003. Nanogoethite is the dominant reactive oxyhydroxide phase in lake and marine sediments. *Geology*, *31*(11), 993-996.

Valiela, I., McClelland, J., Hauxwell, J., Behr, P.J., Hersh, D., Foreman, K., 1997. Macroalgal blooms in shallow estuaries: controls and ecophysiological and ecosystem consequences. *Limnology and Oceanography,* **42**, 1105–1118.

Vão–Arquitectos Associados, 1991. Estudo de Recuperação e Ordenamento da Lagoa de Óbidos, Concha de São Martinho do Porto e Orla Litoral Intermédia, vols. I, II and V (in Portugese).

Vaz N., Lencart e Silva J.D., Dias J.M. 2012. Salt fluxes in a complex river mouth system of Portugal. PLOS ONE. 7, 10, e47349.

Vaz N., Dias J.M., 2008. Hydrographic Characterization of an Estuarine Tidal Channel. *Journal of Marine Systems*, **70**, 168-181.

Wang, S.R., Jin, X.C., Pang, Y., Zhao, H.C., & Zhou, X.N., 2005. The study of the effect of pH on phosphate sorption by different trophic lake sediments. [Article]. *Journal of Colloid and Interface Science*, **285**(2), 448-457.

Ward, T., Butler, E. and Hill, B. 1998. Environmental Indicators for National State of the Environment Reporting, Estuaries and the Sea, Commonwealth of Australia, pp. 81.

Wasmund, N., Andrushaitis, A., Lysiak-Pastuzak, E., Muller- Karulis, B., Nausch, G., Neumann, T., et al., 2001. Trophic status of the south-eastern Baltic sea: A comparison of coastal and open areas. *Estuarine, Coastal and Shelf Science*, **53**, 849–864.

Zar, J. H., 1996. Biostatistical analysis. USA: Prentice Hall.

7. General discussion

The overall aim of this thesis is to create a better understanding of the physical processes underlying the hydrodynamic and water quality behaviour in Óbidos Lagoon. Our specific interest is into the processes of tidal flow and wave action in lagoons hydrodynamic, and to investigate lagoon trophic state after adoption protective measures (e.g., diverting the urban loads to a submarine outfall). To achieve research objective, essential data was collected and numerical models applied.

The following summarizes the conclusion sections of the separate chapters that form the main contain of the thesis in the light of research questions formulated in Chapter I.

7.1. Assessing the driving forces in lagoon hydrodynamic and water renewal

The simulation study presented in Chapter II and III was motivated by the importance of being able to detect underlying changes in lagoon sea level and water renewal. It was designed in order to provide an insight of the factors associated to sea level fluctuations and water renewal. The results of the simulations indicated that wave forcing must be considered in the lagoon, particularly, during storm periods. From many of the physical forcing's investigated within this thesis, it was found that tide, which is the forcing most commonly used for reproduced the sea level variability, was often inadequate in terms of rise in lagoon sea level during wave storms.

For the simplest scenario, where the forcing used over time is the tide, it was found that explains 80% of the variability found in sea level. If the underlying trend in the data was strong influenced by the storm waves, sea level sampling reached up to 1 m in amplitude together when wave height reaching 6 m. In these episodes of storm waves the wave set-up could explain 20% of the sea level fluctuations. The results of varying wave's simulation indicated that sea level amplitude is influenced by the seasonal signal of wave's characteristics. The periods of low wave activity does not have a sufficient level of wave power to detect changes in sea level and 1% is affected.

The episodic storm wave's events have a strong impact in the lagoons hydrodynamic due to the morphology of the inlet. Simple lagoon model showed that sea level rise in the lagoon is controlled by wave set up at the inlet. The setup induces a barotropic pressure gradient that generates the strong residual circulation directed towards the lagoon on both channels (northern and southern) promoting flood-dominance. The tidal asymmetry results in stronger currents (~1.0 ms-1) during the flood and ebb phases (~7h) longer than flood phases (~5h).

The subsequent ebb-dominance modifies the residual circulation patterns limiting the water circulation in the upper lagoon. Therefore, analysis of water renewal times explored in Chapter 3 shows a spatial gradient diminishing from the upper to the lower lagoon. The inlet is strongly influenced by tidal exchanges, and the water flows more freely into, than out of, in the lower lagoon. By contrast, the water renewal time in the upper lagoon is much larger, on the order of a month, due to limited mixing. In the lower lagoon were the tidal flushing and strong currents occurs, the renewal time is on the order of two days. These contrasts can be more pronounced in the periods of energetic waves and river floods. The effect of coastal waves can increase the mean residence time in 10% at the lower lagoon and 50% at the upper lagoon. On the contrary an increasing in the freshwater flows can decrease the water renewal time by about 40% in the upper part.To summarize, sea level variations in the Óbidos Lagoon and consequently water renewal times are related to tidal forcing, as well as wave-induced forces during high wave activity periods. The water renewal is also influenced by a third mechanism, which is the flow flux from water river discharges during flood events.

7.2. Evaluation of civil engineer interventions in hydrodynamics and water renewal

A new set of simulations were presented in Chapter IV designed to analyse scenarios of civil engineer interventions. These are conducted to evaluate the changes in tidal asymmetry for characterizing the impact on hydrodynamics and water renewal. Two project solutions were evaluated: Solution 1 includes a guideline wall to limit the inlet migration, dredging of the main channels and 7 transverse channels in the lower lagoon, and a main channel in the central body with connection to Bom Sucesso and Barrosa branches; Solution 2 adds to the solution 1 the dredging of the Barrosa branch and Arnóia river delta.

Obtained results showed that proposed solutions minimizes flood dominance and maximize ebb dominance, increasing the tidal prism by about 20% to 35% in relation to the reference. For project solution 1, a reduction in water renewal of about 50% compared with reference is observed in the lower lagoon. In the upper lagoon reductions are less effective varying from 8% to 30%, in the arms and delta. It means that the arms maintain the same magnitude than reference, scale of months. In the project solution 2 the model predictions suggest an increase in water renewal by about ~40% in Barrosa branch. This kind of response is due to the fact that the export of the water through the channel or lagoon branch depends on the relation between capacity of the cross-sectional channel area and the volume of the bay created after dredging.

Civil engineer interventions affect the lagoon hydrodynamic as well water renewal times. In terms of hydrodynamic the tidal asymmetry is diminished and the flood-dominance reduced. The improvements in water renewal are visible more significant in the more dynamic part, lower lagoon. In the upper lagoon, less hydrodynamic area, the achieving are not significant maintaining a water renewal time in a scale of months.

7.3. Factors controlling the lagoon water quality

The investigation of factors controlling lagoon water quality and thus trophic state was conducted through the analysis effectuated in Chapter V and VI. Due to the low water exchanges in the upper lagoon the water renewal is typically one month. Phytoplankton are not exported out of the system due to negligible outflows, so abundance can increase more easily, compared to the sites were the water renewal time is about two days. The growth of phytoplankton in the upper lagoon is fueled by a combination of long water renewals times and plentiful nutrients. Following from this, the nutrients generated in the watershed entering via river discharges in the lagoon, were assumed as dominant in phytoplankton growth. This standard induced the local water authorities to point out the urban loads (Waste Water Treatment Plants -WWTP) as the important source of several water quality problems in the lagoon and, among other unwelcome effects, the eutrophic state in the upper part. In fact, the water quality data measured within the lagoon, showed that biogeochemical processes are explained by the balance between nutrient input from river discharges and ocean exchange. However, the results of water quality model validation in Barrosa branch, reveals a handicap in reproducing the summer peaks of phosphate and phytoplankton blooms when the river discharges runs dry. Contrary, the phytoplankton variability is well reproduced with correlations above 0.84 in the lower lagoon.

Effectiveness, results shows primary production is primarily controlled by external load of nutrients and water renewal time, but in summer at Barrosa branch exists a third process that explains seasonal and interannual variability of water quality. The data obtained over 24-hours cycles in summer at the Barrosa branch reveal internal loading of nutrients and metals from the sediment serving as an important factor in sustaining phytoplankton growth. The absence of chemical cycles (metals and other components) in the water quality model formulation explained the handicap of the model in reproducing the summer peaks in Barrosa branch.

Conclusions so far show that underlying the processes that explains the seasonal and interannual variability of nutrients and phytoplankton growth in Óbidos Lagoon but does not explain why protective measurements have failed to control eutrophication. To investigate the influence of point sources such as WWTP in lagoon trophic state, the water quality model was used to simulate the load reductions associated to the diverging of WWTP. The limitation of the model to achieve a better fit in the upper lagoon (particularly in BB) does not compromise its use to simulate the impact of the management strategy.

Analyses of model results through the annual exportation of phytoplankton shows a reduction of about 12% (scaled to reference) in phytoplankton biomass after loads diverging.

Further, the appliance of OSPAR guidelines to the major basin (Arnóia/Real Rivers) pointed out the pig farms as the most important source of nutrients to the lagoon. The nitrogen loads from pig farms accounts for 73% of the total nitrogen and 67% of the total phosphorus while urban loads represents 9% of the nitrogen and 11% of the phosphorus load. Simulating the removing of the pig farms in Arnóia/Real Rivers basin predicts a 48% of reduction in annual exportation of phytoplankton. This reduction influence the mean spatial trend of nutrients and phytoplankton diminishing the concentrations at the upper lagoon.

The trophic state multivariate index (TRIX) calculated for the reference situation collocate the lagoon in "Elevated" level of eutrophication and the state of water quality remained with a "Poor" status. The scenario of removing the pig farms is quite visible in the TRIX values reducing the level of eutrophication to "Medium/High" and the state of water quality to "Good/bad".

Results show that control of point sources will not necessarily solve the eutrophication problem. Furthermore, the nutrients from internal sources shows that any nutrients released from the sediment can be used and recycled multiple times perpetuating the eutrophication problem in the Barrosa arm. Results also show that a moderate anthropogenic influence (e.g., removing the pig farms) in terms of the loads stress in the upper lagoon reflects in the level of eutrophication and lagoon trophic state.

The message regarding the Óbidos Lagoon case study is simple "**it is important to use integrated tools to support the water management decisions to provide a better insight of the system**". Furthermore, a clear message to other case studies is that, given the implementation of the Water Framework Directive (WFD) in a large number of impacted coastal lagoons in Europe, it may be important to include in the monitoring programs the day-night fluctuations in water column (particularly in summer) because typical seasonal monitoring does not catch the sharp variabilities.