Challenges for integrated catchment-to-coast modelling in the context of science-policy interface: the Ria de Aveiro coastal lagoon

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ABSTRACT

Ria de Aveiro is one of the European "hotspot" coastal lagoons being studied within the EU-FP7 LAGOONS project. Regarding the water quality status of Ria, the main policy context of relevance is the EU-Water Framework Directive and the activities related to its implementation. In this context, the environmental issue of concern within LAGOONS is the anthropogenic deterioration of Ria's surface waters from the catchment, with particular emphasis on the lagoon water-body. The considered anthropogenic deterioration may be affected by changing climate, land use and water use in future. Therefore, the interaction between climate change, land use change and Ria ecosystems will be examined. The aim of the modelling effort within LAGOONS is to project the Ria's response to climate change and land use change scenarios. For the modelling of the catchment the semi-distributed ecohydrological model SWIM, integrating hydrological processes, vegetation growth, nutrient cycling, and sediment transport at the river basin scale, is used. For the modelling of the lagoon and adjacent shelf Delft3D, an integrated suite for coasts and estuarine areas, simulating flow, sediment transport, water quality and ecological processes, is used. For the climate impact assessment the sets of existing regional climate scenarios from the ENSAMBLES project are used. The use of modelling tools to assess the spatial impacts in the context of the EU-policies pose some additional challenges, namely due to the gaps in data sets and the lack of effective information-sharing systems. The challenges posed by modelling results in the science-policy context will be discussed as well.

KEY WORDS: *Catchment modelling, Lagoon modelling, Water Framework Directive, Future scenarios, Science-policy.*

INTRODUCTION

LAGOONS project

LAGOONS – "Integrated water resources and coastal zone management in European lagoons in the context of climate change" is an EU funded FP7 research project in the theme ENV.2011.2.1.1-1 "Lagoons in the context of climate change". Nine partners from eight countries form an interdisciplinary consortium (Figure 1).

The main and overall objective of the LAGOONS project is to develop science-based strategies and decision support frameworks for the integrated management of lagoons, based on a better understanding of land-sea linkages and the science-policy-stakeholder interface in the context of climate change. Ria de Aveiro (Portugal) is one of the four European "hotspot" coastal lagoons being studied within the EU-FP7 LAGOONS project and the one being presented in this paper.

LAGOONS - Climate change and modelling

Regarding the integrated water resources and coastal zone management in the lagoons in the context of climate change, different sets of regional climate scenarios produced by Regional Climate Models (RCMs) until 2100 for Europe will be applied in the project.

In LAGOONS, the SWIM model (Krysanova *et al*., 1998) is being used for ecohydrological modelling of the catchment areas of the case study lagoons. SWIM is a continuous-time spatially semi-distributed model, integrating hydrological processes, vegetation growth (agricultural crops and natural vegetation), nutrient cycling (nitrogen, phosphorus and carbon), and sediment transport at the river basin scale. The model is coupled to GRASS and MapWindow open source geographic information system project, and has modest data requirements. Its spatial disaggregation scheme has three levels: 1) basin, 2) subbasins and 3) hydrotopes within subbasins.

In LAGOONS the modelling of the lagoons' hydrodynamic and ecological parameters is being performed by different models adapted to specific conditions of each of the lagoons. More details on hydrodynamic and water quality models are available in LAGOONS project webpage (http://lagoons.web.ua.pt - LAGOONS D6.1. 71 pp.).

In Ria de Aveiro case study area the Delft3D-Flow package (WL|DelftHydraulics, 1996; Lesser *et al*., 2004) was chosen for the modelling of the hydrodynamics, given that its ability to support curvilinear grids allows the timely calculation of the several model configurations needed for the calibration, validation and scenario simulation with the necessary resolution in the relevant areas of the lagoon. This model allows for the simulation of hydrodynamic and biogeochemical quantities at the tidal, fortnightly, seasonal and event scales.

In the context of climate change and modelling the sub-objectives of the project are: i) conduct quantitative drainage basin modelling and to create scenarios for future developments in land-water interactions in coastal lagoons; ii) use the outputs of the drainage basin modelling as input for quantitative lagoons modelling and scenario analysis; iii) present and evaluate these modelling scenarios through a series of three stakeholder workshops in each case area. These workshops will enable participation and will provide local knowledge and input into the refinement of the scenarios; iv) develop strategies and decision support frameworks for pan-European dissemination and application. These will be based on the results of the scenarios as well as on the analysis of legal and policy frameworks, and of the actors and institutions active in the coastal lagoon management. However, the use of modelling tools to assess the spatial impacts in the context of EU policies pose some additional challenges, namely due to the gaps in data sets and the lack of effective information-sharing systems. The challenges posed by modelling results in the science-policy context will be discussed as well.

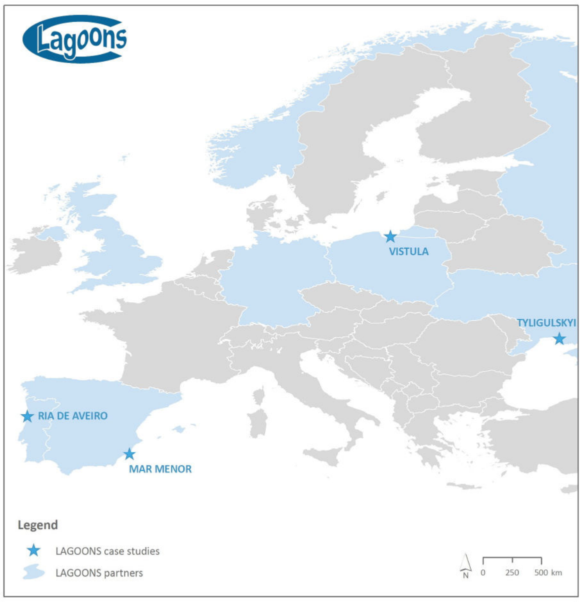

Figure 1. The geographic distribution of the LAGOONS partners and the LAGOONS case studies.

CASE STUDY AREA

Ria de Aveiro coastal lagoon and catchment area

The Ria de Aveiro is a shallow coastal lagoon located on the north-west coast of Portugal (40°38'N, 08°45'W) and integrated in the Vouga River catchment area (Figure 2). The catchment area has approximately 3362 km^2 whilst the lagoon corresponds to a complex wetland area that varies approximately from 66 km^2 to 83 km^2 according to the tidal cycle (respectively low and high spring tide). The lagoon forms four main channels with several branches, islands, inner basins and mudflats.

The main tributaries of the Vouga river are the rivers Sul, Caima, Antuã and Águeda. The Antuã river forms a sub-basin reaching the Vouga river in the lagoon area (http://www.arhcentro.pt/). Other smaller rivers also discharge into the lagoon, namely the river Boco, the Cáster and the Mira.

More details on physiogeographical conditions of the Ria de Aveiro and Vouga River catchment area are available in LAGOONS project webpage (http://lagoons.web.ua.pt - LAGOONS Report D2.1b).

The Aveiro region is under the influence of a temperate maritime climate with a warm period between July and September and a cold period between December and February. Rainfall occurs mainly between October and May, with higher precipitation periods in December and January (AMBIECO, 2011).

The Vouga river catchment area covers 31 counties, with a total population of 961316 inhabitants (2011 census), and is mostly occupied by forest and farmlands. According to 2011 census, Ria has a population of 353688 inhabitants in the watershed area, with main activities in the industrial and service sector. However, for the local population farming and fishing activities are still socio-culturally and economically important.

Ria is part of the Natura 2000 network, has the designation of Special Protection Area, and includes several areas classified as Sites of Community Importance. The lagoon's natural capital, including the variety of ecosystems services and biodiversity are essential for the development of the region (Lillebø et al., 2011).

Ria is managed within a complex policy and legislative context, with a wide variety of entities and actors engaging in the use and management of the lagoon (Alves et al., 2013).

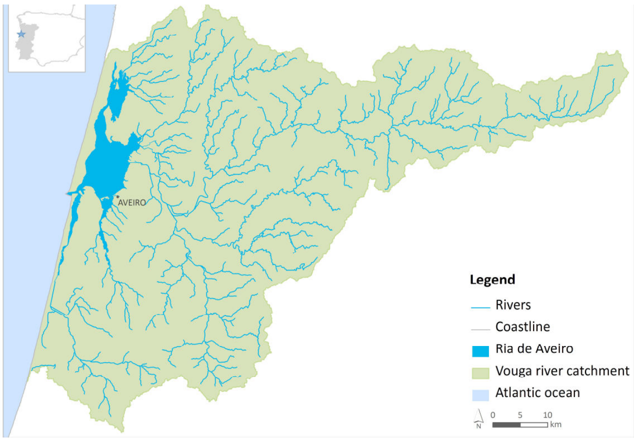

Figure 2.Ria de Aveiro and the Vouga river catchment area.

FIRST RESULTS

Ecohydrological modelling of the Vouga river catchment for impact assessment

The objectives of the Vouga catchment modelling are (a) to evaluate water discharge and nutrient (Nitrogen, N, and Phosphorus, P) inputs from the drainage area under climate change and land use change scenarios, and (b) to estimate related uncertainty from different sources. The outputs from the catchment modelling will be later used as input for the quantitative lagoon modelling.

The following data were used for the modelling of the catchment: the Digital Elevation Model with 50m resolution, the Corine Land Cover map from 2006, the soil map from the Soil Geographical Database for Europe, maps of catchment and subbasin boundaries and river network. For the model calibration the period 2002 – 2005 with the best data availability was chosen. Data from 21 climate stations are available for the region, but only 14 of them are located inside or close to the basin, and many time series have gaps in data. Nine hydrological gauges measuring water level exist in the catchment, and the corresponding flow curve equations allow estimating water discharge within the pre-defined ranges. Water quality data are available as concentrations of N and P measured once a month in 20 gauges. Statistical data on crop types and crop yields is available for the agrarian part of the catchment for 2009.

For the last gauge Ribeirada on the main river (ca. 40 km from the mouth) with 878 km^2 catchment area data from 11 climate stations can be used, and 6 of them are within the catchment, but data for winter months are missing for many stations, and climate data at high elevation are missing as well (no stations). For the next important gauge Requeixo with 464 km^2 catchment area data from 4 climate stations can be used, but only one of them is within the catchment and has precipitation data only for one year, and temperature and radiation data are available only from the remote stations. Besides, it is known that groundwater from aquifer located outside of the catchment is used, but there are no data.

The ecohydrological modelling of the Vouga catchment for climate and land use change impact study can be divided in the following sequential steps:

(1) data preparation for SWIM,
(2) hydrological calibration and validation,
(3) calibration and validation for water quality,
(4) evaluation of the available Regional Climate Models for the historical period,
(5) climate impact assessment by application of a set of climate scenarios,
(6) land use change impact assessment by application of the land use change scenarios.

SWIM is usually calibrated using observed daily discharge for the comparison with the simulated discharge. Therefore, the measured water levels were converted to daily runoff data using the corresponding flow curve equations of each station. Data from 2002 and 2003 were used to calibrate the model, and the period 2004-2005 was used for validation. At the most downstream gauge Ribeirada of the Vouga River the Nash and Sutcliffe Efficiency (NSE) of 0.73 was achieved during the calibration. The validation results reached a NSE of 0.74. SWIM was also calibrated for the Cértima River, an important tributary to the Vouga, for the gauge Ponte Requeixo with a NSE of 0.83 and 0.61 respectively. Besides statistical measures, the simulated and observed hydrographs were analysed visually. Figure 3 shows the average simulated and observed daily flow curves at gauges Ribeirada and Ponte Requeixo.

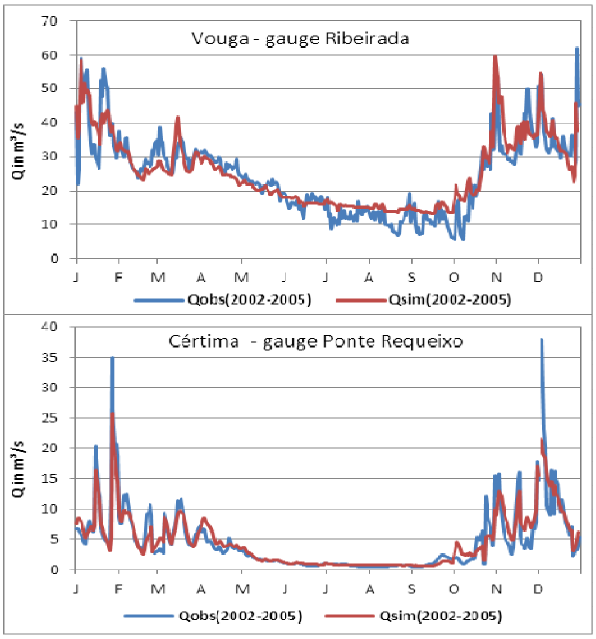

Figure 3. Comparison of simulated and observed mean daily flows at gauges Ribeirada and Ponte Requeixo.

The graphs show satisfactory agreement between the modelled and measured discharges. However, some peak flows, especially during winter are underestimated. This can be caused by mainly two reasons: (i) insufficient climate data, and (ii) inaccuracy of the flow curve equations. Most of the gaps in precipitation data occur during winter, which could lead to an underestimation of rainfall, and consequently discharge for this period.

Moreover, the available records are from climate stations at lower elevations and cannot capture the orographic influences in the basin. This could result in additional underestimation of rainfall and runoff. In the case of the Cértima River there is only one rainfall gauge located within the catchment boundaries, and it has precipitation records only for the last year of the simulation (2005). For this reason climate interpolation is very much dependent on data from stations outside the catchment. As a result, local rainfall events causing peaks in the observed data can not be simulated by the model.

Concerning point (ii) it has to be noted that the uncertainty in estimating observed flow increases with the water levels reaching the validity ranges of the flow curve equations. In case of very high water levels this can lead to an overestimation of the measured discharge.

Main gaps in the data causing problems for the modelling can be summarised as follows: (a) missing climate data at high elevation, (b) gaps in climate data, and very poor data for the gauge Requeixo, and (c) estimation of water discharge from water level using the flow curve equations is inevitably connected with uncertainty.

Climate change and Ria de Aveiro modelling

Due to its complex geometry and tidal characteristics, transport in the Ria de Aveiro lagoon has to be modelled with a spatially-explicit grid. To achieve this, the Delft3D-Flow package was chosen for the modelling of the lagoon hydrodynamics. Its ability to support curvilinear grids allows the timely calculation of the several model configurations needed for the calibration, validation and scenario simulation with the necessary resolution in the relevant areas. Delft3D-Flow is a three-dimensional, finite differences hydrodynamic and transport model which simulates flow and transport resulting from tidal and meteorological forcing. In the present application, the hydrodynamic model solves the Navier-Stokes shallow water equations with hydrostatic, Boussinesc and f-plane approximations (WL|DelftHydraulics, 1996; Lesser *et al.,* 2004). Delft3D-Flow uses a horizontal Arakawa-C grid with control volumes and for most applications an Alternating Direction Implicit (ADI) integration method. To depict accurately the flow both in the tidal channels and in the intertidal flats, a numerical grid was built (Figure 4b): i) to cover all of the area of interest; ii) to represent the main hydrodynamic features of the lagoon; iii) to be numerically robust by complying with the Courant–Friedrichs–Lewy (CFL) criterion; iv) to prevent spurious propagation of open boundary effects inside the area of interest; and v) to do all of the above with the minimum number calculation points in order to allow a timely calculation of all the hydrodynamic and biogeochemical variables. The curvilinear properties of the grid allow a ~30 m resolution in narrow tidal channels and a ~700 m resolution at the offshore open boundary. A 2-dimensional depth-averaged approximation was made given that the Ria de Aveiro is mostly a vertically well-mixed system (Dias et al, 1999). The bathymetry of the Ria de Aveiro used here results from the interpolation to the numerical grid of a set of topo-hydrographic surveys from 1987-88, 2003 and 2011 (Figure 4a). The heat model uses air temperature, the combined net (short wave) solar and net (long wave) atmospheric radiation, relative humidity and wind speed to calculate heat losses due to evaporation, back radiation and convection. Boundary conditions for temperature are prescribed at the oceanic open boundary and a total of 6 freshwater points were defined as outflows representing the Vouga, Antuã, Boco, Caster, Gonde and the system of streams discharging at head of the Mira Channel. The transport of salt is calculated taking into account the input of freshwater from the catchment and the salinity prescribed at the oceanic open boundary. More details on the features and calibration of the hydrodynamic model can be found in (Lencart e Silva *et al.*, *in press*).

The Delft3D-WAQ model was chosen to model the water quality for its compatibility with the hydrodynamic model and extensive library of water quality variables, parameters and processes. The Delft3D-WAQ model solves the advection-diffusion-reaction equations to calculate the space and time variation of biogeochemical and water quality state variables and derived quantities. In this implementation, the water quality model uses hydrodynamic quantities, temperature and salinity calculated by Delft3D-Flow and the same spatial grid as the hydrodynamics. Currently, the modelled state variables are: i) organic carbon, organic and inorganic N, P and Si separately in their particulate and dissolved forms; ii) chlorophyll where diatoms and dinoflagellates are modelled separately; iii) dissolved oxygen; and iii) total suspended solids. The primary production model assumes a constant C:N:P:Si ratio. All of these variables have both the ocean and the catchment as boundary conditions. Whilst the latter is provided and explicitly modelled by the SWIM model, the former is included resorting to remote sensing images and existing climatologies (*e.g.* Garcia *et al.* 2010).

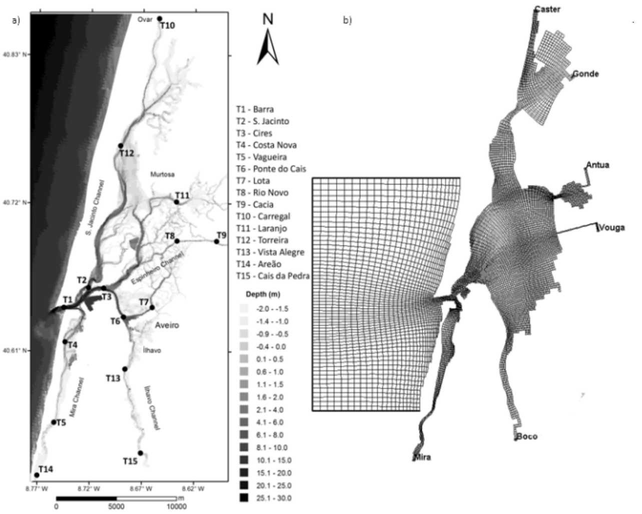

Figure 4.(a) Study area, bathymetry and stations used in the hydrodynamic model calibration (b) Numerical grid, discharge locations and open boundary (thick line).

Presently a number of challenges are posed to the modelling of catchment-to-coast water quality in Ria de Aveiro in the context of climate change. During the calibration procedure uncertainty is generated in the lagoon model due to the use of the results from the SWIM model at the catchment boundary. The catchment model has its own uncertainties and ideally, the calibration in the lagoon should be done with observed data at each discharge point from the catchment into the lagoon. In this case, the main constrains are felt due to the timing of the peak flow and mainly at the upper reaches of the lagoon whilst farther downstream tidal dispersion acts as a low-pass filter in the time domain. In terms of hindcast and nearcast modelling, the main challenges are: i) the old bathymetry (1987 – 1988) in the intricate net of channels and salt pan areas in the lagoon central zone; ii) the high uncertainty of the position of the top limit of the intertidal, leading to uncertainties on the shape of the intertidal slope and on the lagoon's storage volume, thus reducing the ability of the model to reproduce accurately the shallow water tidal harmonics such as the M4 and MSf; and iii) the absence of an up-to-date synoptic survey of the lagoon's sediments, of their nutrient levels and granulometry, hampering the correct prescription of the bottom boundary with special relevance in a lagoon where the residence time is between 7 and 15 days for the upper reaches. Modelling for the 2041-2100 interval poses additional challenges such as: i) the dependency of the sediment nutrient and fines content on the long term evolution of the lagoon's bed; and ii) the unavailability of projected oceanic conditions for the IPCC (Intergovernmental Panel for Climate Change) story lines adopted and for the variables needed, such as nutrients, chlorophyll and dissolved oxygen.

DISCUSSION

The context of science-policy interface

The EU Water Frame Work Directive (Directive 2000/60/CE) establishes a framework for protection of groundwater, inland surface waters, transitional waters and coastal waters, towards the objective to achieve, by 2015, "*good surface water status"*, meaning that "*both its ecological status and its chemical status are at least good"*. Although there are uncertainties regarding the future state of coastal ecosystems, modelling have been recognised as a useful tool for projecting and evaluating likely states of the water quality status. The use of modelling tools to assess the spatial impacts in the context of the EU-policies pose some additional challenges, namely due to the gaps in data sets and the lack of effective information-sharing systems.

Taking Ria de Aveiro as an example it has been pointed out that there are data gaps regarding the catchment area and the lagoon that need to be addressed to improve the integrated catchment-to-coast modelling in the context of climate change. Regarding Ria de Aveiro, researchers, stakeholders and policy-makers have started to intensify efforts to coproduce knowledge that is valuable to all communities, particularly in the context of water management and human activities in the context of climate change. LAGOONS team has established a close cooperation with Ria de Aveiro administration for water management, i.e., the Department for Planning, Information and Communication from the Portuguese Environment Agency – former ARHCentro. This cooperation has resulted in the sharing of data, information and knowledge. We see this active dialogue between stakeholders and LAGOONS as an added value for the implementation of the WFD, since it allows both researchers and stakeholders to define together innovative methods of communication and sharing of information with local communities, namely regarding the goals of the WFD and the new challenges in the context of climate change.

From this study we also highlight that the encountered constrains have to be communicated to stakeholders and policy makers, and possibilities to solve them should be discussed with the authorities. Meaning that in the context of science-policy interface an additional challenge is posed - it is necessary to improved dialogue between the scientific and policy-making communities and between the scientific and stakeholders communities (Gooch & Stålnacke, 2010). Science-policy interface is only a part of the challenge facing integrated lagoon management. The demands made for increased stakeholder and public participation provide other important interactions, the science-stakeholder and the policy-stakeholder interfaces (Gooch & Stålnacke, 2010). Therefore, in the LAGOONS project a series of three stakeholder workshops in each of the case lagoons are planned. At these workshops, scenarios at different stages of their development will be presented and discussed. In this way scientific knowledge and the quantitative modelling results produced by the LAGOONS team will be combined with the local knowledge and perceptions of the stakeholders at all stages of the project.

FINAL REMARKS

LAGOONS project integrated catchment-to-coast modelling in the context of science-policy interface

The novel approach proposed by the LAGOONS project, is devoted to the enhancement of the connectivity between research and policy-making exploiting the recently developed concept of SPSI (science-policy-stakeholder interface) (Gooch & Stålnacke, 2010) and SPI-CIS (science-policy interface – common implementation strategy).

ACKNOWLEDGEMENT

The European Commission, under the 7th Framework Programme, supported this study through the collaborative research project LAGOONS (contract n° 283157).

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