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Integrated coastal zone management in South America: A look at three contrasting systems

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ABSTRACT

The management of coastal systems where overlapping economic interests compete for the same resources make the use of integrated approaches indispensable. The Integrated Coastal Zone Management (ICZM) focuses mainly on three major goals: (1) overcoming the conflicts associated with the sectorial management, (2) preserving the productivity and biological diversity of coastal systems, and (3) promoting and equitable and sustainable allocation of coastal resources. The DPSIR (Drivers-Pressures-State-Impact-Responses) framework is a common tool that allows the description of environmental problems by defining the relationships between anthropogenic activities and the environment. In this context, the use of numerical models as integrative tools in ICZM has grown significantly over the years.

This work focused on three estuarine systems in South America: Santos estuary (Brazil, 24° S) and Bahía Blanca estuary (Argentina, 39° S) in the Atlantic coast and Aysén fjord (Chile, 45°S) in the Pacific coast. These estuaries differ significantly in their physical, chemical and biological conditions, as well as on their socio-economic settings and human-related problems. Numerical models have been used to study the relation between the pressures derived from human activities and their impact on the state of each system.

The results presents a contribute to increase the scientific knowledge needed to support the implementation of local legislations and policies, to assess different scenarios of coastal activities and sources use, to support management decisions and, ultimately, to promote sustainable of coastal resources.

1. Introduction

From a human history perspective, the intrinsic characteristics of estuaries have made them preferential sites for human occupation and, consequently, intense areas of development. A direct consequence of human occupation of these coastal areas is that estuaries rank among the environments most affected by human presence and activities (Lindeboom, 2002). The fast expansion over the last decades of socio-economic activities on coastal and estuarine areas such as tourism, nature conservation, coastal fisheries and industrial and urban development has extended and complex the management tasks. In recent years, there has been a growing concern to maintain a steady growth in economical activities and social development in estuarine areas, while preserving their natural features and ecological services (Levin, 1998; Dietz et al., 2003).

From a historical perspective, the use of ocean and maritime access has been at the heart of the southern hemisphere's economic and political development. Over the last decades, and especially after Río 1992, South American countries have been developing a strong environmental awareness. This is evident in the ratification of international and regional conventions and agreements, and in the implementation into the national legislation of many countries to reflect the need of a sustainable development (UNEP, 2003).

There also are a significant number of regional agreements and a vast body of laws, rules, and regulations to ensure systematic and

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coordinated actions for protecting the environment and promoting sustainable development (Bertucci et al., 1996; Solano, 1997). Most South American governments have developed and implemented comprehensive environmental legal frameworks with relevant laws and procedures for specific resources and activities like marine resources, coastal areas, tourism, etc. However, local empowered stakeholder participation is still in an early stage in relation to integrated management (Bachmann et al., 2007; Delgado et al., 2007).

The South American continent is endowed with a unique and valuable marine heritage, which enclose several of the world's largest and most productive estuaries. The accelerated development in most South American countries is posing demanding challenges in the management of natural resources, especially in coastal areas (Lemay, 1998). Integrated Coastal Zone Management (ICZM) is a broad, multi-purpose effort aimed at improving the quality of life of the communities dependent on estuarine resources, and helping local decision makers to achieve sustainable development of estuarine areas, from the headwaters of coastal watersheds to the outer marine areas. As such, integrated coastal management approaches are required, in order to combine all aspects of the human, physical and biological aspects of the coastal zone within a single management framework, as reported recently by Neves et al. (2008).

It is imperative to address the ecological and socio-economic links in the management of dynamic systems such as estuaries and coastal areas. The DPSIR (Drivers-Pressures-State-Impact-Responses) framework provides a scheme for achieving this objective (Bowen and Riley, 2003). This framework has become increasingly accepted and applied to different case studies to aid problem solving that involve a range of coastal marine environments including estuaries, coastal lagoons and coastal areas (Elliott, 2002; Scheren et al., 2004; Holman et al., 2005). In many cases this framework has been complemented with use of numerical models, which have been increasingly becoming indispensable tools in management decisions (Neves, 2007).

This work show three distinct realities of ICZM in transitional waters systems in South America: the Santos estuary in Brazil (24°S), the Bahía Blanca estuary in Argentina (39°S) and the Aysén fjord in Chile (45°S). Besides their geographical location, these coastal systems cover a wide spectrum of management challenges because they vary significantly in their ecological state and human pressures, ranging from the almost pristine state of the Aysén fjord, to the heavily occupied and degraded Santos estuary.

Together, they represent key coastal zones regarding their integrated management and implicit challenges, since all show conflicting interests of different kinds. Thus, beyond their differences, they share some of the major regional environmental concerns, namely, the transformation of the landscape and seascape with the loss of natural patrimony, increased human waste and industrial disposal including those from aquaculture activities.

The goal of this study was to work towards a social and environmental sustainable estuarine system management, by showing the usefulness and advantages of using numerical modeling as an important tool in the decision making process within ICZM.

2. Study sites

Three coastal zones located in South America (Fig. 1) showing conflicting interests between urban, port, industrial and agricultural pressures and environmental maintenance represent the study sites chosen for this study. The selected areas, from North to South, are the Santos estuary in Brazil, the Bahía Blanca estuary in Argentina and the Aysén fjord in Chile. The three sites differ in their physical and hydrodynamical conditions, ecological features, climate, continental inputs and socio-economical pressures.

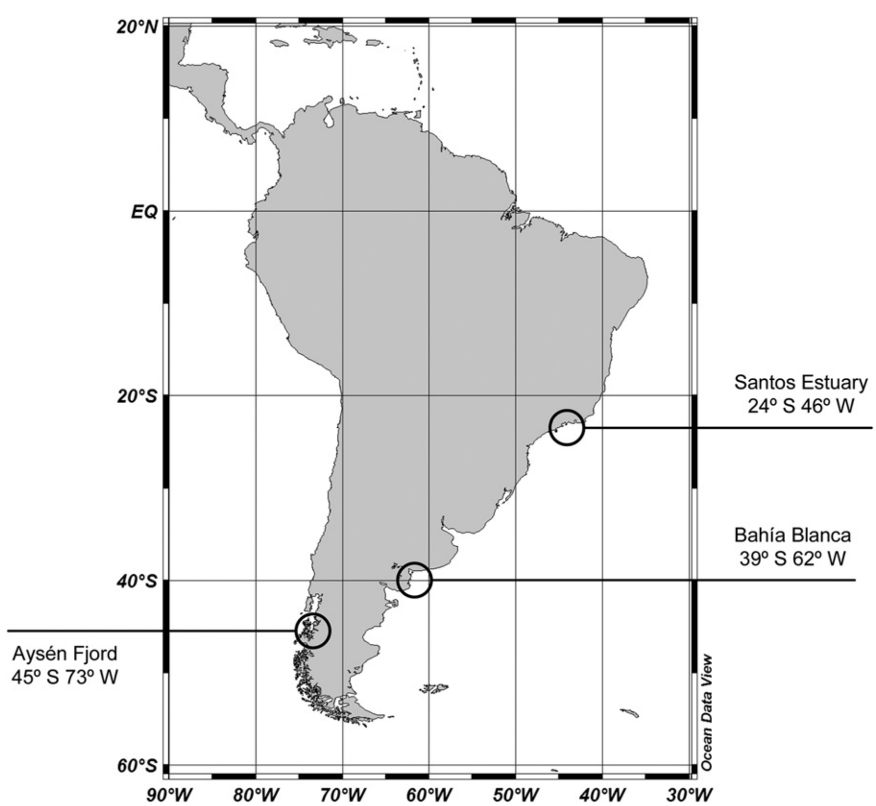

Fig. 1. Location of the study sites.

Table 1
Major biotic and abiotic features of the three estuarine systems.

Feature	Santos Estuary	Bahía Blanca	Aysén Fjord
Zone	Sub-tropical	Semiarid	Subpolar Oceanic
Mixing characteristics	Partly mixed	Vertically well mixed	Permanently stratified
Dilution potential	Moderate	High	Low
Vegetation	Mangrove swamps High emergent vegetation Tidal flats	Spartina fringes Low emergent vegetation Tidal flats	Not marine
Nutrients	Exporter	Exporter	Importer

Table 1 summarizes the biotic and abiotic characteristics of each system and Table 2 addresses the main socio-economic forces.

2.1. The Santos estuary

The Santos estuary (Fig. 2) is located in the coast of the Sãao Paulo state, Brazil. It consist in a set of channels namely Santos channel in the eastern side, with an average depth of 15 m maintained for navigation purposes through dredging, and São Vicente channel in the western side, a shallower channel with an average depth of 8 m, separating the island from the mainland. Freshwater contributions come from mainland as rivers and tributaries.

The Santos estuarine area is heavily occupied by urban, industrial and port activities holding the largest port and the largest industrial complex of the Brazilian coast, the Cubatão industrial pole, which includes a petroleum refinery and petrochemical and metallurgical complexes. The Cubatão's industrial complex contributes with more than 5% to the national Gross Domestic Product. In terms of population, this region accounts for around one million of inhabitants that almost doubles during tourism peaks. The urban waste water of Santos and São Vicente is mainly discharged through a submarine outfall located at the centre of the bay that connects the system with the Atlantic Ocean. However, untreated sewage water enters directly to the coast and arises from slum quarters located at the channels margins, becoming a major problem for public health. Along with the sewage waters, other oxygen demanding and hazardous compounds are dispensed into the estuary including nutrient salts, metals, organic compounds and petroleum hydrocarbons. The heavy anthropogenic interaction led the Santos estuary with a classification of polluted area (Sousa et al., 1998).

From the ecological point of view, the Santos estuary has considerable importance due its natural high productivity and for being the habitat for wide range of fauna including birds, mammals, fish and invertebrates. Nanoplanktonic phytoplagellates and diatoms alternate the dominance due to its adaptation to the changing light and nutrient conditions, caused by the neap-spring tide cycles. Other primary producers in the region are the seaweeds, conspicuous in many areas in the soft substratum of mangrove forest and Spartina spp. which occupy many mangrove fringing areas.

The Santos estuary can be regarded as a typical sub-tropical mangrove system. Although it is partially degraded due to a significant anthropogenic pressure, it still contains a large area of mangrove forest in the coastal area. According to Lamparelli and Moura (1998), the metropolitan area where the Santos estuary is located, known as Baixada Santista, has an area of about 120 km^2 of mangrove forest, accounting for 52% of the total in São Paulo State. More than 70% of the Baixada Santista is classified as protected in an attempt to preserve remnant areas of the threatened Atlantic Forest and conserve the mangroves of the Santos estuary (PSMC, 2006). Around 16% of the original mangrove area in this region has been converted to urban and industrial uses, 40% of the forest is well preserved, mostly in the in the Bertioga region and in some parts of São Vicente and the remaining 44% are degraded mangroves, associated with industrial pollution (CETESB, 1991).

The main stakeholders in Santos area include local and regional government, industrial and harbour consortia and NGOs.

Table 2
Major socio-economical features of the three estuarine systems according to the DPSIR framework. Information retrieved from Mateus et al. (2008) and references therein.

Feature	Santos Estuary	Bahía Blanca	Aysén Fjord
Drivers	Industry & ports Pop. growth Pop. density	Industry & ports Pop. growth Agriculture	Salmon Farming
Population	1,000,000	350,000	90,000
Economic activities	Petrochem. park Refineries Fertilizer plants Thermoelectric plant Port activities Metal industries	Petrochem. park Refineries Fertilizer plants Thermoelectric plant Port activities Several industries	Salmon farming Artisan fishing
Human utilization	Food source Housing Bathing waters Tourism	Food source Housing Bathing waters	Food source Housing Aquaculture Tourism
Pressures	Urban/industrial wastewaters Dredging	Urban/industrial wastewaters Dredging	Salmon farming organic inputs
Major Impacts	Eutrophication Habitat change	Eutrophication	Local bottom modification
Overall State	Highly modified Heavily polluted	Modified Polluted	Near pristine Unpolluted

2.2. The Bahía Blanca estuary

The Bahía Blanca estuary (Fig. 3), as indicated by its name, is a bay located on the Southern coast of the Buenos Aires Province, Argentina, on the uppermost terrace of the Argentinean continental shelf according to the bathymetric division proposed by Parker et al. (1997). The channels and small bays present an NW-SE orientation running through extensive tidal areas, namely from North to South: Principal Channel, where the main human settlements are located, Falsa bay and Verde Bay. Main natural fresh water inputs in the Bahía Blanca estuary are located at the innermost part of the Principal Channel.

The Bahía Blanca estuary, though in a lesser degree, presents similar pressures than the Santos estuary. The population of its main city, that gives name to the system, has increased to a total of 350,000 inhabitants over the last two decades and still has a large growing potential.

Wastewater is an important source of freshwater in the estuary comprising 23.3% of the overall freshwater, with similar flows to the main freshwater inputs, the Napostá Grande and the Sauce Chico creeks that contribute with 1 m^3 s^{-1} and 1.9 m^3 s^{-1} respectively (Carrica, 1998). As a result, loads of organic matter and nutrients are discharged along the Principal Channel that could lead to localised eutrophication problems. Nutrient concentrations are elevated inside the Principal Channel all year round, yet there are no signs of eutrophication in the system. Another threat to the system is the potential risk of oil spills due to the monobuoys located at the centre of the Principal Channel used for vessels refilling.

On the Principal Channel is located one of the most important deep water ports of Argentina and though the harbours and the navigation channel are dredged to a nominal depth of 13 m, a tidal prediction model "is urgently required" for navigational security (Perillo and Piccolo, 1991; Pierini, 2007). In this channel are also located a large petrochemical, fertilizer and thermoelectric plants.

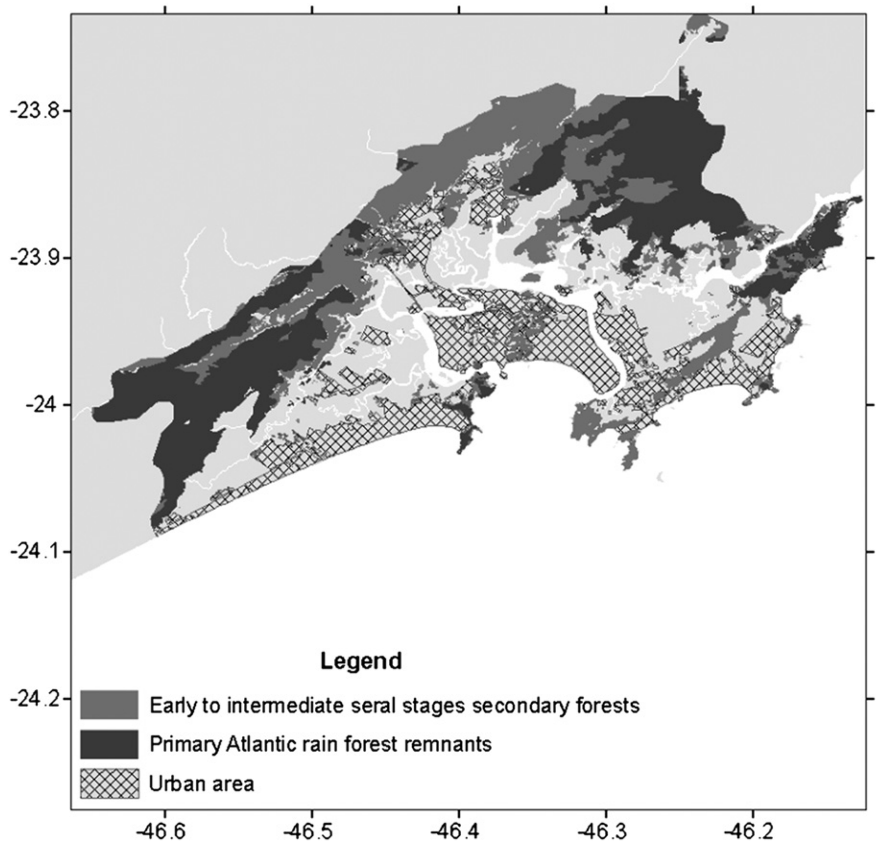

Fig. 2. The Santos Estuary.

The Bahía Blanca estuary tidal range increases from mesotidal to macrotidal along the Principal Channel. This ranges produces the vertical mixing of the water column, however in the inner area due to the freshwater discharges and the evaporation, horizontal salinity and temperature gradients can be observed. Phytoplankton blooms take place during winter, which is unusual for these latitudes, and are dominated by diatoms. The intertidal areas plays an important role in the ecology as it represents around 51% of the system area and due to its high halophytes coverage (Pierini, 2007).

2.3. The Aysén fjord

The Aysén fjord communicates with the Pacific Ocean through the Chilean southern channels and fjords system (Fig. 4). This system corresponds to the coastal area comprised approximately between 41°S and 56° S and is one the vastest and most complex estuarine areas with approximately 84000 km of coast located in 1400 km of linear coast. The system consists in a wide channel, Moraleda Channel, with nearly North-South orientation connecting to the Pacific Ocean through a complex system of channels that run through numerous islands. The Aysén fjord connects to the innermost part of the southern basin of the Moraleda Channel, and consists on a fjord-like inlet with a total length of around 60 km and a width between 4 and 6 km. Typical depths found in the channels are around 200–300 m till reaching the continental break where increase rapidly to 4000 m depth. The oceanographic knowledge of this area is scarce (Palma and Silva, 2004; Silva and Palma, 2005).

A typical Aysén fjord transect would show the U-shaped valley with steep slopes due to its glacial origin (Caceres et al., 2004). At the head of the fjord, the Aysén River discharges being the main freshwater contributor with a catchment basin of around 14000 km^2 and typical flow values between 500 and 1000 m^3 s^{-1}. The river inputs fed by the rainfalls along with the ice melted from the glaciers are very important to the system's ecological functioning and to the hydrodynamical forcing along with ocean tides and local wind stress.

Puerto Chacabuco, located in the innermost part of the fjord, is a key element in the economic activity of the Aysén region due to the important marine commercial and touristic port. The salmon farming industry is the main socio-economic driver being also the source of organic matter into the system both from the cages and from the associated manufacturing industry. About 80% of the region population is located in the main urban areas, Coyhaique, Puerto Aysén and Puerto Chacabuco with around 50000, 17000 and 1500 inhabitants respectively. The lacks of knowledge of how the system reacts to these environmental pressures, along with the nearly pristine conditions of some areas, were the propitious conditions to motivate the Aysén fjord as a study site.

3. Methodology

In recent times, a concept that have been commonly applied in coastal management is the DPSIR framework (RIVM, 1994, 1995; Turner et al., 1998). Its holistic approach aims to identify insightfully links and cause–effect relationships in the studied systems, thus providing significant information that can be useful for the management of conflicts between different coastal uses and interests. It also facilitates the use and dissemination of information between society, managers and scientists. This approach emphasizes the analysis of biotic and abiotic components of ecological systems and their interaction as influenced by society. However, in its classical application the DPSIR framework does not consider

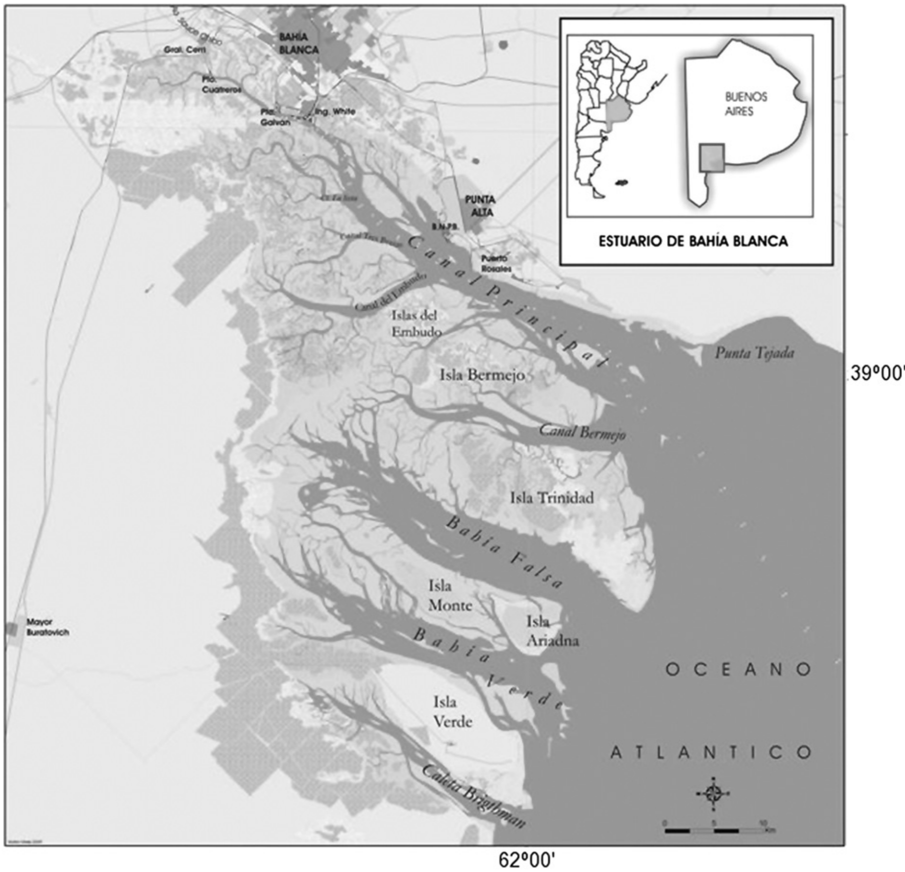

Fig. 3. The Bahía Blanca Estuary.

involving social actors or stakeholders, other than experts and decision makers.

To amend this apparent shortcoming, a new approach has been proposed, namely the Physical-Ecological-Social system (PHES-system) approach (Marín et al., 2008). Making use of participatory approaches (Delgado et al., 2009), this framework takes into consideration several of the requirements of the ICZM, such as the inclusion of human societies as components of coastal zones, the integrated analysis of eco-social components, and the use of conceptual models to describe the different visions held by the social actors. Indeed, incorporating the visions of local social actors is necessary since: "social actors, including scientists, will perceive different ecosystem components and interactions" (Delgado et al., 2009). The PHES-system is a site dependent method able to deal with a wide range of problems (e.g. eutrophication, sediment transport, toxic substances, sewage discharges) and provide answers to different scenarios proposed by the local social actors.

In this work both approaches have been used at each site to some extent. The DPSIR framework has been applied to identify the major drivers in each system and the way they translate into Pressures. Some of these pressures were quantified and the effect of its addiction to the system assessed in term of Impacts on the State of the system. The participation of stakeholders were translated to parameters incorporated into the conceptual and numerical models of the systems, following the proposed methodology of the PHES-system application (Tironi et al., 2010).

The use of numerical modeling tools were at the core of this study. Because these models have the capability to bridge the gap between small scale and large scale processes, they become an essential tool for understanding complex processes that link different compartments of the system (e.g., benthic and pelagic systems) and run across the land–sea interface by linking catchments' and estuarine processes. Two numerical tools were used in this study: a catchment model, the SWAT model (Borgvang and Selvik, 2000; Schoumans and Silgram, 2003), and a 3D hydrodynamical-ecological model, the MOHID model (http://www.mohid.com, Braunschweig et al. (2003)). The results obtained with the SWAT model were used as inputs of river flows and loads to the MOHID estuarine models.

The model addressed the interaction between human-ecosystem by incorporating (i) loads generated from land based activities that are carried into the coastal ecosystem by surface waters and groundwater, (ii) direct use of the coastal system for activities interacting directly with the local fauna (e.g. fishing, fish farming, dredging, waste disposal) or with its habitat and (iii) all other features that were defined with the collaboration of the stakeholders and that are site-specific.

4. ICZM study cases

4.1. The Santos estuary

As already mentioned, the Santos estuarine system is heavily impacted by human occupation and activities. A significant part of the anthropogenic pressure is in the form of diffuse sewage discharges in several places scattered inside the estuary (Braga et al., 2000; CETESB, 2001). Most of these discharges are associated with close slum quarters, and sometimes over, the waterline, often with absent or provisional sewage drainage systems. Together

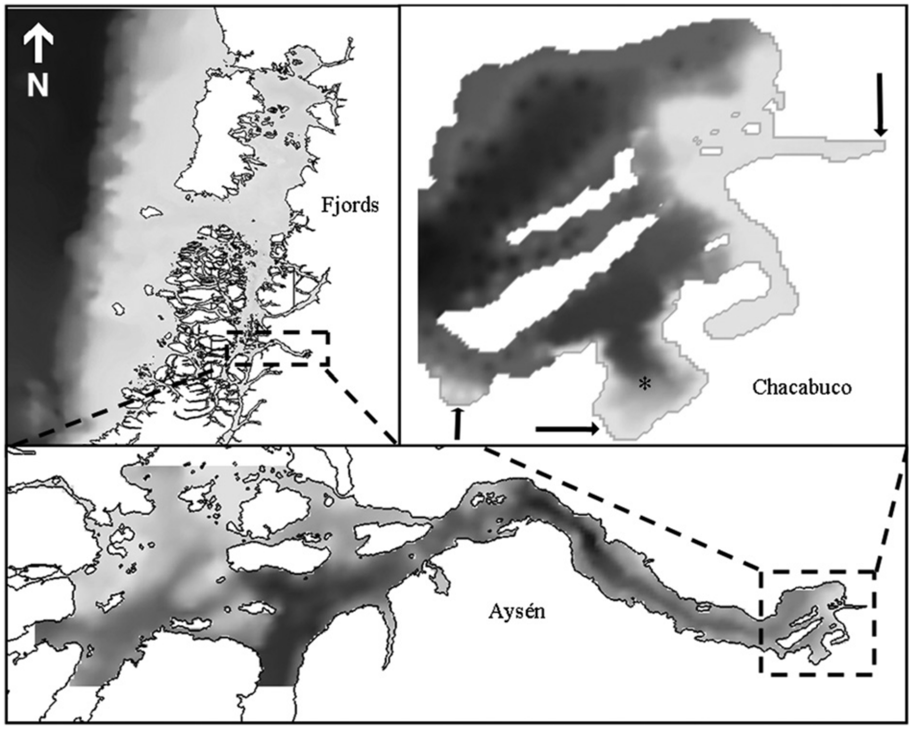

Fig. 4. The Aysén fjord area with a caption to the Chacabuco bay (marked with *). Arrows show the location of the main freshwater inputs.

with the faecal contamination, the discharges into the system also have an associated load of nutrients, both in a mineral and an organic form.

One of the management challenges in the Santos estuary was to determine the impact of the actual pressures had in the estuary ecology and water quality, and what would be the effect of acting in the sources of pollution (Response). To tackle these issues, numerical models were uses to (1) produce a conceptual model of the system in term of ecological processes, and (2) to study the effect of the faecal pollution on the water quality in the estuary.

4.1.1. Ecological status in Santos estuary

In order to account the pressure in terms of nutrient enrichment of the estuary, the model considered 33 sewage discharge points inside the estuary (Fig. 5). These comprise the submarine outfall, three sewage treatment plants and direct inputs from slum quarters and quarters without a sewage network. Each discharge was characterized by flow rate, associated nutrients and dissolved organic matter concentrations. The flow and concentration of sewage treatment plants were calculated from data obtained from SABESP (São Paulo State Basic Sanitation Company) and direct discharges were calculated for each district by the Brazilian Institute of Geography and Statistics (IGBE, 2000) estimating from the population number and through water consumption measured values by neighborhood. This number stands as a raw estimation based on the households not connected to the municipal sewage system.

Considering the large mangrove areas inside the estuaries, the model accounts for the shading effect of mangrove trees that strongly reduce the amount of light reaching the water surface. A simple benthic model was coupled to the pelagic model to account for nutrient diagenesis in the sediment.

The model has been calibrated with available published data (Braga et al., 2000; Bosquilha, 2002; Lima, 2003), as well as field data from a monitoring program designed to quantify the spatial and seasonal patterns in the estuary (Fig. 5), that toke place during winter (August 2005) and summer (March 2006). The model was validated using the field data for temperature, dissolved oxygen, nutrients (ammonia and phosphate), and chlorophyll.

The model was able to reproduce the major features of a typical tropical estuarine ecosystem such as Santos estuary: large temperature variation along the salinity gradient, high mean water temperatures, low light penetration, and variability in the flushing times and sediment and nutrient discharges caused by marked temporal variability in fresh water discharges (Eyre and Balls, 1999). The seasonal cycle is mostly governed by river discharges associated with the rainy season and by the light regime.

The model results suggest that São Vicente channel is the main exit route of materials from the estuary, a part of which enters the estuary again via the Santos channel. The model shows a distinct dynamic between these two channels, controlled mainly by the residence time and the presence of nutrient sources. The residence time in São Vicente channel is higher than in Santos channel, a difference that controls much of the dynamics of material between the channel and the bay.

Although the recycling of nutrients in the system appears to be important, there is a clear control by allochthonous nutrients. Much of the behavior of the system is determined by the large amounts of nutrients that enter via freshwater. A striking pattern to notice is the oxygen demand in the system, most obvious in the importation of oxygen from the bay. In contrast to oxygen, the estuary exports nutrients and organic matter to the coastal area. This behavior of the system, as a large bioreactor, poses a challenging demand its management, considering the large anthropogenic pressure expressed in the marked eutrophication of the estuary. These results strongly suggest that the Santos estuary is in a highly eutrophic condition, compromising the water quality in the adjacent coastal areas.

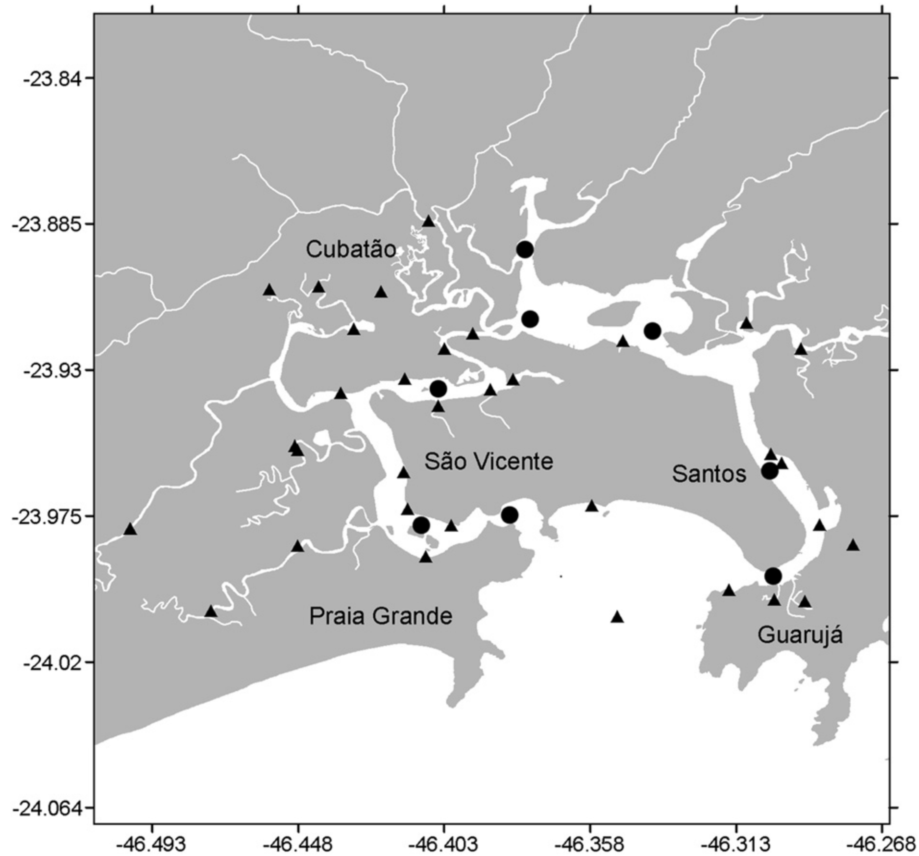

Fig. 5. The Santos Estuary: sewage discharge points define for the model simulations (▲) and sampling station for the data survey campaigns (•).

Overall, the model is able to reproduce the features from the conceptual model derived from field data (Fig. 6). The most significant features where the model agrees with data can be summarized in:

- A general pattern in dissolved nutrient concentrations with higher values in the direction of the estuary's head waters, especially in the areas of industrial effluents, and with relatively low values in the outer areas close to the open sea. This pattern is shaped mostly by physical mixing processes. Some increases are found near densely populated urban areas where sewage is directly discharged into the estuary. A clear gradient of dilution from the estuary's interior to its mouth is seen along the natural channels (Braga et al., 2000).
- Export of organic matter, inorganic nutrients and phytoplankton to the bay highlighting the contribution of the estuary to the eutrophication of Santos bay, especially during the rainy season when river flow is higher (Moser et al., 2005).
- The increase in particulate matter is mostly from allochthonous sources, not from local phytoplankton production.
- Nutrient limitation does not play a significant role in phytoplankton dynamics. While in the inner parts of the estuary due to the nutrient inputs from rivers and direct sewage discharges, in the bay area this can be explained by the inorganic nutrients contributed by the submarine outfall (Moser et al., 2004). The contribution of the outfall in particularly evident in the ammonia concentrations in Fig. 6.

Under a DPSIR framework, the model establishes a clear relation between anthropogenic nutrient sources (Pressures), the cycling of carbon biomass in the system and oxygen-related problems (State). The outfall emission, river discharges, storm drains and sewage discharges all contribute to its enrichment with nutrients. At the same time, the emissions have a clear impact on oxygen dynamics by increasing the organic matter concentrations, enhancing heterotrophic activity, which in turn contributes still more nutrients to the system.

4.1.2. *Faecal contamination*

Until recently, less than 13% of Municipal Wastewater in Brazil was treated before disposal in a river, lake or ocean (UNEP, 2003). As such, the faecal pollution in the Santos area is a common challenge shared with many other Brazilian coastal systems. The main health problems observed in coastal populations in Brazil include the increase and re-emergency of diseases like yellow fever, dengue, malaria, water borne disease (diarrhoea, hepatitis, typhoid fever, cholera) and virus diseases (Garreta-Harkot, 2003).

Escherichia coli concentrations were used in this study as indicators of aquatic pollution and anthropic interference in Santos-São Vicente estuarine system. Two microbiological data sampling campaigns performed project showed a seasonal variability with higher values during summer. Results that are in agreement with the increase in tourist population, along with a greater contribution of diffuse loads from precipitations, both being a typical summer phenomena in the region.

The faecal coliform concentrations show greater spatial variation both in the Santos and Sao Vicente channels. São Vicente has higher concentrations with values above 10^3 CFU/100 ml, most probably associated with the amount of slum quarters and quarters out without sewage network in São Vicente channel. In the

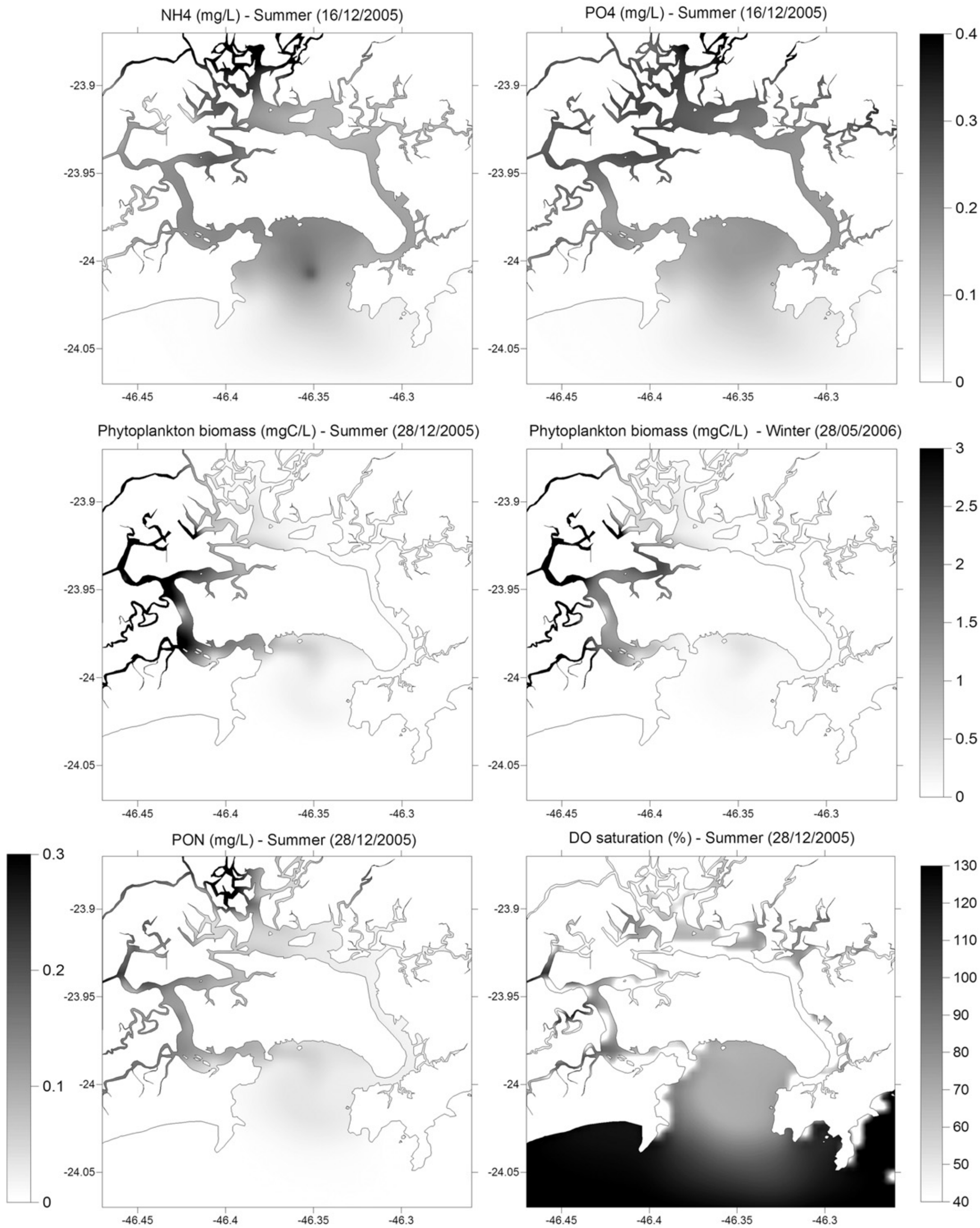

Fig. 6. Model results for ammonia, phosphate, phytoplankton biomass, particulate organic nitrogen (PON) and dissolved oxygen saturation.

estuary's head, near the Cubatão area, there are two major river discharges (Mogi and Piaçaguera), Piaçaguera and despite the characteristic higher *E.coli* concentration of these discharges, the model shows concentrations below 100 CFU/100 ml. A reason for this result can be found in shallowness of these sites, prone to higher solar radiation levels in the water column, the main agent that controls the survival of enteric bacteria in the water (Sarikaya and Saatci, 1995; Serrano et al., 1998). However, it must be stressed that in salt waters this group of bacteria is not the more adequate indicator given its limited survival time (USEPA, 1986).

Spring and neap tide cycles cause great variation on *E. coli* concentrations, as seen in the model results (Fig. 7). The concentrations in these areas are regulated by hydrodynamic conditions. During a spring ebb tide the model shows that these channels contribute to increase the faecal contamination at Santos bay, where the beaches are located, mainly close to the São Vicente channel, indicating some possible contamination by sewage from the estuary channels to the beaches. The impact of the submarine outfall located in the center of the bay is also evident in the results.

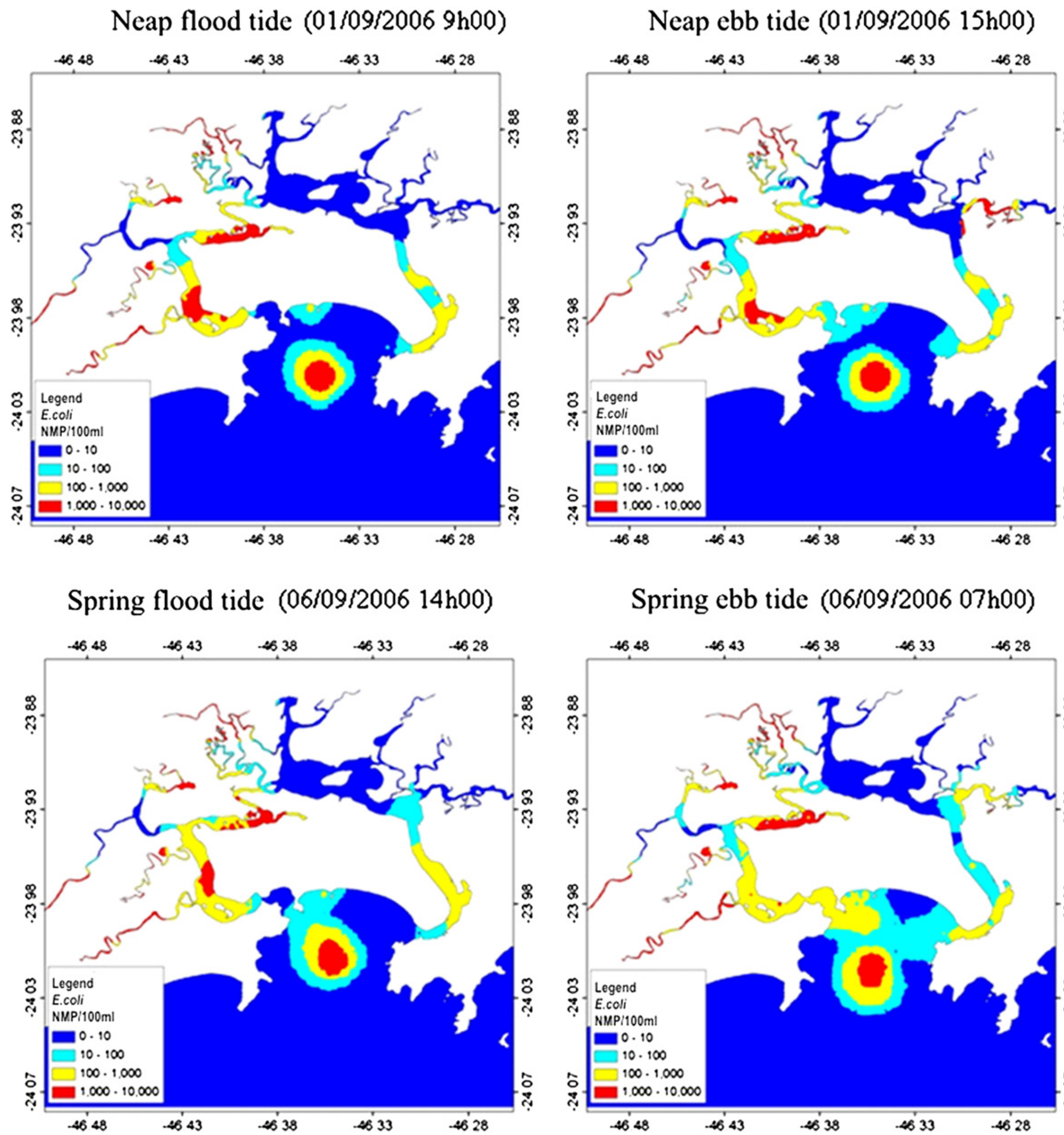

Fig. 7. Model results for faecal *E. coli* (CFU/100 ml) for different tidal conditions.

4.2. Bahía Blanca estuary

4.2.1. Faecal contamination

There are four Urban Waste Waters Treatment Plants (UWWTP) discharging in the Bahía Blanca estuary, with the highest flow from the Bahía Blanca UWWTP at 0.75 $m^3 s^{-1}$, corresponding to 77% of the total wastewater (Heffner et al., 2003; Pierini, 2007). Sewerage systems in Bahía Blanca city are designed with overflow structures that discharge into local waterways when the hydraulic capacity of the system is exceeded due to heavy rains. During dry periods, overflow can also take place due to blockages or pump failures. The aim of this study was to analyze the potential risks of sewage pollution in the estuary with the installation of a new UWWTP on the coast in the inner Bahía Blanca estuary near bathing waters, i.e. the Maldonado Municipal pool.

The model application couples two different modeling schemes. While the hydrodynamics and environment properties as temperature, salinity and solar radiation were calculated by an eulerian approach, the discharge of faecal pollution and evolution of the plume was treated as lagrangian tracers in particle with properties affected by surrounding environmental conditions.

Treated wastewater was monthly sampled at the five stations at the outfall near Napostá Grande Creek (Pierini, 2007). The model was able to predict the complex two dimensional flow features and provided a rational tool for environmental decision making as observed values were in agreement with model results Fig. 8.

The use of mathematical modeling helped to interpret the large *E. coli* variations observed along the estuary. The results suggest that the location of the new UWWTP requires the construction of a very efficient, sensitive and expensive tertiary process in the treatment plant. In a malfunctioning simulated scenario (outflow concentration of 10^5 CFU Unit/100 ml), the results show that the effluent could generate a large polluted area. Consequently, the outflow must be (re)located to an always submerged point, several meters below the low tide level where the currents are continuous as in the main channel.

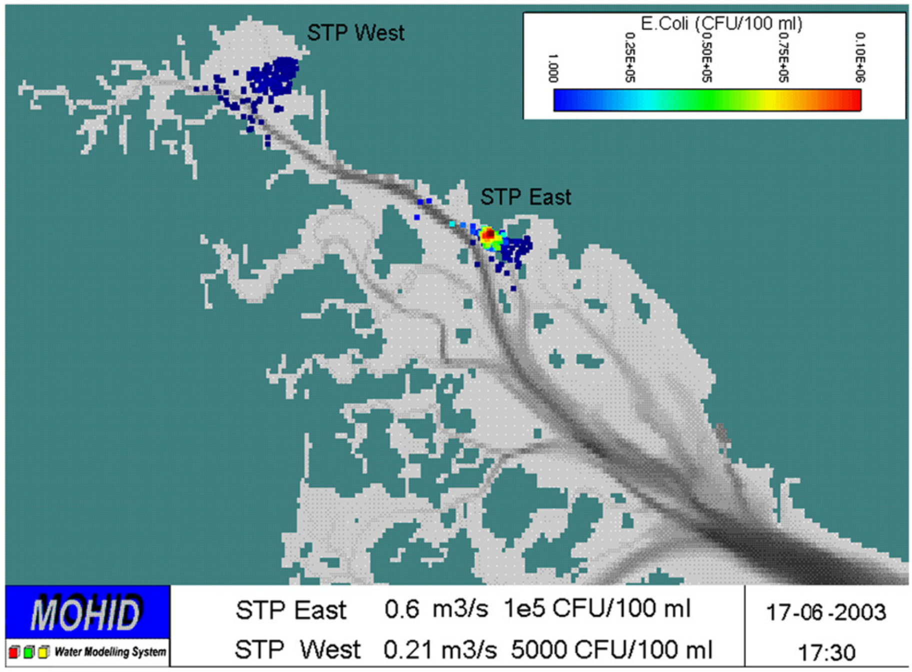

Fig. 8. Spatial distribution of *E. Coli* with STP West and East discharges in Bahía Blanca estuary.

4.2.2. Oil spills

The Bahía Blanca estuary coastal waters are known for their heavy oil tanker traffic mainly due to the transport of crude oil from the Patagonian ports to the Bahía Blanca refineries. In the middle reaches of the Principal Channel, two monobuoys (Punta Cigüeñas and Punta Ancla) serve to load and discharge crude oil to and from vessels. As a consequence, the risk of an oil spill to take place in these coastal waters is considerable whether by accidents or by operational manoeuvres (deballast, bilge discharge and bunkering among others). As a recent example related with serious environmental consequences in the Bahía Blanca estuary coastal zone, on May 19th, 1992, the Presidente Illia oil tanker accident spilled about 700 m3 of crude oil.

To develop management guidelines, the MOHID model was used to identify risk areas, evaluating the fate of spilled oil in the monobuoys locations under different wind conditions (NNO, SSO, NNE and SSE, in Fig. 9). The conclusions based on the results point to a high degree of risk in the whole northern coast of the Bahía Blanca estuary, especially the area east of Principal channel wherethe Natural Reserve of Bahía Blanca, Falsa bay and Verde bay is located. The areas of Southern coast runs a low degree of risk which increases during periods with prevailing Northerly winds.

From a precautionary approach, the MOHID model oil application for Bahía Blanca could reveal itself as a powerful tool in defining management responses to an oil slick incident by identifying the areas where collection and protection operations would be most urgent. Adequate meteorological information and spills monitoring alert are the important variables in order to obtain a good degree of predictions accuracy.

4.3. Aysén fjord

4.3.1. Aquaculture waste management

At the time of the work reported here Chile was about to replace Norway as the first producer of salmon products in the world, and salmon farming was one of the main economic drivers of the Aysén region. On 2006, all over the region's inner channels, fjords and bays, more than 700 aquaculture facilities were functioning, accounting for nearly 30% of Chilean salmon exports.

In general terms, the marine stage of salmon farming productive cycle consist of an accelerated and controlled growth of juvenile individuals, until they obtain an appropriated weight for their processing and commercialization. Fish are maintained in floating net cages and fed with pellets made of a variable fraction of marine fish flour and oil, in quantities depending on the phase of the growth cycle controlled by automatic feeders. Below and around the net-cages, salmon farming produces a series of environmental impacts: (1) waste disposal over the water column and bottom, like uneaten food pellets, fish faeces and antibiotics, (2) invasion by exotic fish species and pathogens after fish escape from cages, in areas where salmon aren't native species, like in Chile and (3) habitat destruction (Miranda and Zemelman, 2002; Naylor et al., 2003; Naylor and Burke, 2005; Cabello, 2006).

The main and common cause of these environmental impacts is the particulate waste disposal in the form of food pellets and faeces to the water column and bottom. In particular, these impacts are: (a) artificial inputs of organic carbon, nitrogen and phosphorous, (b) increase in primary productivity, modifying bottom's community structure, (c) negative impacts over benthos biodiversity and (d) the formation of an anoxic layer in the sediments under the cages (Findlay et al., 1995; Cromey et al., 2002; Soto and Norambuena, 2004; Corner et al., 2006).

A commonly adopted management and assessment tool for particulate wastes in salmon aquaculture is the dynamic simulation by means of lagrangian particle-tracking models (Cromey et al., 2002; Cromey and Black, 2005). These models simulate the dispersion and sedimentation of particles in the study site bottom. These models, coupled with additional numerical models involving physical, biogeochemical and ecological process, like those available in MOHID modules, contribute to a more integral assessment of the environmental impacts associated with salmon farming (Panchang et al., 1997; Perez et al., 2002; Corner et al., 2006). This tool was applied to the Chacabuco bay, an area that represent quite well the different uses of Aysén fjord waters.

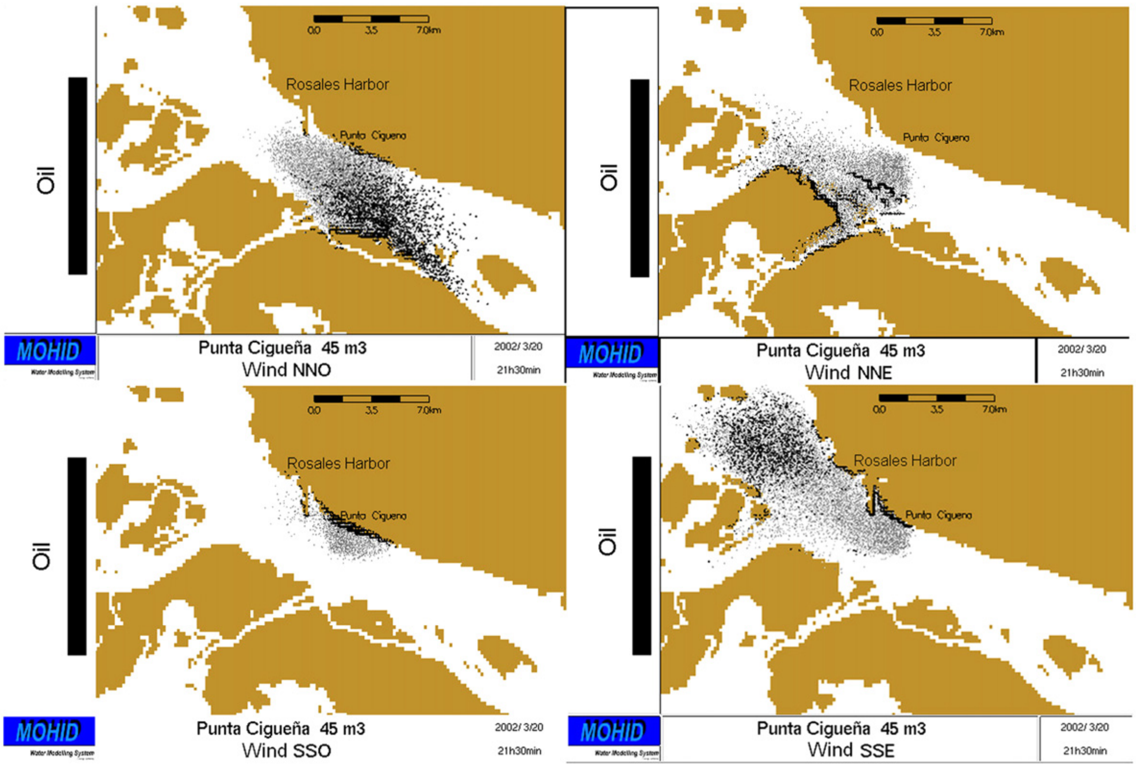

Fig. 9. Spatial oil spill distribution with different wind directions at the accident area (Punta Cigueña) and impact zones.

The results of the lagrangian particle-tracking module (pellets and faecal dispersal after 7 days of simulation of five cages throwing 2250 particles every 2 h) is shown in Fig. 10. The majority of the origins showed pellets dispersing mostly beneath the cages or in distances between 100 m and 300 m from the cage's centre, with differences in the dispersal area depending on the origins depth (Tironi et al., 2010). In total, pellets covered between 17% and 27% of the Chacabuco bay area. The most sensitive variables inside the model parameters were those defining resuspension; specifically erosion, and deposition shear stress. The management tool was delivered to local decision makers in a user-friendly, Spanish-translated interface. The tool has already been used in the process of generating new environmental regulations for the Aysén region (DGA, CONAMA, personal communication).

In fact, the simulated volumes were close to real production values for particulate wastes discharges from Chilean salmon according to environmental impact assessment reports from salmon farmers (POCH-consultores, 2004). In this study it was used a 100 $\times$ 100 m grid covering an area of 147 km^2.

The simulation of salmon farming particulate waste dispersal using MOHID lagrangian module shows matching results when compared with previous experiences with similar approaches (Cromey et al., 2002) and in general, with previous simulations of particulate waste dispersal (Panchang et al., 1997; Perez et al., 2002; Corner et al., 2006).

The involvement of local actors in the research process brought a series of benefits that proved to be decisive for the success of the project. Some of the gaps in the significant amount of field data

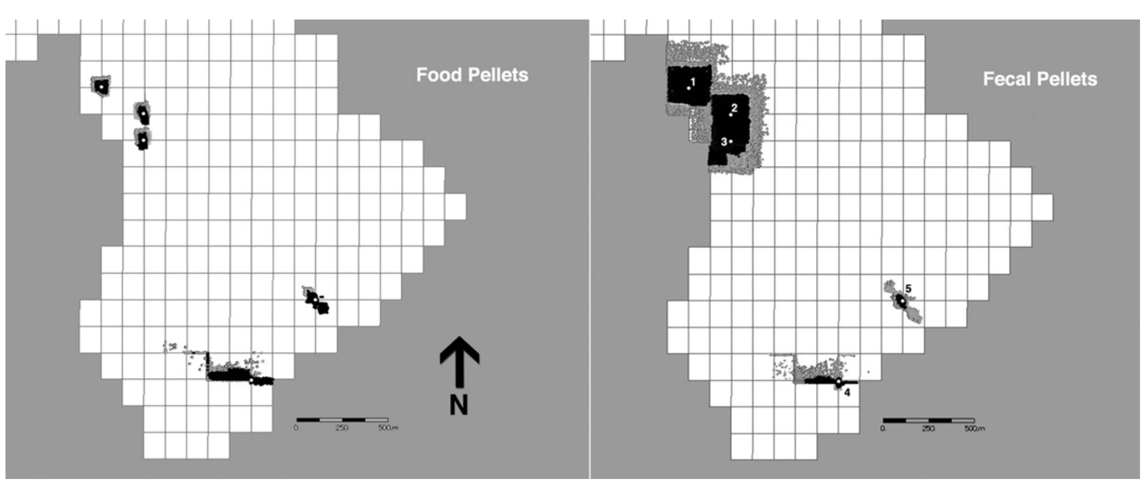

Fig. 10. Final spatial distribution of our 16 days simulation. Darker particles represent the results from the default simulation, while greyscale particles symbolise particle dispersion from the sensitivity scenarios. White circles show each cage location.

required to set the initial boundary conditions for the model and for the validation process, were solved with data provided by government stakeholders. Also, the working relationship generated with local actors allowed us to identify each of their administrative, technical and institutional capabilities, all key information when generating public research reports and decision support systems to final users (Pedersen et al., 2005). Finally, the interaction with local actors led to the definition of modeling scenarios, linking research objectives with their specific interests, as reported by Hanson et al. (2006).

5. Challenges in ICZM in South America

Habitat transformation (for infrastructure expansion, aquaculture, agriculture, etc.), and sewage and garbage disposal are among the most recurrent problems in South America coastal zones. As such, these areas undergo fast and frequently drastic transformation. The three sites studied here present all these problems to some extent, ranging from a small to significant pressures in Aysén fjord and Santos estuary, respectively. The nature of these pressures, in turn, determines the magnitude of the impacts in the systems, and the cumulative effects has change each study site over the years. Many of these changes, typical of coastal areas, are experienced as environmental, economic and social problems.

While major challenges of coastal systems are clearly related to human activity, the direct link between the pressures and the ecological changes is difficult to understand and quantify (Delhez and Barth, 2011). Model applications, such as the examples presented in this work, provide a solution to some of these challenges by helping to establish a cause–effect relation between human activity (pressures) and their impact on the state of the system. This relation is probably more evident in Santos estuary where the number of known sources of faecal pollution is considerable and the socio-economic settings more challenging.

The use of models in this context is never a straightforward task because the highly dynamic nature of coastal ecosystems adds to the complexity of the observation and modeling exercises (Wild-Allen et al., 2011). The level of complexity involved is portrayed here in the model application from a more simple case (Aysén fjord) to a more complex one (Santos estuary). Nevertheless, the model applications proved useful in quantifying and predicting the effects of human activities on the inter-related components in space and time.

5.1. Degradation of coastal ecosystems

Many areas have or are experiencing a rapid and often drastic transformation and degradation to coastal and marine areas. Land conversion is causing degradation of coastal habitats, including mangroves, estuaries and coral reefs. Mangroves, for example, have been disappearing fast over the past 20 years. Coastal water quality has been declining throughout the region, due to increasing discharges of untreated municipal waste. All sites show degradation of coastal ecosystems related with pollution and contamination problems, either from sewage in the case of Santos estuary and Bahía Blanca, or from aquaculture in Aysén fjord.

When facing these challenges, the work of scientists and managers should aim towards predicting changes to the natural systems, and it has been stated that our success in managing the marine environment is only as good as our ability to predict the consequences of human activities (Elliott, 2002). The simulations made for each study site reveal that the basic links between pressures and the state of the system can be assessed with the model (e.g. Figs. 7, 9 and 10), highlighting its role as a predictive tool.

5.2. Land use and resource allocation conflicts

Land reclamation for residential, industrial, agricultural and tourism purposes has caused the degradation of coastal and marine ecosystems in most coastal countries in South America. The massive and largely unplanned investments in sectors like aquaculture, port and industrial facilities expansion, and tourism in coastal and estuarine areas has been pointed out as the reasons of accelerated land use changes and associated conflicts. Frequently new activities compete for the same resource upon which traditional communities depend. Among the three study sites, the Santos estuary emerges as the system where all of these problems occur, and with a higher frequency and intensity than the others.

When compared to other tropical regions such as Southeast Asia, the importance of aquaculture in South America is relatively small. Nonetheless its importance is growing in countries such as Ecuador, where a significant shrimp mariculture industry has developed mostly in mangrove converted areas and salt ponds. More recently important breakthroughs have taken place in aquaculture in Chile (mostly salmon), induced by attractive export markets and made possible by favourable environmental conditions for their growth (Lemay, 1998). This activity has been steadily growing at an impressive rate of 30% a year, when compared with 9.5% worldwide. As shown here for the Aysén fjord, the environmental impact of this activity has been generating growing concerns, especially because of the habitat losses; eutrophication associated with effluent discharges, other changes is estuarine water quality and the introduction of exotic species.

5.3. Degradation of coastal water quality induced by land-based sources

Estuarine and coastal habitats are receiving waters for significant volumes of municipal and industrial wastewater discharges, combined with urban and agricultural runoff, and other point and non-point sources. In many estuaries there are signs that the natural dilution capacity is being exceeded by the volumes and concentration levels of effluents, a fact that is evident in the Santos estuary and raising some concerns in Bahía Blanca.

Since models are a good complement for traditional observation research methods, their role in the management decision process is well established (Neves, 2007). Our modeling approach to the study of faecal contamination in these sites (Figs. 7 and 8) has provide relevant information on the link between known contamination sources and the state of the water quality. The use of modeling tools allowed for the study of the effect of contamination sources on the water quality over different temporal and spatial scales, leading to a better understanding of the role of environmental factors such as physical (e.g. hydrodynamic, temperature) and chemical (e.g. salinity) conditions, the geomorphology of the sites, etc.

The Global Programme of Action for the Protection of the Marine Environment from Land-based Activities from UNEP has summarized the environmental priorities for the Region as: (i) Inadequate discharge of liquid urban effluents; (ii) Pollution due to industrial effluents; (iii) Pollution related to the inadequate use of agrochemical products; (iv) Degradation of aquatic environments due to expansion of urban limits; (v) Inadequate final disposal of urban solid residues; and, (vi) Activities related to extraction, transport and storage of oil or derivates (Marcovecchio, 2000). Curiously enough, some of these thematics have been addressed in this study, and the results obtained from the use of modeling tools provide insightful clues for the management of the study areas.

6. Concluding remarks

Coastal ecosystems have been altered over large areas as a consequence of human activities (Vitousek et al., 1997). A significant number of estuarine areas in South America rank among these systems that have been affected to some degree. Many of these systems show conflicting interests between urban, port, industrial and agricultural pressures and environmental maintenance. From heavily populated area of Santos estuary to the near-pristine water conditions of Aysén fjord, the sites addressed here cover a wide range of ecological and socio-economical conditions, and their inevitable conflicts and challenges in management. These systems share some similarities and also some conspicuous differences, but together they face many of the main challenges discussed above. Nevertheless, the work presented here shows that numerical models are a valuable management tool because they can be applied to systems with distinct physical, chemical and biological features, and with different socio-economic contexts.

Water resource management has been identified as a guiding objective by South American countries, with the following subdivisions: (i) Water supply; (ii) Watershed management; (iii) Management of marine coast and related resources; and (iii) improved quality of groundwater (UNEP, 2003). The legal frameworks for coastal management are being revised in many countries and in some cases modified to change the sectoral focus to a more integrated management approach. From this perspective, the challenge of coastal ecosystem management in South America can be address with common, shared, methods as the work presented here.

A point to be highlighted is the versatility of the methodologies and tools such as numerical modeling employed in this project. The use of models presents a contribute to increase the scientific knowledge needed to support the implementation of local legislations and policies, to assess different scenarios of coastal activities and sources use, to support management decisions and, ultimately, to promote sustainable of coastal resources.

Ultimately our work consolidates the link between numerical predictive models and decision support systems, and emphasizes the need for scientists, managers and politicians to work together in the field of ICZM.

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