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Accumulation of conservative substances in a sub-tropical coastal lagoon

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A B S T R A C T

Coastal lagoons provide important ecosystem services worldwide but are subject to high and multiple environmental stresses. Little information exists on the inner creeks of low-flow coastal lagoons, where the low-exchange rates may exacerbate anthropogenic impacts. In this work, we used a model with high spatio-temporal resolution to describe the hydrodynamics and to estimate the accumulation of conservative contaminants in the upper estuary of the Urias sub-tropical coastal lagoon, in northwestern Mexico. The lagoon shows a weak anti-estuarine behavior and its hydrodynamics is governed by astronomical tides and topography. The mean steady-state water age in the three lagoon areas was ~15, ~30 and ~70 days in the Harbor, Intermediate and Upper Areas, respectively. Thus, the Upper Area, which shelters a mangrove forest, is the most vulnerable to pollution due to the high potential for accumulation. As a best case scenario, the simulation of the release of conservative substances in the Upper area indicated that, 50 days after the release started, conservative pollutants mostly remained in the Upper Area and were not significantly exported to the open ocean. This methodology can be used to model the impact of conservative substances in coastal lagoons worldwide, and can be complementary and useful for the optimization of long-term coastal zone management activities.

1. Introduction

Globally, coastal zones are important areas for human settlement and development, and the establishment of wildlife habitats. Coastal lagoons provide important ecosystem services such as physical protection, water regulation, waste treatment, nutrient cycling, food resources, refugia for fish and shellfish species, recreational and cultural experiences (Costanza et al., 1997; Hobbie, 2000; Martínez et al., 2007; Pendleton, 2008).

Approximately 41% (2.5 billion people in 2002) of the world's population live at or near the coast (UNDP, 2005). Mexico has 9 330 km of coastline, providing ~19.6 $\times$ 10^9 $US in environmental services (Martínez et al., 2007). The Mexican population living in the coastal zone was 29.9 $\times$ 10^6 in 2003 (29% of the Mexican population), and it is estimated that it will increase to 34.2 $\times$ 10^6 by 2015 (UNDP, 2005). Human settlements cause environmental stress in coastal ecosystems such as estuaries and coastal lagoons. Furthermore, climate change impacts may cause serious degradation of the marine ecosystems, with consequences for human health and welfare (IPCC, 2007).

In subtropical and arid areas, some low-inflow estuaries and semi-enclosed bays do not receive a continuous supply of freshwater. Furthermore, during the warm season evapotranspiration can exceed the freshwater supply, causing an increasing salinity gradient from the ocean connection to farther areas (Vaz et al., 1990). In these cases, the salinity gradient can produce a surface inflow and a bottom outflow, named anti-estuarine circulation or inverse estuary (Valle-Levinson, 2010). Estuaries are also affected

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by tides that produce daily tidal currents, with lower and higher circulation during neap and spring tides, respectively. The combination of these factors produces complex circulation patterns in these estuaries (El-Sabh et al., 1997).

Circulation controls the transport of pollutants and, therefore, water quality and their accumulation in sediments. In order to control and reduce their impact on coastal lagoons, it is important to develop management tools to evaluate their hydrodynamics and pollution dispersion (Valle-Levinson et al., 2001). The "residence time" is a classical hydrodynamic parameter used to study, amongst others, the impact of pollutants in semi-closed aquatic ecosystems. However, it shows some practical limitations such as the different ways in which it is calculated and named, thus making intercomparisons difficult (Monsen et al., 2002). Also, in aquatic ecosystems with highly heterogeneous hydrodynamics, this parameter has limited significance (Jouon et al., 2006).

On the other hand, the "water age" or "age tracer" is calculated by using an aging term in the advection-diffusion equation (England, 1995; Delhez et al., 1999; Deleersnijder et al., 2001). The age tracer is usually set to zero in a boundary and reaches steady-state conditions when a balance between water aging and the flux of younger water is attained. This method has been used to study global ocean circulation (e.g., England, 1995), straits (Sandery and Kämpf, 2007), bights (Zhang et al., 2010) and low-inflow estuaries (Kämpf et al., 2009; Kämpf and Ellis, 2014; Kämpf et al., 2010). In coastal lagoons, this parameter can be used to study the connectivity to the open sea and can be useful to identify areas where pollutants may accumulate. However, little attention has been paid to internal creeks in low-inflow estuaries, where the low exchange rates may exacerbate anthropogenic impacts and cause higher salinity, which is the principal biota controlling variable (Joyce et al., 2005), thus increasing environmental risks.

The Urias coastal lagoon is a sub-tropical low-flow estuary. In the upper estuary, the internal creeks present relatively low tidal currents (less than 0.30 m/s, Montaño-Ley et al. (2008)), which could produce the accumulation of pollutants. Furthermore, this area hosts a mangrove forest, a very valuable ecosystem for its environmental services (Costanza et al., 1997). The area receives untreated pond water releases from a shrimp farm, making the mangrove forest vulnerable to pollution (Páez-Osuna, 2001).

In this work, we implemented a high-resolution model to describe the hydrodynamic conditions prevailing in the Urias coastal lagoon, with special attention to the internal creeks, areas under high environmental pressure. In order to evaluate the accumulation of conservative contaminants in the upper estuary, we simulated the discharge of a conservative substance as a best case scenario of pollutants released from the shrimp farm. We expect model results to be useful for coastal zone management of the Urias coastal lagoon, with especial attention to the upper estuary, which is directly exposed to pollutant discharges. These results may shed light on the study and management of pollutants accumulation in low-inflow estuaries worldwide, especially the internal creeks, which may experience high environmental stresses.

2. Methodology

2.1. Study area

The Urias Coastal Lagoon (UCL) is located near the city of Mazatlan, Sinaloa state, Mexico, along the southeastern coast of the Gulf of California (Fig. 1). It has a surface area of 18 km^2 and a length of 17 km. According to Ochoa-Izaguirre et al. (2002) the average annual rainfall in the area is 0.8 m. The average annual surface temperature is 25 °C and the monthly average temperature ranges from 19.7 °C in February to 28 °C in August. The average annual salinity has been reported to have a value of 34, a maximum during the drought season (39.4) and a minimum during the rainy season (31.7). In the present work, salinity was reported using the Practical Salinity Scale.

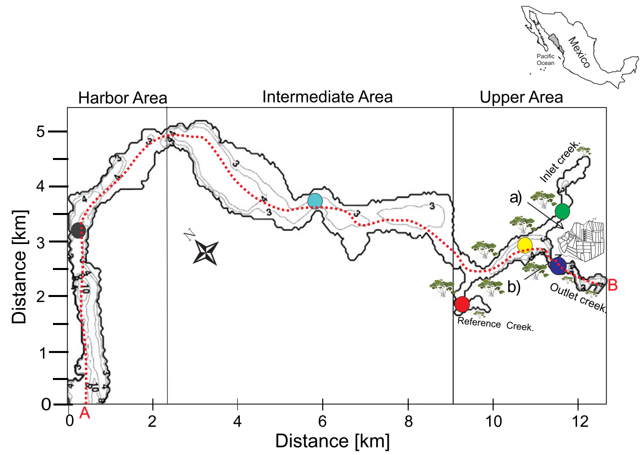

Fig. 1. Bathymetry of the Urias Coastal lagoon (depth contours in meters), main areas, inlet (a) and discharge (b) points of the main shrimp farm, and mangrove forest zone (trees). Test points: Harbor (black circle), Intermediate (cyan circle) and Upper (yellow circle). Areas: Outlet (blue circle), Inlet (green circle) and Reference (red circle) creeks. The dashed red line is a transect A–B used in the profile results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This estuary can be described as a coastal lagoon with an internal platform barrier (Lankford, 1977). The lagoon circulation is tidally dominated and characterized by a mixed tide with an average range of about 1 m. Montaño-Ley et al. (2008) report a maximum tidal velocity of 0.6 m s^{-1} in the navigation channel and predict tidal ranges of 1.2 m during the spring tide. Predominant winds are associated with weather systems from the NW and, only from June to September, from the SW.

The main lagoon axis is parallel to the coast and several channels branch from the main body creating a complex bathymetry. In the upper part of the lagoon, channels are surrounded by mangrove forests, where a shrimp farm discharges untreated waters (Ochoa-Izaguirre et al., 2002). Water depth ranges from 1 m to 3 m along the main lagoon axis and increases along the navigation channel up to a maximum of 13 m. The navigation channel is dredged approximately every two years in order to maintain this depth (Montaño-Ley et al. (2000)).

The UCL upper estuary shelters a shrimp farm with a semi-intensive culture management (Páez-Osuna et al., 1997). In 2004, the farm had 57 earthen ponds (total area: 250 ha) and stocked approximately 20 PLm^{-2} of *Litopenaeus vannamei*. The water pond is pumped from the inlet creek (Fig. 1) to a reservoir channel, which distributes it to the ponds by gravity flow. Ponds drain through a channel that carries the untreated waste water to the outlet creek (Fig. 1).

2.2. The model

The lagoon hydrodynamics was simulated with the Stony Brook Parallel Ocean Model (sbPOM) (Jordi and Wang, 2012), a parallelized version of the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987). POM is a finite difference, primitive equations ocean circulation model with a second order momentum turbulence closure sub-model, terrain-following sigma coordinates, free surface and a split time step. For this study we used computational