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Spatial and temporal flushing time approach in estuaries influenced by river and tide. An application in Suances Estuary (Northern Spain)

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ABSTRACT

Since Water Policies around the world establish the need to manage the aquatic systems through the use of water bodies, a hydromorphological descriptor such as the flushing time may be utilized as a good homogeneity and water quality criterion to distinguish between different types of water bodies. In order to achieve this task, a methodological procedure has been proposed involving a hydrodynamic forcing analysis, an approach to calculate flushing time and a sensitivity analysis of the results applied to the Suances Estuary. This method allows taking into account the different spatial regions on an estuary and the temporal variations of the main forcing. Consequently, the role of bathymetry, freshwater river inflows and oceanic tides on the flushing time is investigated using a two-dimensional numerical model. The hydrodynamic module integrates the depth-averaged mass and momentum equations in the time and space domains as well the transport module solves the depth-averaged advection-diffusion equation. Both modules were calibrated and validated using field data collected during spring and neap tidal cycles. Water levels and current velocities were used in the hydrodynamic module while salinities were compared in the transport module. In order to characterize the spatial variation in water renewal conditions, several boxes were selected along the estuary to evaluate the flushing time. The mass reduction is monitored in time and the flushing time at each part of the estuary was computed for several scenarios and analyzed with a multi-sensitivity analysis.

Most of the river estuary basins in Northern Spain are characterized by their small surface area, short length and steepness, leading to a rapid hydrological response to rainfall and, consequently, a high variability in the river flow. During extensive dry periods during which the river flow is very small, pollutants could remain for long periods in the estuary posing an environmental risk.

1. Introduction

With about 50% of the global population living in the coastal zone, the influence of human activity upon estuarine environments is immense as indicated by the high number of point and diffuse pressures identified in European estuaries. An important attribute that aids the classification of the environmental state of estuaries is the water renewal time scale. Marine and aquatic scientists refer to this attribute as the amount of time taken to effectively flush a confined region, this being the most important physical influence on water quality in the system.

In Europe, the Directive (2000/60/EC) (WFD) establishes the need to manage aquatic systems using water bodies, that is, the use of basic and homogeneous units with the same structural and functional characteristics. In this context, a hydromorphological descriptor such as the renewal rate of the water bodies may be used as a good homogeneity and water quality criterion (Choi and Lee, 2004; Huang, 2007).

Regarding this descriptor, there are different concepts such as the residence time and the flushing time (henceforth RT and FT). These concepts use different methods for their calculation and represent very useful parameters to understand the patterns of pollution dispersal or ecological processes within a water body. RT is considered a local measure with spatial variation, whereas FT is considered a measure of the system level and a unique value for the entire water body (Choi and Lee, 2004). Consequently, RT is defined as the period of time required for a water parcel, initially located at the point considered, to leave the domain (Takeoka, 1984; Soulsby and Tetzlaff, 2008), implying that the definition deals with moving individual pieces for a spatially varying situation (Zimmerman, 1976). On the other hand, the estuarine FT considers the average amount of time fresh water spends in the system (Alber and

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Sheldon, 1999), that is, the rate at which river freshwater is flushed out of an estuary (Huang, 2007).

Thus, based on the scientific evidence of the FT viability to estimate this process in the whole estuary (Alber and Sheldon, 1999; Choi and Lee, 2004; Huang, 2007), this concept was selected to carry out this study.

The flushing of a water body is achieved through transport mechanisms that promote water removal, such as, tidal currents, river contributions and the density gradient induced circulation, meteorological events and the topographical configuration (Wang et al., 2004). Nevertheless, the FT does not take into consideration the estuarine complexity with different spatial behavior. A reasonable solution to satisfy this issue would be dividing the estuary into several boxes (sub-domains much bigger than grid-cells) of similar characteristics (Braunschweig et al., 2003; Malhadas et al., 2009; Malhadas et al., 2010) such as the head, the main channels, the intertidal flats or the mouth. With this approach, a considerable amount of the required computational cost is reduced and the different spatial behaviors inside the study area are maintained.

Another significant issue is the study site forcing (tides, rivers, winds, waves) which determine the hydrodynamic and temporal variations experimented by the system leading to different FT results (Yuan et al., 2007). For example, if the FT has been calculated only for medium conditions of the forcing starting at one tidal phase situation, e.g., high tide, the obtained result might not be realistic because the forcing influences on FT could not be neglected.

The factors that influence the water body renewal in narrow and shallow estuaries as well as the methodology for the FT calculation are presented next. We propose analyzing the river flow and tidal range distributions in the study zone to take into consideration the influence and the seasonal variability of the major forcing and to select the model scenarios. To apply the modelling to a specific water body split into several boxes, a homogeneous concentration of a conservative tracer is conferred to all its segments at several instants in which the volume of that water body corresponds to the high, ebb, low and flood tides. While the modelling takes place, the conservative tracer is gradually dispersed due to the influence of the physical forces. The spatial distribution of the remaining conservative tracer is then used to calculate the residual mass of the conservative tracer at a specific moment (Gómez et al., 2006). Finally, to carry out the results evaluation, a multi-sensitivity analysis was performed to understand the role of river discharges and tides within the study zone, a shallow mesotidal estuary namely the SE. For this objective, we implemented and applied a numerical model, including wetting and drying processes, on the confluence of SE and Saja-Besaya River, where two significant industrial facilities are located (Ortega et al., 2005; Puente et al., 2008; Alvarez-Guerra et al., 2008). The model domain was generated by the application of GIS techniques. As a result, we obtained a 2D grid covering the SE and the adjacent coastal zone. Model calibration and validation of the 2D grid were conducted for water levels, current velocities and salinities. The validated model was then used to calculate FT with the proposed approach which takes into account the geospatial and temporal variations.

2. Study area

The Suances Estuary (−4.0237/43.4007 ED50) is a narrow and shallow mesotidal estuary, with typical spring-neap cycle tidal ranges varying between about 5.1 m (extreme spring) and 0.7 m (extreme neap), located in the northern Spanish coast (Fig. 1). It is 5.5 km long, with a 150 m mean width and a surface area of 389 ha, 76% of which is occupied by intertidal flats. The shallowest depth is 3.2 m (above the mean sea level) corresponding to the tidal flats located along the Suances Estuary (henceforth SE) and the depth of the main channel varies between 1 m (head) to 8 m (mouth) while in the adjacent coastal sea, the deepest depth within the study area is 43 m (below the mean sea level) near the northwest corner. Land reclamation has reduced the original estuarine area by 30%, while 50% of the estuary is bordered by dikes (over 13000 m), which dramatically modify its hydrodynamic conditions, especially since 1878 with the construction of a jetty in the mouth of the estuary for transport facilities (Gobierno de Cantabria, 2005; Romero et al., 2008).

The main freshwater input to the system comes from two similar rivers draining relatively small basins, the Saja and the Besaya, which occupy a catchment area of 966.67 km^2 with a perimeter of 166.27 km. The freshwater inflow, in natural conditions, varies from about 1 to 600 $m^3 s^{-1}$, with typical flows in the range of 7–24 $m^3 s^{-1}$ (García et al., 2008). These river basins converge in the town of Torrelavega (56000 inhabitants). After the confluence of the Saja River and the Besaya River, a small river stretch (1890 m) flows up to an industrial wier which limits the end of the tidal influence into the river basin, in other words, the head of the SE. This river stretch is called Saja-Besaya River as the catchment area of both rivers is very similar (Fig. 1). The relatively small surface area, short length and steep lead to a rapid hydrological response to rainfall between 15.91 and 20.76 h and, consequently, a high variability in the river flow. During the last century, this estuarine zone has been affected by major industrial developments. The location of industrial zones 1 (IZ1) and 2 (IZ2) are shown in Fig. 1. Both zones modify the basin river hydrology extracting water (2.25 m^3 s^{-1}) and discharging wastewater (1.25 m^3 s^{-1}). Furthermore, it is worth pointing out that the Alsa-Torina reservoir discharges about 10 millions of cubic meters to balance out the industrial withdrawals during summer and drought periods.

3. Set up of the numerical models

3.1. Model description

Water elevation, velocity and passive tracer fields were calculated using a two-dimensional coastal and estuarine model. This model involves the solution of the momentum and tracer equations dividing the study area into square cells. The numerical computation is carried out on a spatial domain that represents the entire estuary through a finite-difference grid. The cell dimension is a function of the size of the study area, and its resolution depends on the desired level of detail (García et al., 2010b).

The hydrodynamic module used in this paper solves the two-dimensional vertically integrated hydrodynamic equations based on the three-dimensional Reynolds Averaged Navier–Stokes equations (frequently termed RANS) for incompressible and unsteady turbulent flows, including the effects of the earth's rotation, bottom friction and wind shear. The system of equations, in Cartesian coordinates (x increasing eastward and y increasing northward) and following the hydrostatic assumption and Boussinesq approximation, are expressed as:

$$\frac{\partial H}{\partial t}+\frac{\partial (UH)}{\partial x}+\frac{\partial (VH)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial (UH)}{\partial t}+\frac{\partial (U^2H)}{\partial x}+\frac{\partial (UVH)}{\partial y} = fVH - gH\frac{\partial \eta}{\partial x}-\frac{gH^2}{2\rho_0}\frac{\partial \rho_0}{\partial x}+\frac{1}{\rho_0}\left[\tau_{xz(\eta)}-\tau_{xz(-h)}\right] + H\upsilon_e\left[\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right] + 2H\frac{\partial \upsilon_e}{\partial x}\frac{\partial U}{\partial x} + H\frac{\partial \upsilon_e}{\partial y}\left[\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right] \tag{2}$$