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Seasonal and axial variations of net water circulation and turnover in the estuary of Bilbao

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ABSTRACT

A two-layer box model based on salinity and freshwater inflow data was developed and used to estimate net water circulation, contributions of gravitational circulation exchange and tide-driven exchange, and turnover times for the estuary of Bilbao, a small estuary of the Basque coast (Bay of Biscay). Average monthly estimations for the 2001–2010 period were made and related to river discharge and saltwater inflow. Seasonal variations of surface-layer outflows were strongly related to the river discharge regime, even in the lower estuary (inner Abra harbour). Bottom-layer salt-water inflow from the outer Abra was the main driver of bottom landward flow, vertical advection and surface-layer outflow in the inner Abra, but not in the channelized zone that extends from the inner limit of the Abra harbour to the tidal limit. Gravitational circulation exchange dominated in the entire estuary over the annual cycle. Tide-driven exchange proportionately increased in summer and showed the highest contribution (42%) in the lower estuary in August. Flushing and residence times increased in summer in relation with the decrease of freshwater discharge, although in the innermost zone of the estuary they were also high in winter due to the retention of freshwater at the inner estuary under extremely high discharge conditions. Flushing and residence time maxima of 21.5 and 28.6 days respectively were obtained for the entire studied zone in August. It is of note that turnover times differed largely between the upper (flushing time of 0.4–2.4 days) and bottom (flushing time of 2–10 days) layers in the channelized zone. Results supported intuitive conclusions drawn in previous studies about the spatio-temporal dynamics of dissolved oxygen, chlorophyll and zooplankton populations in the estuary of Bilbao, in relation to the effect of water circulation and turnover.

1. Introduction

Time-scales that describe the mixing, transport or escape of estuarine water exert a significant physical control on ecological processes in estuaries, since they have important implications in estuarine material transport, biological production and water quality (see Monsen et al., 2002). For example, the biogeochemical processing of nutrients and its export from estuaries has long been claimed to depend on water turnover times (Muller et al., 1994; Boynton et al., 1995). Also, estuaries with short turnover times relative to phytoplankton growth rates have low concentrations of phytoplankton and primary production (Jassby et al., 1990; Lucas et al., 1999). Similarly, in some estuaries the occurrence of eutrophication and hypoxia/anoxia has been attributed to the long estuarine turnover time (Cerco and Cole, 1993). Overall, turnover time can exert an important control on the sensitivity of estuarine ecosystem functions to external stressors (Evans and Scavia, 2013).

There are several transport time-scales to quantify the turnover rate of water in an estuary. Two of the most widely used ones are flushing time and residence time, with subtle but important conceptual differences between them. Flushing time has been defined as "the ratio of the mass of a scalar in a reservoir to the rate of renewal of the scalar" (Geyer et al., 2000, as cited in Monsen et al., 2002). Flushing time is often taken as the time required to replace

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the existing freshwater in the whole or a segment of an estuary at a rate equal to the river discharge (Dyer, 1973); alternatively, when tides exclusively flush the system the tidal prism approach can be used to estimate flushing time (Dyer, 1973). Residence time is the time required for a parcel of water to escape the estuary from an existing location (Dronkers and Zimmerman, 1982).

However, it should be taken into account that contemporary literature on time-scales of water transport in semi-confined coastal systems includes multiple new and redefined time-scales such us “average residence time” and “local residence time”, which are based on different methods of calculation (see Abdelrhman, 2005). In any case, the use of more than one of these time-scales may be useful to obtain a more integrative picture of the overall time scale of water transport in the system, and of its spatial and temporal variations.

The estuary of Bilbao is a small stratified estuary draining into the inner Bay of Biscay. By the 1980s this estuary had become a highly polluted system (domestic sewage and industrial wastes) in which one of the main water quality problems was the development of hypoxia throughout extensive areas (Iriarte et al., 1998; Borja et al., 2006). The implementation of a sewerage scheme and the significant industrial decline in the area over the last three decades or so have caused a general improvement of the water quality and a significant recovery of the biological communities of the estuary (Borja et al., 2010). But the oxygen recovery response of the estuary to the sewage pollution abatement has not been the same all along the estuary, summertime hypoxia still being a characteristic feature of bottom waters of the inner estuary (Iriarte et al., 2010; Villate et al., 2013). It has been shown that in these bottom waters of the inner estuary dissolved oxygen (DO) variations correlate significantly with river discharge and water column stratification and it has been hypothesized that the positive correlation with river discharge may to some extent be a reflection of the increased residence time of the water during the driest season (Villate et al., 2013). However, there are few estimates of turnover times of the estuary of Bilbao. Some of these estimates are turnover times obtained for standardized conditions of river flow (high, mean and low) and tide, and are values either for the entire estuary or for the whole channelized zone or for the outer and inner Abra (Valencia et al., 2004). In addition, a single turnover time does not represent the spatial and temporal variability in the transport processes in estuaries (Shaha et al., 2010), particularly in stratified systems like the estuary of Bilbao. There are also some unpublished data of residence times of the estuary of Bilbao, estimated for different points along the longitudinal axis of the channelized area using the two-layer hydrodynamic MIKE12 model (García-Barcina, 2003). Simulations were performed only for 4 situations: low river flow neap tides, low river flow spring tides, average river flow neap tides and average river flow spring tides. Hydrodynamic modelling methods can be complex and have increasing data requirements and costs in terms of trained personnel and equipment (Sheldon and Alber, 2006), being often beyond the capabilities of many ecologists and other environmental scientists and managers (Hagy et al., 2000). Salt-balance methods, however, are relatively simple tools that when used with a two-layer box model approach, as required for stratified estuaries, are useful to estimate turnover times for different segments of an estuary in surface and bottom layers (Officer, 1980; Hagy et al., 2000). The aim of the present work was to estimate horizontal and vertical transport as well as flushing times and residence times in the estuary of Bilbao with a higher spatio-temporal resolution than in previous works (García-Barcina, 2003; Valencia et al., 2004), by using monthly salinity and river flow data for a period of 10 years. This has allowed us to obtain a standardized view of the spatio-temporal transport and turnover dynamics of this estuarine system, including the inter-annual variability, which cannot be overlooked, given the significant year-to-year variations in river flow (Aravena et al., 2009). For this purpose, salt balance methods with a box modelling approach (Officer, 1980; Hagy et al., 2000) have been used and this has also allowed us to assess how turnover times estimated with these relatively simple methods compare to previous estimates obtained using more complex hydrodynamic models.

With this work we have also tried to ease in part the scarcity of information on the spatial and temporal variability of time-scales of water transport in small estuaries, because in this type of systems, very often coarse estimations for the entire estuary are used for comparative purposes (Rasmussen and Josefson, 2002; Valencia et al., 2004). Furthermore, given the differences in turbulence and mixing properties between small and large estuaries, if we are to achieve a proper understanding of the hydrodynamics of small estuaries, we should aim at obtaining information on time-scales of water transport in these small estuaries (Trevethan and Chanson, 2009).

2. Study site

The estuary of Bilbao (Fig. 1) is a small ($\approx$23 km long from the tidal limit to the shore line) system located in the inner Bay of Biscay (43°23′–43°14′N, 3°07′–2°55′W) on the coast of the Basque Country. In this estuary two clearly different zones can be distinguished: a narrow highly channelized zone in the inner part, followed by a funnel-shaped wider embayment called Abra in the outer part. The channelized zone of the estuary has an extension of 15.2 km from the tidal limit located in Abusu to the Txurruka pier (Portugalete-Areeta), a variable width (from 25 m in Abusu to 270 m in the Gobela area) and a variable depth (from 0.5 m in Abusu to >10 m in the inner Abra). In the Abra harbour, in turn, there is an inner zone with a maximum width of 1.8 km and a maximum depth of 15 m and an outer zone with a mean width of 3.8 km and a maximum depth of 32 m. For the present study, we have not considered the wider, more open zone of the Abra and have delimited an estuarine area that goes from the tidal limit of Abusu to an imaginary line that joins the Espigon E1 dock (Santurtzi) and the pier of Arrigunaga beach. Physical features of the studied zone are shown in more detail in Table 1.

The system is forced by a semidiurnal tidal regime, and tidal amplitude in the Abra harbour ranges from 4.6 m (spring tides) to 1.2 m (neap tides). Valencia et al. (2004) estimated that the water volume contained within the entire estuary, this comprising the channelized zone and the Abra harbour, varies from 349×10^6 m^3 to 452×10^6 m^3 for a tide height of 0.0 m and 4.5 m, respectively, and within the channelized zone from 8.5×10^6 m^3 to 23.8×10^6 m^3. The same authors reported minimum and maximum tidal prisms of 23×10^6 m^3 and 108×10^6 m^3 for the entire estuary, and of 3×10^6 m^3 and 20×10^6 m^3 for the channelized zone. River flow is on average (36 m^3 s^{-1}) relatively low in comparison to the basin volume and the tidal prism, and as a result, most of the estuary is usually euhaline (salinity > 30). The channelized zone is highly stratified in its inner half all year round, but stratification weakens gradually towards the Abra harbour (Iriarte et al., 2010). In the outer Abra harbour salinity values approach those of the surrounding shelf waters, where they range from 35.0 to 35.8, and fluctuate more inter-annually than seasonally (Hughes et al., 2010). Under unusual high flood conditions, the entire channelized zone may be filled by freshwater at low tide, and the strongest salinity gradient moves to the Abra harbour.

3. Methods

3.1. Description of the physical model

Calculations of net physical transport, flushing rates and turnover times were performed following a box model approach on a