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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 spatiotemporal 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 (≈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

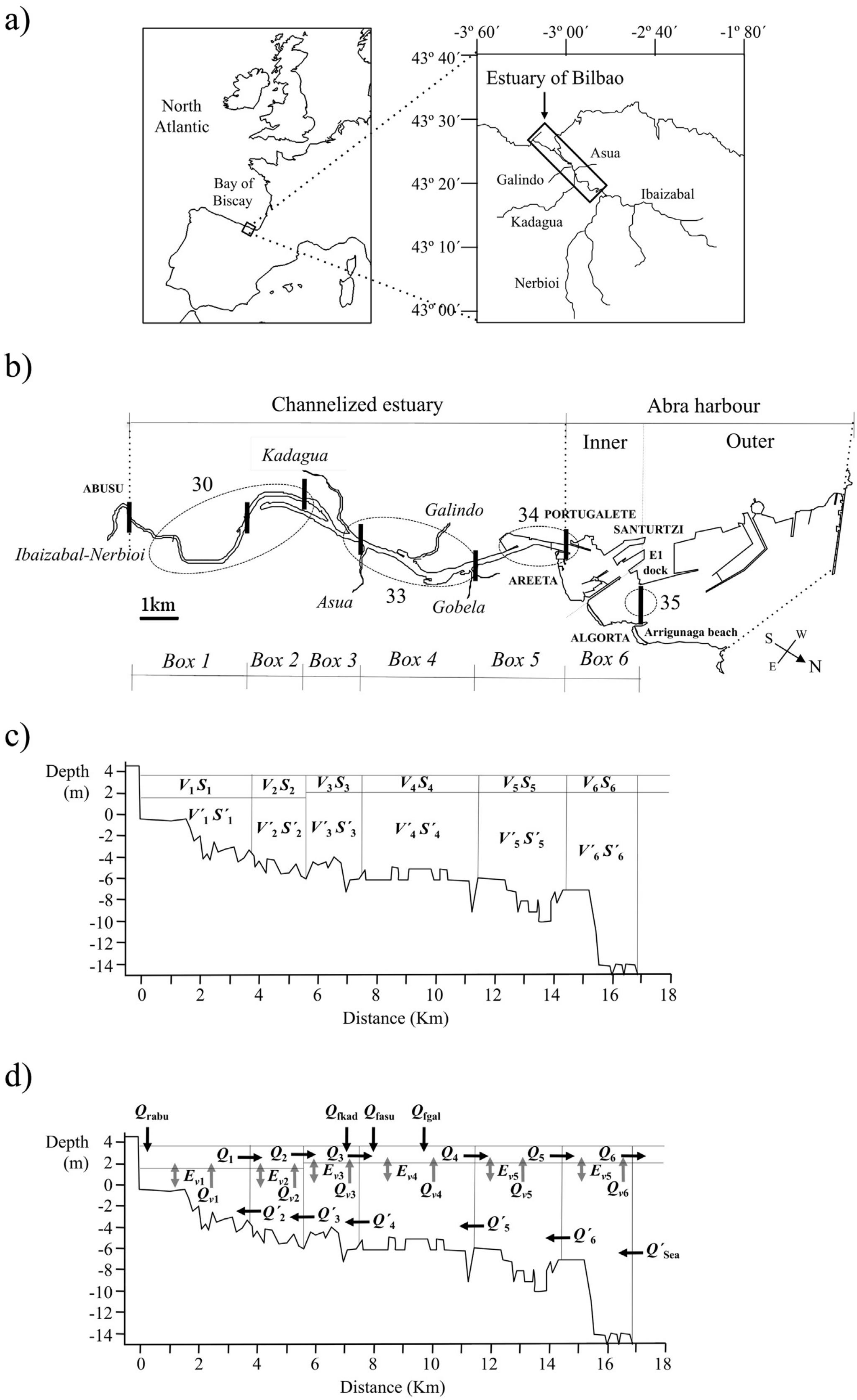

Fig. 1. Location of the estuary of Bilbao and map of its watershed (a). Map of the estuary of Bilbao, with indication of sampling zones (30, 33, 34 and 35) and limits of the boxes along the longitudinal axis (b). Schematic diagrams of the 2-layer box model structure showing the box boundaries and the estimated volumes (V_m and V'_m) and salinities (S_m and S'_m) (c), or the estimated exchange coefficients of seaward advection (Q_m), landward advection (Q'_m), vertical advection (Q_{vm}) and vertical non-advective exchange (E_{vm}) in each box (m) and the inputs of freshwater (Q_{rabu}, Q_{fkad}, Q_{fasu} and Q_{fgal}) (d).

Table 1
Length, average width, average maximum depth, volume and calculated salinity minima (Min.) and maxima (Max.) of each box and of the total studied area of the estuary of Bilbao for surface (S) and bottom (B) layers, and for the entire water column (E).

		Layer	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6	Total
Length (km)			4.10	2.30	1.99	3.46	2.75	2.41	17.01
Width[a] (m)			58.5	80.5	107.4	167.7	164.5	1574.3	321.3
Depth[a] (m)			5.8	8.4	9.1	9.3	11.4	15.6	9.5
Volume (m^3)		S	0.56×10^6	0.42×10^6	0.76×10^6	1.07×10^6	1.07×10^6	7.28×10^6	11.18×10^6
		B	0.64×10^6	0.67×10^6	2.42×10^6	4.16×10^6	4.66×10^6	46.77×10^6	59.32×10^6
		E	1.20×10^6	1.09×10^6	3.18×10^6	5.23×10^6	5.73×10^6	54.05×10^6	70.50×10^6
Salinity	Min.	S	0.0	0.0	0.1	1.1	1.7	7.6	5.2
		B	0.0	0.0	13.5	25.0	25.1	29.0	27.1
		E	0.0	0.0	10.3	20.1	20.7	26.1	23.7
	Max.	S	22.8	27.9	30.7	33.2	33.7	34.7	33.3
		B	32.9	34.2	34.4	34.8	35.4	35.8	35.6
		E	28.2	31.8	33.5	34.5	35.1	35.6	35.2

[a] Mean values for a high water of 3.6 m.

monthly time scale, in response to monthly average freshwater inputs and average salinities of the various boxes. For the calculation of net transport for the estuary of Bilbao the methodology described by Hagy et al. (2000) for stratified estuaries, based on the box model approach of Officer (1980) has been used. The box model estimates the net non-tidal circulation in two layers, a surface layer with a net circulation of freshwater from the head to the mouth of the estuary and a bottom layer in which seawater enters into the estuary towards the head of the estuary. This circulation estimates are based on the freshwater inputs, the volume of each box and the distribution and exchange rates of salinity.

Taking into account the hydro-geomorphological characteristics of the estuary of Bilbao, the box model was built dividing the main channel of the estuary in 6 sections (boxes 1–6). Each of these boxes was subdivided in two layers, surface and bottom, and the depth of each layer was decided depending on the vertical salinity profiles. For boxes 1 and 2 surface and bottom layer division was established at 2 m depth, for boxes 3–6, at 1.5 m depth. The box model was built with 12 boxes in total. The longitudinal and vertical distribution of the boxes is depicted in Fig. 1.

3.2. Estimation of box volumes

The volume of the estuary was estimated with the ArcGis 10.0 computer programme, using its Polygon Volume option for a mean high water of 3.6 m. To that purpose an orthophotograph of the estuary at high tide from 2010 was integrated from the WEB Mapping Service (WMS) of the Geoeuskadi.net website in order to obtain the estuarine surface area by triangulation (TIN: Triangulated Irregular Network). This information together with the bathymetric data (depths) of the estuary provided by AZTI-Tecnalia and the Port Authority of Bilbao were used to calculate the volumes of the surface (V_m) and bottom (V'_m) layers of each of the 6 boxes.

3.3. Freshwater inputs

Freshwater inputs were estimated from river flow data that were obtained from the Hydro-meteorological Data Service of the Provincial Council of Bizkaia. Monthly means of the flows of the main rivers and streams discharging into the estuary of Bilbao: Ibaizabal-Nerbioi (measured at the Abusu gauging station) entering at the head, Kadagua (sum of flows measured at Herrerias and Sodupe gauging stations) entering at the level of box 2, and Asua and Galindo (measured at Asua and Galindo gauging stations respectively), entering at the level of box 3, were calculated for the 2001–2010 period. Freshwater inputs to each model segment were estimated as the sum of gauged run-off data obtained from flow gauging stations in one or more places on the largest 3 tributaries to the estuary of Bilbao (Ibaizabal River, Nerbioi River and Kadagua River), and on two other small tributaries (Asua and Galindo Streams) (Fig. 1).

3.4. Net physical transport

3.4.1. Calculation of mean salinities and time rate of change of salinity

For these calculations time series of salinity recorded as monthly vertical profiles at 4 non-fixed points along the estuary of Bilbao from 2001 to 2010 were used. Salinity was measured *in situ* using a WTW multi 350i Multi-Parameter Water Quality Meter every 0.5 m depth during high tide at neap tides. These salinity data were measured as part of an environmental and plankton monitoring program initiated in 1997.

For the salinity calculations a volumetric interpolation (3D) of the monthly measurements of salinity was performed using the Inverse Distance Weighted (IDW) method included in the programme Groundwater Modeling System GMS 8.2.4 (Groundwater Modeling System 2012 Aquaveo). Interpolation was made between the site of Abusu at the head of the estuary, which corresponds to the inner limit of Box 1, and the imaginary line designated as the outer limit of Box 6 in the Abra harbour. This outer limit coincided with the outermost sampling site of the monitoring program and values of salinity measured in each sampling point were used for calculations. However, in the inner limit, at the Abusu site, a 0 salinity value was used for interpolation between this point and the innermost sampling point of the monitoring program, as the Abusu site always has freshwater, although the water level may vary slightly by the effect of tides. Therefore, the mean salinity values for each surface (S_m) and bottom (S'_m) box were calculated using these interpolations. The time rate of change of salinity (dS_m/dt (surface) and dS'_m/dt (bottom)) for each month was calculated as the difference in mean salinity between two consecutive months (James D. Hagy, personal communication).

3.4.2. Calculation of advective and non-advective exchange coefficients

In order to estimate the estuarine exchange coefficients between a box and the surrounding environment, the model assumes that the volumes of the boxes (V_m and V'_m) remained unchanged from 2001 to 2010 during the calculated mean high water. These calculations are based on the volumes of the boxes, the river flows (Q_{rabu}, Q_{fkad}, Q_{fasu} and Q_{fgal}), the mean salinity of the boxes (S_m and S'_m) as a conservative tracer, and the time rate of change of salinity of the boxes (dS_m/dt and dS'_m/dt).

The model is used to estimate horizontal advective Q_m (seaward), Q'_m (landward)) and non-advective ($E_{m-1,m}$ (with the up-estuary box) and $E_{m,m+1}$ (with the down-estuary box) exchanges in two directions, vertical advective exchanges (Q_v) and non-advective vertical exchanges (E_v), by solving a system of linear equations describing the salt and water balance. Horizontal non-advective exchanges ($E_{m-1,m}$ and $E_{m,m+1}$) are assumed to be negligible compared to horizontal advective exchanges (Q_m and Q'_m), given that in the estuary there is a well-developed two-layer gravitational circulation, thus reducing the number of unknowns and making the equations solvable (Hagy et al., 2000). The exchanges that have been taken into consideration have been depicted in Fig. 1.

From the salt balance the vertical non-advective exchange (E_{vm}) is obtained and takes the form

$$E_{vm} = \frac{\left(V_m\frac{dS_m}{dt} + Q_mS_m - Q_{m-1}S_{m-1} - Q_{vm}S'_m\right)}{S'_m - S_m} \tag{1}$$

where S_m is the salinity of the box; S_{m-1} is the salinity in the adjacent up-estuary box; S_{m+1} is the salinity in the adjacent down-estuary box; S'_m is the salinity in the vertically adjacent box; Q_m is the seaward advective transport at surface to the adjacent down-estuary box, Q_{m-1} is the seaward advective transport at surface from the adjacent up-estuary box; Q_{vm} is the vertical advective transport into the box; Q'_m is the landward advection at the bottom to the adjacent up-estuary box; Q'_{m+1} is the landward advection at the bottom from the adjacent down-estuary box; Q_{fm} is the freshwater input into the box. The water balance for the surface and bottom boxes is $Q_m = Q_{m-1} + Q_{vm} + Q_{fm}$ and $Q_{vm} = Q'_{m+1} - Q'_m$.

For the rest of the calculations, equations (6) and (7) from Officer (1980), as used by Hagy et al. (2000), were utilized to introduce the variations in salinity and freshwater flow in each box, so that

$$Q_m = \frac{\left(S'_{m+1}\left[\sum_{j=1}^{m} Q_{fj} + Q_r\right] + \left[\sum_{j=1}^{m} V_j\frac{dS_j}{dt} + \sum_{j=1}^{m} V\prime_j\frac{dS'_j}{dt}\right]\right)}{S'_{m+1} - S_m} \tag{2}$$

Officer's (1980) equation to calculate landward advection is

$$Q'_{m+1} = Q_m - \left(\sum_{j=1}^{m} Q_{fj} + Q_r\right) \tag{3}$$

where Q_r is the river discharge at the head of the estuary and Q_{fj} are the freshwater flows of the rest of rivers that accumulate down-estuary (Q_{fm}). Terms are summarized and defined in Table 2.

Table 2
Definitions of terms for box model equations (eqs. (1)–(4)). The subscript "m" refers to model segment number. Terms refer to the surface layer boxes unless "prime" (e.g., V') is used, indicating that the term refers to the bottom layer box.

Term	Definition	Units
V_m, V'_m	Box volume at the calculated high water	m^3
S_m, S'_m	Mean salinity	None
Q_r	Freshwater inflow to surface waters at the head of the estuary	$m^3\ s^{-1}$
Q_{fm}	Freshwater inflow to surface waters from the rest of rivers (m) that accumulate down-estuary	$m^3\ s^{-1}$
Q_m, Q'_m	Advective flow out of a model segment. Flows are landward in the bottom layer	$m^3\ s^{-1}$
Q_{vm}	Vertical advection from the bottom layer to the surface layer	$m^3\ s^{-1}$
E_{vm}	Non-advective exchange rate between the bottom layer and surface layer	$m^3\ s^{-1}$

3.5. *Gravitational circulation and tidal exchanges*

The contribution of gravitational circulation exchange and tide-driven exchange to the transport of salt in estuaries is determined by the parameter υ (Shaha et al., 2010), which is the proportion of the tide driven fraction (F_{int}) to the total upstream salt flux (F) in an estuary, as described by Officer and Kester (1991) and Dyer (1997). For a segment (i) of the estuary, υ would be estimated as $\upsilon_i = F_{int\cdot i}/F_i$.· F_{int} represents the tidal exchange and is obtained as the intercept value at zero river flow of the plot of the flushing rate against the river discharge (Shaha et al., 2010).

The flushing rate F_i for a two-layer system with multiple segments is given as

$$F_i = \frac{R\left(\frac{S_{si}+S_{si-1}}{2}\right)}{S_{bi} - S_{si}} + R \tag{4}$$

where R is the river flow, S_{si} is the salinity of the upper layer and S_{bi} is the salinity of the bottom layer.

If υ approaches 1, the upstream transport of salt is entirely dominated by tide-driven processes. If υ is close to 0, up estuary salt transport is almost entirely by gravitational circulation.

3.6. *Turnover times*

Different methods have been used to estimate the replacement time of water in estuaries. In the present work two well-known simple estimators were used for comparative purposes:

(a) Flushing time ($T_f = V/Q$), is a bulk or integrative parameter that describes the general exchange characteristics of a water parcel, and was calculated as the volume of water in a defined (bounded) system (V) divided by the volumetric flow rate (Q) through the system (Monsen et al., 2002).
(b) Residence time (τ). We performed the box residence time calculations developed from two-layer box models by Officer (1980). The box residence times for the upper boxes (τ) and lower boxes (τ') were calculated as

$$\tau = \left(\frac{S' - S}{S'}\right)\frac{V}{R} \quad \tau' = \left(\frac{S' - S}{S}\right)\frac{V'}{R} \tag{5}$$

where S' is the average salinity of the lower box, S is the average salinity of the upper box, V is the volume of the upper box, V' is the volume of the lower box and R is the river discharge.

Both "flushing time" and "residence time", are conceived as measures of water-mass retention within defined boundaries (Monsen et al., 2002). Although it is important to highlight they are the result of different calculations, both serve to assign a time scale to the retention of a water body (Phelps et al., 2013). The usefulness of these simple models is limited when applied to a heterogeneous single-box framework. Volumes that are not well mixed need to be divided into sub-volumes that may be treated that way, but the method can easily be extended to multiple zones, because turnover times from individual zones are additive (Sheldon and Alber, 2006). Thus, in our study the models were applied to each of the water parcels defined for the two-layer box model explained in Section 3.2, and then to estimate turnover times for the entire portion of the estuary analysed in the present work (boxes 1–6 and 1′–6′), the channelized zone (boxes 1–5 and 1′–5′) and within the channelized zone for the surface layer (boxes 1–6) and the bottom layer (boxes 1′–6′), by the addition of the corresponding values. Because the lengths of the segments established in the box model were different, in order to compare the axial trends in turnover times, the values for each segment were normalized by dividing them by the length of the segment (days km^{-1}).

4. Results

4.1. Volumes

As shown in Table 1, the smallest volumes (around 1 × 10^6 m^3 in each box) and the smallest differences between the volumes of the upper and bottom layers were obtained for the narrower and shallower segments (boxes 1 and 2) of the inner estuary, where the channel bed usually presents v-shaped cross sections and the mean halocline depth is deeper than in the middle and outer estuary. The volumes of the boxes and the difference between the volumes of the upper and bottom (2–5 times higher in the bottom) layers increased in the middle and outer segments of the channelized zone, where the width and depth of the channel increase seaward and the mean halocline depth is shallower. In the segment corresponding to the inner Abra harbour (box 6) the water volume is larger than in the entire channelized zone (54.05 × 10^6 and 16.45 × 10^6 m^3, respectively), and the upper box contains only 13.5% of the total volume.

4.2. River flow and salinity

The monthly mean river flow values of the main tributaries of the estuary of Bilbao during the 2001–2010 period (Fig. 2) show that the highest freshwater inputs occur at the head of the estuary by the joint discharge of the Ibaizabal and Nerbioi rivers that represents on average 66% of the total inputs, while the discharge of the Kadagua river in the middle estuary is 27%. The downstream contribution of Asua and Galindo streams together was on average 7%. All the tributaries showed the seasonal regime characteristic of our climatic region, with the highest discharges (around 37 m^3 s^{-1} from the Ibaizabal-Nerbioi and around 18 m^3 s^{-1} from the Kadagua) from January to March and the lowest (around 4.5 m^3 s^{-1} from the Ibaizabal-Nerbioi and around 1.5 m^3 s^{-1} from the Kadagua) from July to October. Whilst the contribution of the Ibaizabal-Nerbioi system fluctuated between 75% and 60% without a clear seasonal pattern of variation, the contribution of the Kadagua river showed a seasonal pattern with the highest values (around 31%) in the January–March period and the lowest values (around 21%) in the August–October period, rather opposite to that observed for the Asua and Galindo streams.

The monthly mean salinities calculated for the boxes of the two-layer model of the estuary of Bilbao during the 2001–2010 period (Fig. 2) illustrated the almost permanent condition of salt wedge in the system, with a much larger spatial and seasonal variability of salinity in the upper layers than in the bottom layers. In the upper layers mean salinity ranged between 1 in February and 12 in August in the innermost segment and from 21.5 in January to 32.5 in October in the outermost segment (inner Abra harbour), whereas in the bottom layers it ranged from 20.5 in January to 31 in August–September in the innermost segment and from 33.5 in January to 35 in September–October in the outermost segment. Bottom layers were euhaline (>30 salinity) in the entire estuary in the summer-late summer period and from the middle estuary outwards all the year.

4.3. Net physical transport

The estimates of mean advective and non-advective exchange coefficients for each month of the 2001–2010 period have been shown in Fig. 3. Seaward advective flows in surface and landward advective flows in bottom showed quite regular patterns of spatial and seasonal variation. Both increased from the innermost segment (box 1) to the outermost segment (box 6), but seasonal patterns of seaward advection, with highest values in winter and lowest values in summer, showed a greater parallelism amongst the different boxes along the entire estuary than seasonal patterns of landward advection. Landward advection in the outermost segment decreased from winter to summer, similarly to what was observed for seaward advection, but in the innermost segment minimum landward advection was obtained in winter (February) and maxima landward advection in late autumn–early winter. The less defined seasonal patterns of landward advection occurred in the middle channelized zone of the estuary (box 3).

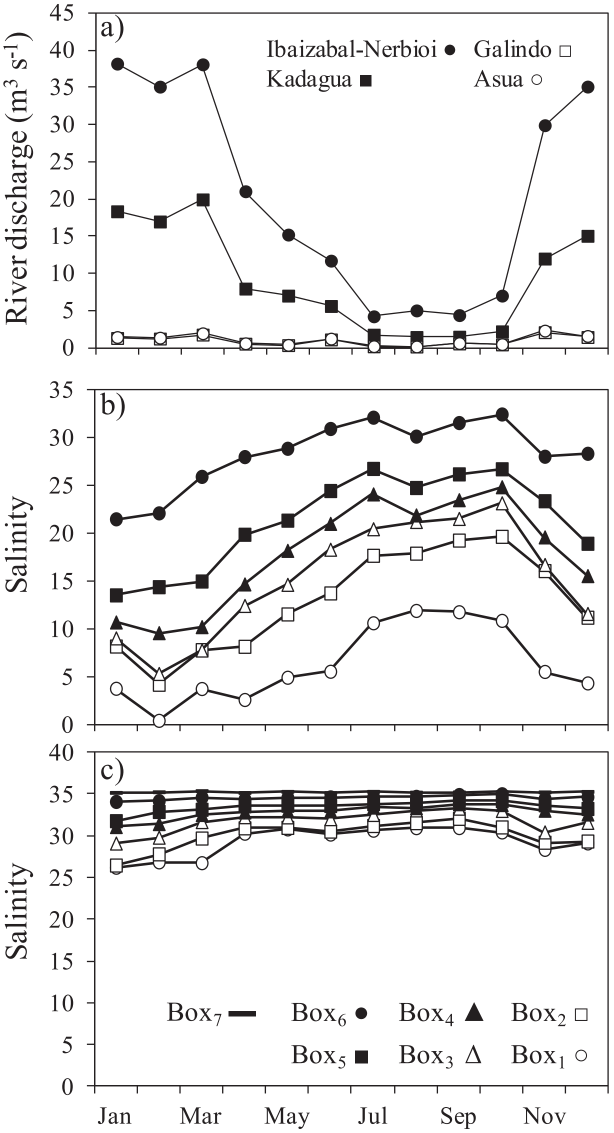

Fig. 2. Monthly freshwater inputs (m^3 s^{-1}) from the main tributaries (a), and monthly mean salinity in the upper (b) and bottom (c) boxes of the model for the 2001–2010 average year in the estuary of Bilbao.

Vertical advection and non-advective exchange also showed a decrease from the outer to the inner estuary, but spatial and seasonal variability did not show the regularity between segments observed for seaward and landward advections. Seasonal patterns of vertical advection showed a certain parallelism with those of landward advection, this being much more evident in the outermost and the innermost segments. Non-advective exchange, however, did not show clear patterns of temporal variation and increased abruptly in January in all the segments.

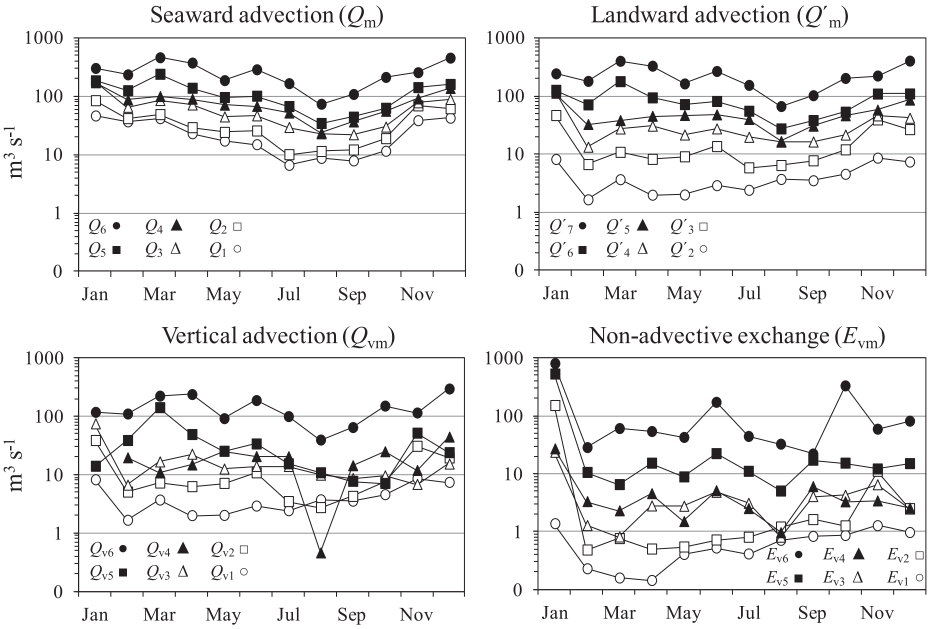

Fig. 3. Monthly mean variations of the exchanges coefficients of seaward advection (Q_m), landward advection (Q'_m), vertical advection (Q_{vm}) and vertical diffuse exchange (E_{vm}) estimated for the 2001–2010 average year in the estuary of Bilbao.

The results of the correlation analysis of advective flows and non-advective exchange with freshwater flow and salt flow from the sea (Q'_7) shown in Table 3 indicate that seaward advection was strongly related to freshwater flow in the segments of the channelized zone (boxes 1–5), and to a lower extent in the outermost segment (box 6). By contrast, in the latter segment seaward advection showed a stronger relationship with salt flow from the sea than with freshwater flow, whereas in the segments of the channelized zone the relation of seaward advection with salt flow was weak. Landward advection was found to be related to both freshwater flow and salt flow from the sea only in the outermost segment (box 6). This segment was the only one where vertical advection showed a strong relationship with salt flow from the sea.

4.4. Gravitational circulation and tidal exchanges

The plots of flushing rate against river discharge (Fig. 4) and the values of the estuarine parameter υ calculated for each month during 2001–2010 (Fig. 5) revealed that gravitational circulation exchange dominated entirely the transport of salt during the entire annual cycle in all the estuarine segments. However a clear seasonal pattern was observed in the contribution of both mechanisms, since the contribution of tide driven dispersive flux of salt increased from winter to summer with a maximal contribution of 0.42 (42%) in the outermost segment (box 6 in the Abra) in August. However, the role of tidal exchange was almost negligible ($\upsilon < 0.1$) in the segments of the outer channelized zone of the estuary (boxes 4–5) all the year. Spatially, the highest contribution of tide driven dispersive flux of salt occurred in the outermost segment, whereas in the channelized zone it was lower in the outer segments than in the inner segments, but with the highest values in the middle segment (box 3).

4.5. Turnover times

The mean flushing time of water in a bounded water body calculated for each month during 2001–2010 and for each of the boxes of the two-layer box model of the estuary showed larger differences between surface and bottom layers than horizontally or seasonally (Fig. 6). In surface boxes values ranged between 0.05 and 1.14 days, with most values below 0.4 days, whereas in bottom boxes it ranged between 0.25 and 8.12 days, with most values higher than 0.4 days. A clear seasonal pattern with maxima in summer and minima in winter was observed both for surface and bottom boxes, except in the bottom box of the innermost segment where the highest values were obtained in winter and spring. The

Table 3
Correlation values and *p*-values (in parentheses) between the different advective coefficients (Q_m, Q'_m and Q_{vm}) and total freshwater flow (Q_{fw}) and salt flow from the sea (Q'_7). Significant correlations in bold.

Seaward advection	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6
Q_{fw}	**0.99 (<0.0001)**	**0.89 (<0.0001)**	**0.81 (0.001)**	**0.85 (<0.0001)**	**0.92 (<0.0001)**	**0.75 (0.005)**
Q'_7	**0.66 (0.019)**	0.55 (0.065)	0.51 (0.087)	**0.87 (0.018)**	**0.83 (0.001)**	**0.99 (<0.0001)**
Landward advection		Q'_2	Q'_3	Q'_4	Q'_5	Q'_6
Q_{fw}		0.45 (0.140)	0.57 (0.052)	0.53 (0.078)	0.57 (0.056)	**0.85 (0.001)**
Q'_7		0.27 (0.401)	0.29 (0.355)	0.27 (0.405)	0.47 (0.125)	**0.83 (0.001)**
Vertical advection	Q_{v1}	Q_{v2}	Q_{v3}	Q_{v4}	Q_{v5}	Q_{v6}
Q_{fw}	0.45 (0.140)	**0.59 (0.045)**	0.41 (0.188)	−0.06 (0.849)	0.57 (0.052)	0.48 (0.112)
Q'_7	0.27 (0.401)	0.29 (0.355)	0.20 (0.530)	0.33 (0.289)	**0.63 (0.029)**	**0.95 (<0.0001)**

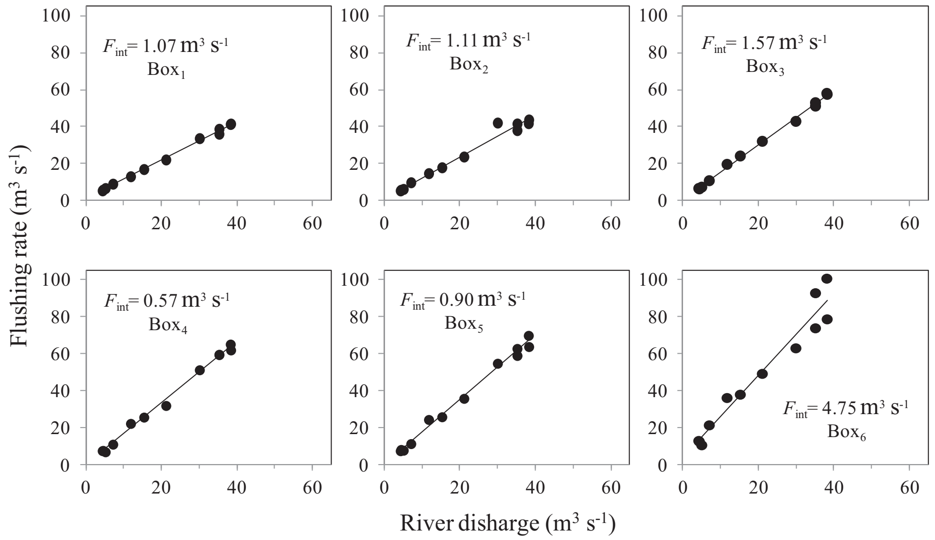

Fig. 4. Relationships between flushing rate (F) and river discharge for each box of the estuary of Bilbao for the 2001–2010 period. F_{int} (the intercept value) indicates the tidal exchanges.

addition of individual box values gave flushing times ranging from 5 days in winter (January) to 21.5 days in summer (August) for the entire portion of the estuary we studied, and from 2.5 days in winter (January) to 12.2 days in summer (August) for the channelized zone. Within this zone, however, flushing time ranged from 2.1 days in January to 9.8 days in August in the bottom layer, and from 0.4 days in January to 2.4 days in August in the upper layer. Spatially, when the flushing time of the boxes was corrected for the length of each segment, the highest value corresponded to the outermost segment (box 6), and within the channelized zone to the middle segment (box 3).

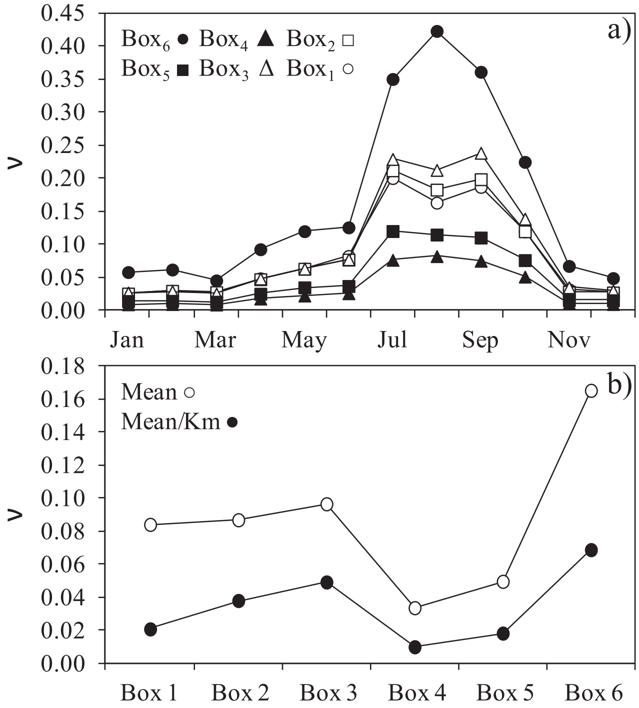

Fig. 5. Seasonal variation of the estuarine parameter ν (explanation in Methods section) of the segments of the estuary of Bilbao (a), and spatial variation of the annual mean ν values corrected for the length of each segment (b). The estimates are for the 2001–2010 average year.

The box residence time (Fig. 7) showed higher differences between surface and bottom layers than spatially or seasonally, in agreement with what was observed for the flushing time. In surface boxes values ranged between 0.08 and 1.57 days, with most values below 0.6 days, whereas in bottom boxes it ranged between 0.3 and 11.6 days, with most values higher than 0.6 days. Similarly, a clear seasonal pattern with maxima in summer was observed both for surface and bottom boxes, except in the bottom box of the innermost segment where the highest values were obtained in winter and spring. The residence time for the entire estuary ranged from 6.0 days in autumn (November) to 28.6 days in summer (August), whereas for the channelized zone it ranged from 3.6 to 15.6 days in November and August respectively. In the channelized zone, residence time ranged from 3.0 days in November to 12.6 days in July–August in the bottom layer, and from 0.5 to 3.0 days respectively in the upper layer. Spatially, and corrected for the length of each segment, the residence time of both the upper and bottom boxes was highest in the outermost segment (box 6), and within the channelized zone in the middle segment (box 3).

5. Discussion

The two-layer box model constructed for the estuary of Bilbao was useful to obtain an estimation of the bulk water transport and turnover times at spatial (horizontal and vertical) and temporal (seasonal) scales of higher resolution than those provided in previous works (García-Barcina, 2003; Valencia et al., 2004). Relaxing the common assumption that salinity remains constant allowed the model to reveal independent dynamics of river flow and saline inflow in the estuary and to reproduce the essential features of a typical 2-layer gravitational circulation in estuaries (Hagy et al., 2000). Moreover, the integration of 10-year data in the model allowed us to obtain a standardized picture of the spatial and seasonal patterns of water transport and turnover for the estuary of Bilbao. It reduces the bias induced by single-year data in the seasonal pattern of this estuary, in which river discharge regime shows noticeable inter-annual variability (Aravena et al., 2009; Intxausti et al., 2012).

According to the annual cycle of net water flow, water renewal and salinity shown by our results, winter (January–March) is characterized by the highest seaward flow and the shortest

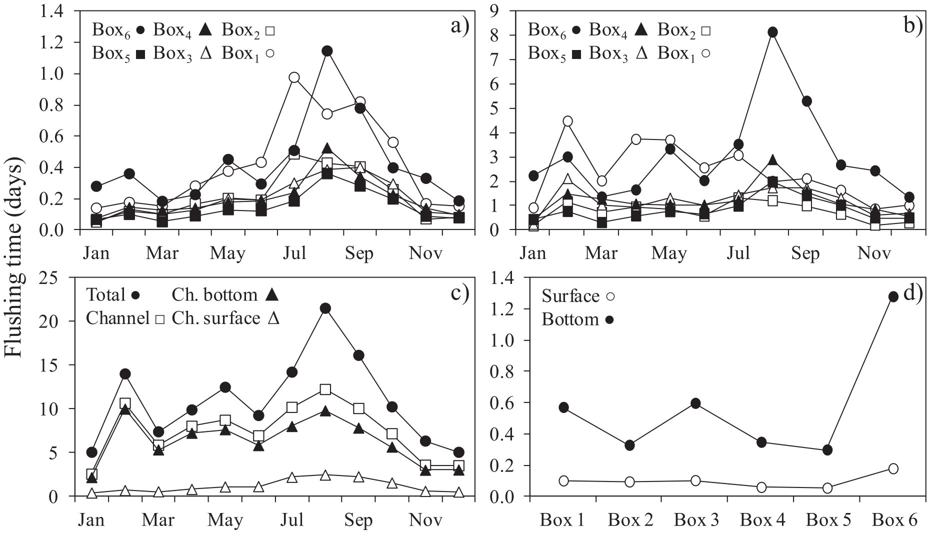

Fig. 6. Seasonal variation of flushing time in surface boxes (a), bottom boxes (b), and in the entire estuary, the channel, the upper layer of the channel and the bottom layer of the channel (c) of the estuary of Bilbao. Spatial variation of the annual mean flushing time in the surface and bottom layers normalized for the length (days km^{-1}) of each segment (d). The estimates are for 2001–2010 average year.

turnover time in the upper layer of the entire estuary, this coinciding with the lowest salinities and a salt transport almost entirely driven by gravitational circulation, as a result of the highest river discharges in this season. The saline inflow at the bottom is higher in winter than in other seasons in the outer part of the estuary, but in the innermost part the water inflow and renewal in the bottom layer was lower than in other seasons. This agrees with the retention of freshwater in bottom layers of the inner estuary when the euhaline (>30 salinity) water body is displaced seaward and forms a vertical front in the winter. This occurs because the usually stratified areas of the upper estuary become tidal-fresh and non-stratified under very high flow conditions. The main features of the spring period (April–June) are the maintenance of high saline inflows in the outer zone, low landward advection in the innermost zone and low residence times in bottom layers; tide-driven processes gain in relevance, seaward advection decreases and turnover times increase in the upper layer. These occur at a time when river discharge decreases and euhaline waters move upstream in the bottom layer. Summer (July–September) conditions are the opposite of those described for winter. In summer, seaward flow reaches annual minima, turnover time and the relevance of tide-driven processes reach annual maxima, euhaline waters penetrate until the innermost segment and salinity reaches annual maxima within the estuary, all this coinciding with the annual minima of freshwater inflow. Except in the innermost segment, where the penetration of euhaline waters in bottom increases, the bottom-layer inflows reach minima in summer. It is well known that the two-layer circulation of water in estuaries may be weakened and the inflows of offshore bottom water may be reduced in the absence of sufficient freshwater inflow (Olsen et al., 2006), and this can cause the estuary to be poorly flushed with seawater during the dry periods (Manoj, 2012). During the autumn, in general, seaward advection, landward advection, vertical advection and water renewal both in upper and bottom layers increase, and the contribution of tide-driven processes and salinity decrease in relation to the increase of freshwater inflows to the estuary.

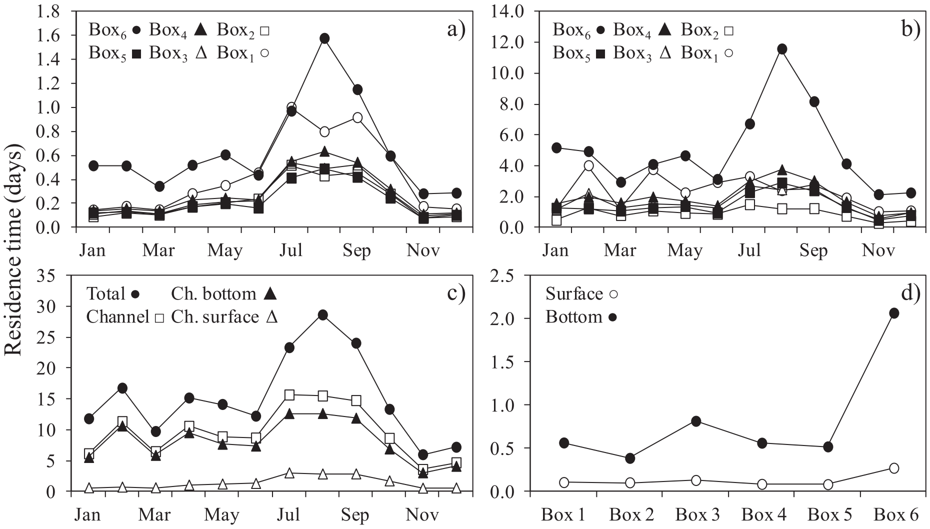

Fig. 7. Seasonal variation of residence time in surface boxes (a), bottom boxes (b), and in the entire estuary, the channel, the upper layer of the channel and the bottom layer of the channel (c) of the estuary of Bilbao. Spatial variation of the annual mean residence time in the surface and bottom layers normalized for the length (days km^{-1}) of each segment (d). The estimates are for 2001–2010 average year.

These results suggest that the fluvial regime plays a key role governing the spatio-temporal variation of water circulation and renewal, and the salinity distribution over the annual cycle in the estuary of Bilbao. Although both river flow and tidal rhythm may affect the spatial and temporal variability of salinity and water turnover in estuaries (e.g. Shaha et al., 2010, 2012; Shivaprasad et al., 2013), our work does not take into consideration the effect of tides because the sampling for salinity data was conducted preferentially at neap tide, and the volumetric approach for the model was that corresponding to this tidal condition. However, the possible changes induced by tides in the seasonal pattern of the estuary of Bilbao should be negligible in the light of the results obtained by García-Barcina (2003) who compared residence times for combined standard conditions of river flow (low or mid flow) and tide (neap or spring). River flow made a high contribution to the water turnover of the estuary of Bilbao and this has also been observed in other estuaries, such as the Mondego (Kenov et al., 2012). The importance of establishing the functional relationship between estuarine flushing time and river discharge in estuaries is widely recognized (Cifuentes et al., 1990; Asselin and Spaulding, 1993; Alber and Sheldon, 1999), because the variation in freshwater volume and discharge make flushing time highly variable from estuary to estuary (Manoj, 2012).

The dominance of gravitational circulation exchange throughout the annual cycle in the entire portion of the estuary we studied is in agreement with the stratified condition of the estuary of Bilbao. The dominance of either gravitational or tidal exchange is a feature that allows to distinguish stratified systems from well-mixed systems, with weak stratification where water exchange is dominated by tidal forcing (Gillibrand et al., 2013).

The maximum values of 12.2 days and 15.6 days obtained for the flushing time and the residence time, respectively, of the channelized zone in summer in our study are not very dissimilar to the values of around 10–12 days of residence time obtained by García-Barcina (2003) in the same zone for low river flow conditions and neap tide. However, in the latter work residence times calculated separately for surface and bottom layers were similar, whereas in the present work bottom layer values (9.8 and 12.6 days, respectively) got a little closer to those estimated by García-Barcina (2003), but surface layer values were significantly lower (2.4 and 3.0 days, respectively). This kind of disagreements in the results may be expected when different methods of estimation are used, but they should be clarified in order to typify the system and for comparison with other estuaries.

Residence times estimated for the entire zone analysed (70.5×10^6 m^3) and for the channelized zone (16.45×10^6 m^3) were of 6–28.6 days and 3.6–15.6 days, respectively. These can be considered as rather similar values which occupy a mid position within the wide range of 0.3–127 days reported from 31 small Danish estuaries with volumes between 0.1 and 3800×10^6 m^3 by Rasmussen and Josefson (2002). In the Basque coast, however, the estuary of Bilbao is one of the systems with a higher volume and flushing time (Valencia et al., 2004).

Regarding the axial variability, results indicate that river flow had a strong effect on the surface-layer outflow of the entire estuary, even in the Abra harbour portion (box 6) of the lower estuary, in contrast to what has been observed in other estuaries where the circulation in the lower basin shows a weak dependence on river flow (Hagy et al., 2000). The landward bottom-layer inflow from the outer Abra had a strong effect on the vertical advection and the surface-layer outflow of the inner Abra (box 6), but surprisingly it was not significantly correlated with the bottom-layer inflow and the vertical advection through the channelized zone. This reflects a discontinuity between the bottom-layer inflows to the inner Abra and the bottom-layer flows to the channelized zone from the inner Abra, likely due to the strong rise of the estuary floor together with the drastic reduction of the basin width from the Abra to the channelized zone. While landward and vertical advection were uncorrelated or weakly correlated with river discharge and bottom-layer inflow from the Abra to the channelized zone, these results suggest more complex interactions between seaward, landward and vertical flows than in the inner Abra.

The inner Abra segment also showed a higher contribution of tide-driven processes and a longer turnover time than comparable segments of the channelized part. Within this latter portion of the estuary, the middle segment (box 3) showed the highest contribution of tide-driven processes and the lowest water turnover, this probably being related to the presence of the dead channel of Deustu, which is isolated from the two-layer dominant circulation of the main channel, and would cause a reduction of gravitational effects and favour water retention. The higher contribution of tide-driven processes in the innermost segments (boxes 1–2) of the channelized zone in relation to the outermost segments (boxes 4–5) may be accounted for by differences in the channel morphology and in the regularity of the estuarine bed and shores. The outer channel is quite straight, U-shaped and mostly with smooth walls, whereas the inner channel is narrower than the outer one, meandering, predominantly V-shaped, with irregular cross sections, and more complex lateral structures. Therefore, increased friction can be expected in the inner channel, which would enhance mixing processes during the rise and fall of the tide.

Residence times obtained for the channelized zone, which includes all the salinity habitats of transitional systems, from freshwater to euhaline waters, are clearly lower than those reported for the transitional zones of several well mixed large European estuaries. For instance, residence time can be as long as about 40 days in the freshwater zone of the Elbe and 50 days in the polyhaline zone of the Scheldt in summer (Geerts et al., 2012), and 70 days in the Gironde (Jouanneau and Latouche, 1981). Limnetic to polyhaline habitats of the estuary of Bilbao are usually confined to the upper layers of the channelized zone (boxes 1–5), and therefore maximum residence times for these salinity habitats (<2 days) are one order of magnitude lower than those of the abovementioned well mixed large estuaries. However, values for the entire studied zone (6–28.6 days), or even the channelized zone (3.6–15.6 days), indicate that residence times in the estuary of Bilbao are higher than those reported for stratified large European estuaries such as the Rhine and the Douro estuaries (2–7 days) (Middelburg et al., 2002). This emphasizes the importance of river discharge on the renewal of water in stratified systems, since both the Rhine and the Douro are river-dominated systems (Middelburg et al., 2002), whereas the estuary of Bilbao may be considered a sea-dominated system.

Axially, turnover time increased abruptly in the outermost box as a result of the sharp increase in width, depth and volume of the estuarine basin from the channelized zone to the Abra harbour, but within the channelized zone no clear spatial trends were observed when flushing and residence times were normalized for the length of each box. Inter-estuarine comparisons of residence times along the estuarine gradient between similarly well-mixed, long-residence time estuaries (Elbe, Weser, Scheldt and Humber) have shown that, after normalization for length per zone, residence times are higher in the oligo- and mesohaline zone for all them (Geerts et al., 2012). In our case, however, because of the high stratification, the segregation of saline zones occurs vertically rather than longitudinally and the residence time of oligo- and mesohaline water-masses located in the upper layers show much lower residence times than poly- and euhaline waters that can be found in bottom layers along most of the estuary and in the surface layer in the outermost zone.

The results on estuarine net transport and turnover times obtained in this study are useful to corroborate intuitive interpretations and conclusions drawn in previous studies conducted in the estuary of Bilbao about the role of estuarine circulation and turnover rates on the spatial and temporal variability of environmental water conditions and plankton (Aravena et al., 2009; Iriarte et al., 2010; Villate et al., 2013).

Recent analyses of the dissolved oxygen dynamics at seasonal and inter-annual scales in this estuary showed that in spite of the overall improvement of oxygenic conditions during the rehabilitation process, the summer development of hypoxia in bottom waters of around 30 salinity of the inner estuary remained, as a result of inherent hydraulic properties of the system that involved stratification and water turnover (Villate et al., 2013). The present study allows to clarify the process by which reduced water circulation and turnover promotes hypoxia in bottom waters of the 30 salinity zone in summer, since water masses of 30 salinity show highest turnover and move seawards during the period of highest river discharge in winter, but move upstream with decreasing river flow, occupy the innermost position and show the lowest turnover in summer. The seasonal pattern of the bottom-layer inflow, which reaches the annual minimum value in summer (August), also contributes to explain the observed seasonal cycle of dissolved oxygen in water masses of 30 (Fig. 8). Landward advection of bottom waters can be a significant source of O_2 to bottom waters in stratified estuaries (Kuo et al., 1991; Kemp et al., 1992), particularly if the water entering the landward flow is well-oxygenated and if the velocity is high (Hagy and Murrell, 2007). In the estuary of Bilbao, water entering in bottom layers from the Abra is well oxygenated in summer (Villate et al., 2013) but the present results show that the bottom inflow in summer is weak and this slows down the replenishment and favours the depletion of oxygen upstream in the estuary. Reduced advection in the bottom layer during summer has also been found to reduce the potential O_2 transport and increase the susceptibility to hypoxia in other systems (Hagy and Murrell, 2007).

Regarding organisms, those living in habitats with unidirectional net water movement such as estuaries have to face the problem of how to avoid being swept downstream and out into habitats where the physical or biotic environment is not appropriate for their growth and reproduction. The difference between a population that is washed out and one that persists in estuaries depends only on the low-density growth rate (Speirs and Gurney, 2001). In the case of the phytoplankton of estuaries, where the limitation by nutrients rarely occurs, the standing stock is mainly governed by mixing and transport processes (e.g. Costa et al., 2009). High river discharge leads to reduced residence time, this leading to increased flushing of phytoplankton biomass out of the estuary (Lane et al., 2007), with a great effect in surface layers where increased flushing may result in a jointly decrease of chlorophyll concentration and salinity (Shivaprasad et al., 2013). This seems to occur in the estuary of Bilbao, which undergoes noticeable changes of salinity and high water renewal in the upper layers over the entire annual cycle. In bottom layers, the seasonal variations of the standing stock of phytoplankton in the estuary of Bilbao (Iriarte et al., 2010) also agree with those observed for the water turnover in this study, since highest chlorophyll concentrations have been observed in summer coinciding with the lowest water turnover (Fig. 8) along the entire estuary.

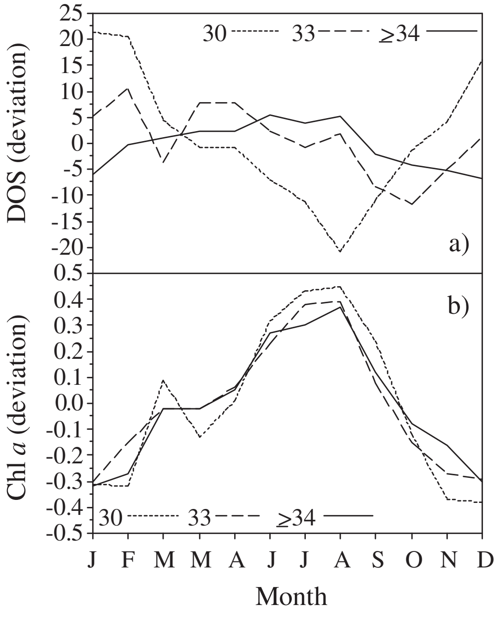

Fig. 8. Seasonal variation (in terms of deviation) of dissolved oxygen saturation (DOS; a) and chlorophyll *a* (Chl *a*; b) in salinity zones of ≥34, 33 and 30 of the estuary of Bilbao.
From Iriarte et al. (2010).

Another interesting effect of water flow and turnover on phytoplankton is that they modulate the interaction of phytoplankton with environmental factors. For instance, an analysis of fitted parameters across estuaries showed that chlorophyll sensitivity to total nitrogen loading correlated positively with water residence time (Evans and Scavia, 2013).

Zooplankton growth rates are lower than phytoplankton growth rates, and this may result in a smaller capacity of the former to make up for population losses due to washing, and to maintain themselves in the optimal habitat. However, estuaries with two-layered bidirectional net water displacement allow the persistence of zooplankton populations able to remain in bottom layers or to move vertically in the water column and utilize alternatively bottom landward transport and surface seaward transport to maintain their position in the required habitat (Wooldridge and Erasmus, 1980; Kimmerer et al., 1998; Ueda et al., 2004). The observations on zooplankton in the estuary of Bilbao suggest that surface flushing might be excessive to allow the development of typical true estuarine populations such as those of *Eurytemora* species in oligohaline-mesohaline waters of the upper layer. This is supported by the fact that *Eurytemora* species have not colonized the estuary during the recent process of estuarine recovery (Albaina et al., 2009), while the eurihaline species *Acartia tonsa* colonized successfully the inner estuary and showed unusual high densities in bottom layers in summer (Aravena et al., 2009). The comparison with large European estuaries corroborates that the hydrodynamical conditions of the estuary of Bilbao differ largely from estuaries inhabited by abundant true estuarine zooplankton communities dominated by *Eurytemora* species, as it is the case of the Ems-Dollard, the Westerschelde and the Gironde estuaries (Sautour and Castel, 1995). Moreover, zooplankton abundance in the channelized zone shows stronger differences between surface and bottom layers than along the estuarine axis. The high seaward net transport and low turnover time obtained in the upper layer of the channelized zone would be responsible for the scarcity of zooplankton in this layer, whereas the net upward transport and higher turnover times favour the development and retention of populations within the estuary below the halocline.

6. Conclusions

The two layer box model used in the present study enabled us to estimate water flows and turnover times with a higher spatial and temporal resolution than before for the estuary of Bilbao, and to obtain a reliable picture of the standard seasonal and spatial patterns of variation of these hydraulic parameters. In the inner Abra (lower estuary) seasonal variations of surface-layer outflow, vertical advection and bottom landward flow were found to be mainly driven by the bottom-layer salt-water inflow from the outer Abra. In contrast, in the channelized zone, which extends from the inner Abra harbour to the tidal limit, seasonal variations of surface-layer outflow were driven by river discharge, whereas those of the bottom-layer inflow and vertical advection seemed to respond to more complex interactions. This may be attributable to a great extent to morphological differences between the two zones. Gravitational circulation exchange dominated in the entire portion of the estuary we analysed over the annual cycle, but the contribution of tide-driven exchange increased in summer. Water turnover time increased in all the segments of the estuary in summer, in agreement with the joint decrease of river flow and bottom-layer inflow from the outer Abra harbour, but high discharges in winter resulted in low water turnover in bottom layers of the upper reaches due to the accumulation of freshwater upstream of the saltwater front. In the channelized zone water turnover time in the upper layer was remarkably lower than in the bottom layer. These results provide us with new insights to explain relevant abiotic and biotic processes and temporal changes in the plankton ecosystem of this system. They could also potentially be used to run biophysical models to allow the water quality and biotic resources to be predicted. This is an important area for future research that would be hugely beneficial for the future management of this estuary.

Acknowledgements

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