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# An assessment of transport timescales and return coefficient in adjacent tropical estuaries

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ABSTRACT

Transport timescales (TTS), namely residence time and exposure time, were computed for adjacent shallow meso-tidal tropical estuaries system using the Lagrangian model D-Waq Part coupled with the hydrodynamic model Delft3D-Flow, and the Constituent-oriented Age and Residence time Theory, CART. The main results are threefold: (a) The TTS differs more between releases at high or low tide than between those at spring and neap tides. The exposure time was also calculated and found to be larger than the residence time by a few days. (b) The exposure and residence times were used to evaluate the return coefficient ($r$) for different scenarios. As with residence and exposure times, the return coefficient was found to differ more between releases at high or low tide than between those at spring and neap tides. (c) For the Caravelas Estuary, where the river inflow was low ($\sim 4\ m^3\ s^{-1}$), the residence time was found to be much larger than for the Peruípe Estuary, where the river discharge was greater and nearly constant during the sampling period ($\sim 20\ m^3\ s^{-1}$). These results shows the importance of advection in decreasing TTS in the Peruípe Estuary compared to the Caravelas Estuary. The influence of the advection and dispersion agrees with previous simple estimates obtained using the newly modified Land Ocean Interaction Coastal Zone (LOICZ) model by Andutta et al. (2014).



## 1. Introduction

Since the dynamics of most estuarine systems is relatively complex, studies of transport timescales (TTS) provide valuable insight into estuarine behaviour. Transport timescales represent a more holistic way of interpreting the flow in complex systems (e.g. Monsen et al., 2002), and allow us to understand how advective and dispersive mechanisms transport water.

Transport timescales are driven by the water currents, which in turn are influenced by sea level oscillation, bathymetry and the temperature and salinity fields. It is therefore necessary to have an accurate representation of these quantities in order to satisfactorily estimate transport timescales.

This article has the following tasks:

(1) to demonstrate, using a 3D hydrodynamic model combined with particle simulations, how release times (e.g. slack waters of high and low tides, neap and spring tides) affect the exposure time and residence time in a shallow meso-tidal tropical estuary.
(2) to compare TTS results from numerical modelling with estimates using the simple newly modified Land Ocean Interaction Coastal Zone (LOICZ) model by Andutta et al. (2014).
(3) to calculate and evaluate the return coefficient ($r$) numerically and analytically using CART. This is a measure of the propensity of a water parcel to return into the domain of interest after leaving it.

### 1.1. Overview of transport timescales

Since the pioneering work by Ketchum (1951) and Bolin and Rodhe (1973), the theory of TTS has evolved (e.g. CART, www.climate.be/cart), and other TTS definitions have been introduced in order to fill scientific gaps. Therefore, there are many different

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transport timescale definitions, e.g. flushing time (Ketchum, 1951; Fischer et al., 1979; Monsen et al., 2002), residence time (Bolin and Rodhe, 1973; Monsen et al., 2002; Delhez et al., 2004; Deleersnijder et al., 2006), exposure time (Monsen et al., 2002), transit time (Holzer and Hall, 2000), influence time (Delhez et al., 2014), age (Bolin and Rodhe, 1973; Monsen et al., 2002), e-folding flushing time (Monsen et al., 2002), turnover time (Sheldon and Alber, 2006) and renewal time (Andutta et al., 2014) – all of which have their own interpretation.

Two timescales, residence time and exposure time, are used to provide an indication of increase or decrease of non-reactive and reactive substances in estuaries, bays, lagoons, and atolls (Andutta et al., 2014). The residence time ($\Theta$) is the time needed for a particle constituent to reach for the first time an open boundary of the domain of interest (e.g. Delhez et al., 2004). The exposure time ($\varphi$) is the time the particle will stay in the domain (e.g. Monsen et al., 2002) (Fig. 2). Therefore, at a given time and location, the exposure time is always larger than or equal to the residence time. The larger the difference between the two timescales, the more often the particles tend to re-enter the domain of interest after leaving it for the first time. To evaluate the exposure time, the computational domain must be larger than the domain of interest (de Brauwere et al., 2011; de Brye et al., 2012). Estimates of these timescales may be obtained in an Eulerian or a Lagrangian framework. The latter often requires sufficiently large number of numerical particles in order to provide a result that statistically approaches the real condition.

A dimensionless return coefficient, $r$, represents the propensity of particles to return into the estuary after reaching an open boundary for the first time, as illustrated in Fig. 1A (de Brauwere et al., 2011). It is defined as the relative difference between $\varphi$ and $\Theta$, i.e.

$$r = \frac{(\Theta - \varphi)}{\Theta}. \tag{1}$$

Clearly, this coefficient lies in the interval [0,1].

The larger the $r$ the more likely it is that particles will re-enter the estuary after crossing one of its open boundaries for the first time. Accordingly, particles that never return into the estuary have $r=0$, while particles returning often or for long periods of time have $r$ close to unity.

### 1.2. Chosen estuary and coastal area

The domain of interest is the estuarine System of the Caravelas and Peruípe Rivers (ESCP), in southern Bahia state, Brazil (see Fig. 2); more details may be found in Appendix 1. It is located at the approximate latitude of 17°50′S, nearly 60 km from the National Maritime Park of Abrolhos, which is one of the largest reef structures of the Atlantic ocean, providing habitat for innumerous marine species. The ESCP has two main mouths: the Caravelas Estuary in the north (17°45′S), with two small channels named Barra Velha (~1 km wide) and Tomba's Mouth (~600 m wide),

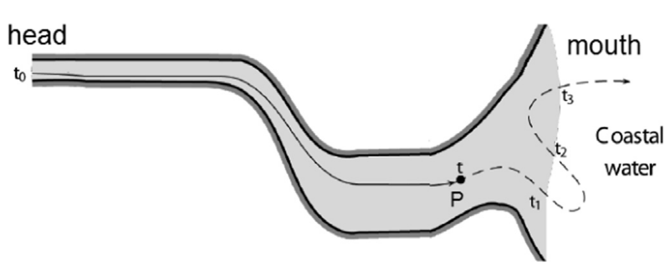


**Fig. 1.** Path of a particle in the estuary from the upstream boundary (head) to the downstream boundary (mouth). For a particle initially at position P at time $t$, the residence time is $t_1$–t, the exposure time is $(t_3 - t_2) + (t_1 - t)$.

and the Peruípe Estuary in the south (17°54′S) with a funnel shape ranging in width from ~3500 m to ~700 m in the first few hundred meters. These two mouths are separated by a distance of ~25 km alongshore, and are internally connected by shallow and narrow channels around Cassurubá or Cassumba Island. Our simulations consider the domain shown in Fig. 1C, for which results were computed according to the number of particles in the control domain with boundaries $\omega_1$ and $\omega_2$.

## 2. Methods

### 2.1. Numerical model

The ESCP comprises a number of channels varying significantly in width, from 60 m upstream to 1000 m near the mouth, and thus a high resolution mesh is necessary to resolve the many small channels in the domain. The numerical model used is the curvilinear-mesh, three-dimensional Delft3D-Flow from Deltares (www.deltares.nl). This model is hydrostatic, and its equations are solved by the method of finite differences (Delft Hydraulics, 2008). A curvilinear mesh is appropriate for the domain, although there are some disadvantages in the horizontal resolution distribution compared to unstructured meshes. Delft3D's curvilinear mesh is efficient in minimizing noise due to the steps in the horizontal plane, and allows the mesh cells to follow the channels more easily compared to non-curvilinear quadrangular meshes. The degree of non-orthogonality between mesh elements is always smaller than 0.02 thus satisfying the criteria ($\cos\pm < 0.02$), which helps to preserve numerical stability of the simulations (Delft Hydraulics, 2008). The diagonal horizontal resolution ranges from ~20 m to ~300 m. The number of quadrangular mesh cells on the horizontal plane is 22,928. A lower resolution is applied in the coastal region ~[130–300] m, but this is increased toward the coast and the estuary ~[20–100] m (Fig. 1B). The refined mesh within the estuary combined with high water speeds requires the time-step to be relatively small (around 1 s), to satisfy the Courant–Friedrichs–Lewy condition. The mesh used in the simulations of the ESCP (Fig. 1B) is relatively complex, covering a small part of the Peruípe River, near the city of Nova Viçosa. This river is the main channel connecting the northern and southern mouths. The main tributaries of the Caravelas River, namely the Cupído and Jaburuna Rivers, are covered by the mesh. With 10 equally spaced sigma vertical layers, this mesh also covers a few kilometers of the adjacent coastal region.

The bathymetry in the estuarine channels was obtained using an Echo sounder and Global Position System. Two tide gauges were installed in Caravelas and Nova Viçosa (see locations A and C in Fig. 2), meant to remove the tides from the Echo sounder data. For the Peruípe River estuary, the bathymetry was measured only in the first 6 km, near anchor station D. Thus an extrapolation was applied, considering the depth to be 4 m for the next 14 km along the Peruípe River. The bathymetry was combined from these sources, and the triangular interpolation application in Delft3D-Flow was used. The bottom topography has depths ranging from ~0.2 m to a maximum of ~18 m (Tomba's Mouth), whilst in the coastal region do not exceed ~10 m.

A more detailed description of the field work carried out to obtain measurements of thermohaline properties and other parameters is provided in Appendix 2.

### 2.2. Model boundary conditions, initial conditions and physical parameters

Rainfall and river discharge measurements in the Peruípe River are shown in Fig. 3B. The river discharge data, obtained from the