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The effect of tidal exchange on residence time in a coastal embayment

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ABSTRACT

Numerical simulations of an idealized lagoon that is connected to the ocean via a tidal inlet show that the mean residence time is inversely proportional to tidal exchange. In the Delft3D model the tidal exchange is controlled by varying the inlet length, width and depth. These changes in the inlet geometry affect the tidal prism and the ebb/flood flow structure, which are shown to control the exchange of lagoon water with seawater. To map residence time within the lagoon, a new method that implements dye tracer is developed and shows that the tidally averaged residence time exhibits significant spatial variability. For inlet systems in which, as a first approximation, the lagoon can be described by a uniformly fluctuating water level, a simple transport model is developed to elucidate the specific processes that control tidal exchange and their effect on residence time. In this transport model tidal exchange is decomposed into two fractions, an ocean exchange fraction and a lagoon exchange fraction. It is shown that both fractions need to be included to better describe tidal exchange. Specifically, inclusion of a lagoon exchange fraction improves previous tidal prism models that assume complete mixing in the lagoon. The assumption of complete mixing results in an under-prediction of residence time. Relating the spatially averaged residence time results to the exchange fractions for each inlet geometry show that the residence time is inversely proportional to the product of the tidal exchange fractions. For these single inlet systems, Keulegan's 0-D hydrodynamic model shows good agreement with Delft3D in predicting the tidal prism, maximum flow velocity, and exchange fractions. With these parameters, estimates of the mean residence time can be reached through a relationship derived from the simple transport model.

1. Introduction

Tidal inlets serve an important role in the hydrodynamics of the nearshore environment, as they are a conduit between the ocean and an embayment such as an estuary, harbor, or lagoon. Besides their logistical importance as our gateway to the sea, these regions also provide critical habitat for wildlife and sustain ecological diversity (Frey and Basan, 1985; Mitsch and Gosselink, 1993). How long water resides in an embayment can influence how chemical and biological processes affect its properties (Anderson et al., 2003; Lee et al., 2011). Residence time is determined by tidal exchange (Stommel and Farmer, 1952; Dean and Taylor, 1972; Fischer et al., 1979). Missing from the literature is a physical relationship between the two. To define this relationship, new methods that quantify tidal exchange and residence time in an inlet system are presented.

The advent of numerical models allows for a robust quantification of residence time using tracers and drogues (Banas and Hickey, 2005; Wijeratne and Rydberg, 2007). The concepts of Bolin and Rodhe (1973), van de Kreeke (1983) are employed to calculate tidally-averaged residence time distributions in a lagoon. These computationally expensive calculations are then used to develop a simple transport model following Stommel and Farmer (1952). Based on the asymmetry of the ebb and flood flow patterns at the ocean side of the inlet, they quantified tidal exchange with a single fraction herein referred to as the *ocean exchange fraction*. This approach is supplemented by introducing a second exchange fraction, the *lagoon exchange fraction* that describes the partial mixing of ocean water with lagoon water within the lagoon. The product of these two fractions provides a better estimate of tidal exchange. The simple transport model relates the spatially averaged residence time in the lagoon with the product of the two exchange fractions, thereby providing a quick assessment of mean lagoon residence time. These methods are applied to various inlet geometries to determine how the inlet width, length and depth influence tidal exchange and residence time.

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2. Methods

2.1. Residence time

Residence time (T_r) is commonly defined as the tidally-averaged time that a Lagrangian particle remains entrained within an embayment (Fischer et al., 1979; van de Kreeke, 1983; Orfila et al., 2005; Wijeratne and Rydberg, 2007). Similarly, a water parcel's age represents how long it has been entrained at any specific time (Fig. 1a). When compared to a simple population model as done by Bolin and Rodhe (1973), water entering the domain is equivalent to the birth of an individual, and the age when that individual expires is equivalent to the residence time, the total time it spent in the domain. At any given time, the total population consists of various individuals of different ages and a flux of individuals coming into (originating within) and leaving (expiring from) the system. This definition, although simple in form is difficult in practice due to the challenges associated with physically tracking water parcels. As such, only approximations of residence times that employ natural tracers are feasible in the field (Mudge et al., 2008). Other measures to quantify the renewal of lagoon water are age (Arega and Badr, 2010), exposure time (de Brauwere et al., 2011; Delhez, 2013), turnover time (Prandle, 1984; Ridderinkhof et al., 1990; Arneborg, 2004), and flushing time (Zimmerman, 1976; Monsen et al., 2002).

To estimate the residence time, a neutrally buoyant Lagrangian particle is typically tracked from the moment it enters the domain to the moment it exits. Specifically, if it is released at time $t = t_0$from a point defined by the Cartesian coordinates (x_0,y_0,z_0), the residence time for that location and release time is defined as $Tr(x_0,y_0,z_0)$ (Fig. 1a). Bolin and Rodhe (1973) and van de Kreeke (1983) show that a fluid tracer (dye) can be used to calculate a tidally-averaged residence time. If dye is released continuously from a point until a tidally-averaged equilibrium is reached, the residence time for that release location is,

$$\overline{T}_r(x_0, y_0, z_0) = \frac{M}{Q_{in}}, \tag{1}$$

where $\overline{T}_r$ is the tidally averaged residence time, M is the mass of dye in the system averaged over a tidal cycle and Q_{in} is the mass flow rate at which dye is released. How this approach is applied to Delft3D is presented in Section 2.3.

2.2. Model geometry

The flow in tidal inlets is primarily driven by water level difference between the ocean and the lagoon (Keulegan, 1951). The hydraulic classification of tidal inlets has been based on the ratio of the basin tidal amplitude and ocean tidal amplitude (Kjerfve, 1986), which in turn can be determined using the Keulegan repletion coefficient K_1 (Keulegan, 1967). Seabergh (2008) presents a thorough summary of the classification by Jarrett (1975) using K_1. Various definitions of embayments, such as for estuaries, lagoons, river mouths, bays, and fjords, have been utilized in the literature (Dyer, 1973; Kjerfve, 1994). Here, the inland body of water that connects to a tidal inlet is referred to as a 'back barrier lagoon' (Fig. 1b). The methods used in the Delft3D modeling presented here are applicable to any embayment that connects to the sea through a restricted channel including the inlets of Florida, the fjords in Scandinavia and Chile, the rias of Spain, the voes and sea-lochs of Scotland, and the loughs of Ireland (Gillibrand et al., 2013).

To form an appropriate idealized domain, the empirical relationship between the tidal prism (P) and cross-sectional area (A) for inlets at equilibrium in the natural environment is used (O'Brien, 1931).

$$A = aP^m \tag{2}$$

Here a and m are dimensionless coefficients. Powell et al. (2006) applied this relationship to 67 ocean entrances along Florida's east and west coasts. For each entrance, the tidal amplitude, wave energy flux, grain size, mean depth, cross sectional area, tidal prism, ebb delta volume and flood delta volume was presented. We have supplemented this data set with inlet length and width estimates of each entrance using Google Earth. To determine a baseline inlet geometry from these observations, Eq. (2) is applied to entrances classified as inlets, resulting in $a = 1.52 \times 10^{-6}$ and $m = 1.22$. The mean tidal prism from these inlets (1.5×10^7 m^3) is then applied to the relationship, resulting in a flow area of 865 m^2. When combined with the mean inlet length (1300 m) and width (188 m) measurements from Google Earth, a representative geometry is obtained. The depth of the basin is assumed to be the same as the depth in the inlet channel (4.6 m) for simplicity. From this baseline geometry, various inlet shapes are considered with varying length, width and depth. Further discussion on the model scenarios is found in Section 2.6 and a summary of the inlet dimensions studied is presented in Table 1. Next the principal semidiurnal tidal constituent (M2) amplitude of 0.5 m is used as the offshore boundary condition. This magnitude is chosen as the approximate representative condition based on work at New River Inlet, NC (MacMahan et al., 2014). With the assumption of a uniformly fluctuating basin water level, the surface area of the lagoon is set to 1.5×10^7 m^2 to achieve the desired tidal prism. When applied to a square geometry, this produces a lagoon that measures approximately 4 km in length and width. Together with the mean basin depth this results in a lagoon volume of 6.9×10^7 m^2.

The tidal prism, the ratio of the lagoon tidal amplitude (a_b) to the ocean tidal amplitude (a_o), the peak flood velocity ($\widehat{U}_{flood}$) and the peak ebb velocity ($\widehat{U}_{ebb}$) are determined for each inlet geometry using Delft3D. The prism is determined from a time series of the cumulative flux of water through a cross section at the inlet mouth. Once the model has initiated, the tidal prism can be calculated as the volume of water that enters the system during a flood or leaves during an ebb. For an M2 tide, both are equal. This approach includes the water that fills and empties the inlet channel. The tidal amplitude ratio is obtained from water level time series at the center of the lagoon and offshore. The flood and ebb velocity are obtained from the center of the inlet channel. The tidal prism can also be obtained by multiplying the tidal range in the basin by its' surface area. This approach results in tidal prisms that are on average 5% different than the cumulative flux method. The difference is attributed to the fact that the tidal range is not uniform everywhere in the basin and inlet.

2.3. Model setup

The flow module of Delft3D is used to simulate the hydrodynamics of idealized tidal inlet systems. Various site-specific modeling studies can be found in the literature, e.g. Wang et al., 1995; Cayocca, 2001; Elias et al., 2012, that demonstrate the ability of numerical models to accurately represent natural inlet systems. Delft3D can be operated in a depth-averaged mode or a three dimensional mode with varying vertical layer thicknesses. A depth-averaged calculation was chosen because of the significant computational cost of running a residence time simulation in 3D. The depth-averaged calculations incorporate the non-linear shallow water equations for the fluid motion and the depth-averaged advection-diffusion equations for the transport. Advective and dissipative terms are balanced by Coriolis, horizontal pressure terms that are derived from Boussinesq approximations,