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Modelling and observations of tidal wave propagation, circulation and residence times in Puttalam Lagoon, Sri Lanka

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Abstract

Tidal measurements and a depth-averaged 2D model are used to examine wave progression and circulation in a long, shallow, micro-tidal lagoon in Sri Lanka. Ranges and phase lags for different tidal constituents are used to calibrate the model. A single drag coefficient, $C_d = 0.0032$, gives almost perfect agreement with data. Current measurements are used for validation of the model. The lagoon tide consists of a combination of progressive and standing waves, where progressive waves dominate in the outer part and standing waves in the inner. A Lagrangian based particle-tracking method is developed to study tidally and wind induced residence times. If tides were the only factor affecting the residual circulation, the residence time inside the narrowest section would be approximately 100 days. Steady winds (of typical monsoon average) decrease the residence times to 60–90 days. Estuarine forcing due to net freshwater supply is not modelled (due to lack of reliable runoff data), but independent, long-term salinity observations and calculations based on volume and salt conservation during periods of negligible freshwater supply (the lagoon is seasonally hypersaline) indicate residence times ranging from 40 to 80 days. Model derived residence times based on tides alone represent a minimum exchange. Even weak forcing, through winds, excess evaporation or freshwater supply efficiently reduces residence times.

Keywords: residence time; water exchange; tidal model; Puttalam Lagoon; Sri Lanka

1. Introduction

1.1. Puttalam Lagoon

Puttalam Lagoon on the west coast of Sri Lanka (Fig. 1) offers excellent conditions for testing tidal models on residual circulation and water exchange. The lagoon is very shallow (1.7 m) and long enough (45 km) to develop well-defined differences in tidal range and salinity. Spring tidal range decreases from more than 50 cm at the entrance to about 20 cm at the head (Wijeratne et al., 1995). During dry seasons, the salinity in the inner end may reach 50 psu (Jayasiri et al., 1998), whereas the overall mean salinity varies from 32 to 42 psu on a seasonal basis (Arulananthan et al., 1995). These rather extreme variations are due to high evaporation in combination with a seasonally variable rainfall, typical of the Indian Ocean monsoon circulation. In this paper, we are presenting data on tides and current measurements, from various positions in the estuary. These are used to calibrate and validate a 2D tidal model. The model is used to examine tidally- and wind-driven residual circulation and residence times. The results are compared with independent calculations of residence times, based on volume and salt conservation (Arulananthan et al., 1995; Arulananthan, 2004).

1.2. Estuarine forcing and residual circulation

Oceanic tides, net freshwater fluxes and winds interact with local topography and (in larger areas) Earth's rotation, to

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Nomenclature

C_a	drag coefficient at the sea surface (2.7×10^{-3})
C_d	drag coefficient at the bottom
D	total depth
f	Coriolis parameter
g	gravitational acceleration
L, L_f	lagoon length, frictional length scale
T_p	tidal period
W_x	wind speed in x-direction $= W \cos \theta$, where θ is the wind direction rel. to the x-axis
W_y	wind speed in y-direction $= W \sin \theta$
U, V	are the depth-averaged velocities in the x- and y-directions
ε	η_0/D, an aspect ratio
η	sea level
η_o	tidal amplitude
ρ_a	density of air (~ 1.29 kg/m^3)
ρ_o	density of sea water (1025 kg/m^3)
$\tau_x^b, \tau_y^b, \tau_x^w, \tau_y^w$	bottom and wind stress in x- and y-directions, respectively.

produce a long-term mean residual circulation in estuaries and lagoons. Sub-tidal barotropic and baroclinic motions in the ocean, driven by large-scale winds, are also important but mainly in deeper estuaries (e.g. Samuelsson and Stigebrandt, 1996; Liungman et al., 2001; Souto et al., 2003). Predictions of the residual circulation, including adherent water exchange and residence times have occupied the scientific community during the last 50 years (e.g. Stommel and Farmer, 1953; Hansen and Rattray, 1965; Prandle, 1985; Nunes-Vaz et al., 1990; Li and Valle-Levinson, 1999; Li and O'Donnell, 2005), but is still a major challenge (Simpson et al., 2005). A majority of authors treat the interaction between tides and freshwater (buoyancy) forcing, fewer (i.e. Geyer, 1997; Scully et al., 2005) the direct forcing by wind. In Puttalam Lagoon, we expect the (small) but strongly variable net freshwater flux to exert large influence on residual circulation and residence times, but also, because of the shallowness of the lagoon that local winds are of importance. Negative or positive fluxes are both likely to increase circulation and reduce residence times. Maximum residence times are expected to appear when net freshwater flux (and wind forcing) is zero. A model, which correctly predicts tidally induced residual circulation, alone will also indicate maximum residence times.

1.3. Tidal response in shallow estuaries

The tidally induced residual circulation is directly related to the nature of the tidal co-oscillation. We expect a diminutive residual circulation in bays with standing tides, but a more efficient circulation where the tide is progressive, typical for shallow bays with tidal asymmetries (e.g. Signell and Butman, 1992). Moreover, the tidal wave motion is often subjected to frictional effects (e.g. Le Blond, 1978) and the tide appears as damped progressive waves. Robinson et al. (1983) investigated the Fleet, a long and shallow lagoon on the south coast of England. In this lagoon, total extinction of the tide occurs before the tidal wave reaches the head. In the Fleet, wave propagation is purely progressive. The frictional length scale, used by Műnchow and Garvine (1991), $L_f = (gD^2T_p^2/\varepsilon C_d)^{1/3}$ (for definitions, see list of symbols) is shorter than the length of the lagoon, L. Even in Puttalam Lagoon, $L_f < L$ ($L_f \approx 30$ km) but the aspect ratio $\varepsilon = \eta_0/D$ is smaller (0.06) than in the Fleet. Thus, complete extinction does not occur (Wijeratne et al., 1995). Instead, the lagoon tide appears as a combination of incident and reflected waves, both of which are subjected to friction. A detailed description of this interaction is found in Bowers and Lennon (1990), discussing tidal propagation in Spencer Gulf, Australia.

1.4. Residence times and water exchange

The residence time may be defined as the time it takes for a particular water parcel to leave a water body through its inlet. Then, for an individual parcel, it depends on the location and the time of release (i.e. Luff and Pohlmann, 1995). This is how we use it here. Sometimes, similar quantities, such as the "age of the water", defined as the time it takes for a water parcel to reach from the entrance (i.e. Björk et al., 2000), or the head (Shen and Lin, 2006) to a particular location within the estuary, are also used.

If, on the other hand, the residence time is interpreted as an average, and not refers to individual water parcels, it may be expressed as $T_r = V/q_i$, where V is the volume of the water body and q_i is the water exchange (the sum of net freshwater supply and exchange with the open sea). Here, water exchange is determined from volume and salt conservation (Wolanski, 1986; Officer and Kester, 1991), while T_r is the time it takes to remove $(1-e^{-1})$ of the volume of the water from the water body. An equally distributed tracer with an initial concentration, C_i will decay exponentially according to $C = C_i e^{-t/T_r}$. The residence time, T_r, as defined here is similar to flushing-time as it is used by Bolin and Rodhe (1973) and to turnover-time, as it is used by Prandle (1984). For steady state solutions, the average residence time should be same, whatever approach is used, presuming that it refers to the same water mass.

In this article we compare our calculations of residence times for individual parcels (based on Lagrangian tracking) with estimates of T_r from volume and salt budgets.

We employ a non-linear 2D model which is used to predict tides and tidal currents (Wijeratne, 2003). For calibration and validation we use tidal and current meter data from various sites in the lagoon. The Lagrangian particle-tracking method is added to calculate residence times due to tides and winds with the aim to improve earlier overall estimates of residence times. Study area and hydrography are presented in Ch 2, tide gauge and current meter data in Ch 3. A summary of results from tidal observations (harmonic analysis, etc.) is given in Ch 4. Ch 5 presents the model including calibration and validation runs. Ch 6–7 shows results from calculations of