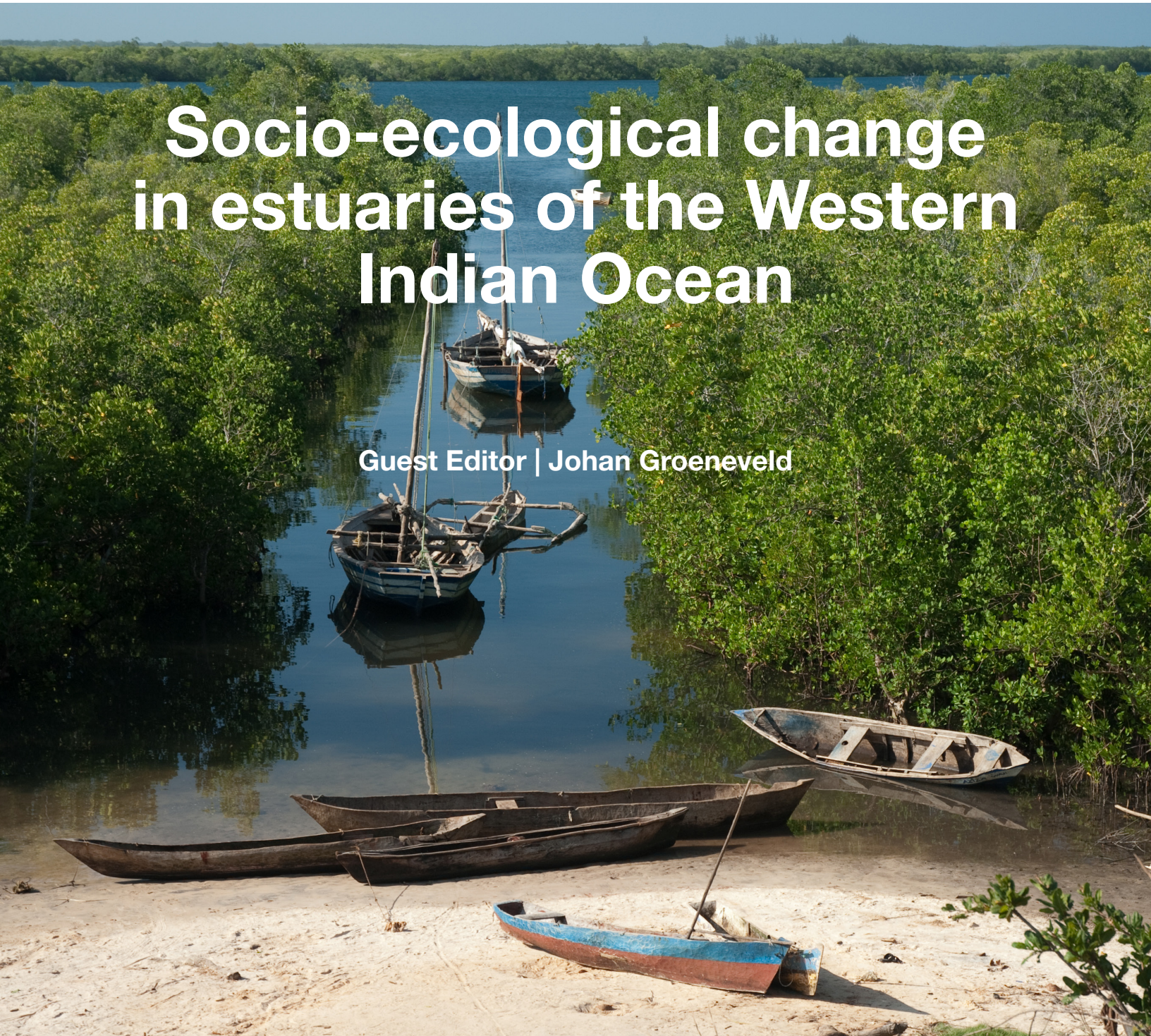


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Socio-ecological change in estuaries of the Western Indian Ocean

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The residual circulation profile of the Bons Sinais Estuary in central Mozambique - potential implications for larval dispersal and fisheries

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Abstract

The residual circulation in estuaries determines the net exchange of water, heat, salt, fine sediments and drifting biological organisms between estuarine and nearshore marine waters. The Bons Sinais Estuary in central Mozambique is ~ 30 km long with the city of Quelimane and an industrial port on the northern bank of its upper reaches. To investigate residual circulation in the estuary, seasonal (wet, dry and transition season) CTD profiling data were collected at 11 fixed stations between the upper estuary and mouth, and vertical current profiles were measured over a full tidal cycle at a fixed mid-estuary station. Strong longitudinal gradients in salinity and density indicated that the estuary was river-dominated during the wet season and tide-dominated during the dry season, but the water column remained partially mixed. Tidally averaged vertical profiles from the mid-estuary station revealed: uniform vertical temperatures, warmest during the wet season; depth-stratified salinity during the wet season, but uniform profiles during the dry and transition seasons with highest salinity during the dry season when the density was also highest. The density was uniform and somewhat lower in the transition season, and in the wet season the density was even lower, but stratified. The vertical velocity profile showed a classical two-layer circulation model, with downstream flow intensifying at the surface, and upstream flow at the bottom, during the wet and transitory seasons, when fresh-water discharges into the estuary. The flow velocities obtained from a calibrated Hansen and Rattray model fitted the observed data well, confirming that a simplified modelling approach is adequate to describe the residual flow of the Bons Sinais Estuary. The residual circulation model provides insights useful for fisheries research and predicting the spread of water-borne pollutants in the estuary.

Keywords: estuarine circulation, tidal asymmetry, tidal straining, gravitational circulation, net flow, larvae transport

Introduction

Understanding the residual circulation in estuaries is important because it determines the net exchange of water, heat, salt, biological propagules and the spread of chemical pollutants (Kjerfve *et al.* 1981; Li, 1997). Residual flow in estuaries is typically downstream in surface layers and upstream in deeper more saline layers near the bottom, because of the density gradient between fresh and salt water (Hansen and Rattray, 1965). Many fish and crustacean species have adapted to using tides and residual currents to move between

nearshore shelf habitats and estuarine environments during different life history stages to spawn, shelter or feed (Potter *et al.*, 1990; Churchill *et al.*, 1999; Whitfield, 1999; Lozano and Houde, 2013; Potter *et al.*, 2015). Residual flow is also important for the transport of fine sediments. Whereas near-bottom flow in rivers and upper estuaries brings fluvial sediments downstream (Dyer, 1995), it also imports marine sediments into lower estuaries, sometimes resulting in the silting of navigation channels or harbours (McSweeney *et al.*, 2016; Xiao *et al.*, 2018).

The classical theory of two-layer estuary circulation, where pressure longitudinal gradient balances stress divergence (Cheng *et al.*, 2011) was developed by Hansen and Rattray (1965), after earlier studies by Pritchard (1956). The classical theory remains valid and continues to be applied despite advances in hydrodynamic modelling (Chatwin, 1976; Prandle, 1985; Geyer and MacCready, 2014). Priya *et al.* (2012) argued that the classical model applies better to mixed or partially mixed estuaries. The main advantage of the simple classical model is the provision of an analytical solution which is easy to interpret for management decisions (Guillou *et al.*, 2000; Savenije *et al.*, 2007).

The Bons Sinais Estuary in central Mozambique (Fig. 1) has high ecological and socio-economic importance. It discharges onto the shallow Sofala Bank which supports the richest prawn and small pelagic fisheries in the Western Indian Ocean (Mazzilli, 2015; Mugabe *et al.* 2021). It plays a vital role as nursery and breeding grounds for coastal fish and crustaceans, especially for shallow water prawns which form the mainstay of coastal fisheries in the region.

The city of Quelimane, capital of Zambézia Province with a population of ~ 400 000 in 2020 (www.populationstat.com) and a harbour for sea-going vessels is located in the upper reaches of the estuary (Fig. 1). Local inhabitants rely heavily on the ecosystem goods and services provided by the estuary, including fish, mangrove wood for fuel and construction, and floodplains for planting rice and other crops or for salt production or aquaculture (Mazzilli, 2015; Francisco *et al.* 2021). These activities encroach on the estuarine functional zone and contribute to pollution, siltation and the degradation of ecologically important habitats (Furaca *et al.* 2021). An understanding of the estuary circulation pattern is therefore crucial for developing deeper insights and management strategies.

There are several studies on the hydrodynamics of the Bons Sinais Estuary. Among these, Hogueane *et al.* (2020) applied a simple tidal (longitudinal) model to describe the main hydrodynamic features of the estuary, Mocuba (2010) mapped sewage pollutants using biochemical oxygen demand as an indicator, Nataniel (2010) and Paulo (2012) studied nutrient flux in mangroves and the estuary and Mazzilli (2015) developed a framework for rapid assessment of the hydrodynamics of data-poor estuaries. Most species caught by fisheries on the Sofala Bank are of the *Engraulidae*, *Clupeidae*, *Sergestidae* and *Penaeidae* families, live in

the region of freshwater influence and are short-lived (1–2 years), recruiting to fisheries within the first year of their life (Hogueane and Armando, 2015), emphasizing the importance of estuarine habitats on fish production.

The approach adopted in this study was to apply a simple model to represent the residual circulation in the Bons Sinais Estuary, to reduce the degrees of freedom and modelling effort required while still capturing the key controlling factors. Direct measurements of currents and the classical theory of Hansen and Rattray (1965) were combined with an analytical solution (MacCready and Geyer, 2010; Geyer and MacCready, 2014) to model residual flow, temperature and salinity flux at a fixed position in the estuary. The fundamental mechanisms governing the transport and exchange of materials in the estuary were inferred and related to the transport of fish and crustacean larvae, an important factor in sustaining local fisheries and food security.

Materials and Methods

Study area

The geographical setting, ecosystems and socio-ecological importance of the Bons Sinais Estuary were summarized by Groeneveld *et al.* (2021). In brief, the estuary is shallow and funnel-shaped, about 30 km long with a maximum width of 2.5 km near the mouth (Mazzilli, 2015). It extends from the junction of the Cuacua and Licuar tributaries and drains into the Mozambique Channel over the northern Sofala Bank (17° 54' S, 36° 49' E; Fig. 1). The Cuacua River was once connected to the Zambezi River – as a part of the Zambezi Delta – and it was navigable until it silted up circa 1820 (Newitt, 1995). Following the construction of the Kariba (1955) and Cahora Bassa (1974) dams in the upper reaches of the Zambezi River, downstream flow and flood peaks were reduced, with several rivers (including Cuacua) becoming disconnected from the main branch of the Zambezi (Beilfuss and Santos, 2001).

The climate along the central Mozambique coast is influenced by a sub-tropical anticyclonic system, southeast trade winds, and the southern extremity of the East African monsoon system (Sætre and Jorge da Silva, 1984). The average wind speed varies between 3 and 5 m s⁻¹, with higher values in summer, from September to January (Hogueane, 1999; Rodrigues *et al.*, 2000). Rainfall averages 1140 mm per annum of which ~ 80 % falls between November and April, and the average annual evaporation is estimated at 1650

mm, exceeding rainfall by about 500 mm (Hogueane, 1999; Muchangos, 1999). Daily air temperature varies from around 25 °C in winter and 28 °C in summer, and atmospheric pressure from 1005 to 1020 kPa in winter and 1000 to 1010 kPa in summer (Hogueane, 1999; Muchangos, 1999).

The estuary receives an average of 500–840 m³ s⁻¹ of freshwater per year from the Cuacua and Licuari

Data

Temperature, salinity and depth were measured with a Valeport CTD instrument, and flow velocity with a Seaguard RCM (Recording Current Meter). The CTD data were collected at 11 fixed stations in the estuary (Fig. 1). The sampling was conducted during dry (18 July 2011) and wet (22 February 2012) seasons, from a boat equipped with a GPS navigation system and echo-sounder for depth recording. The survey

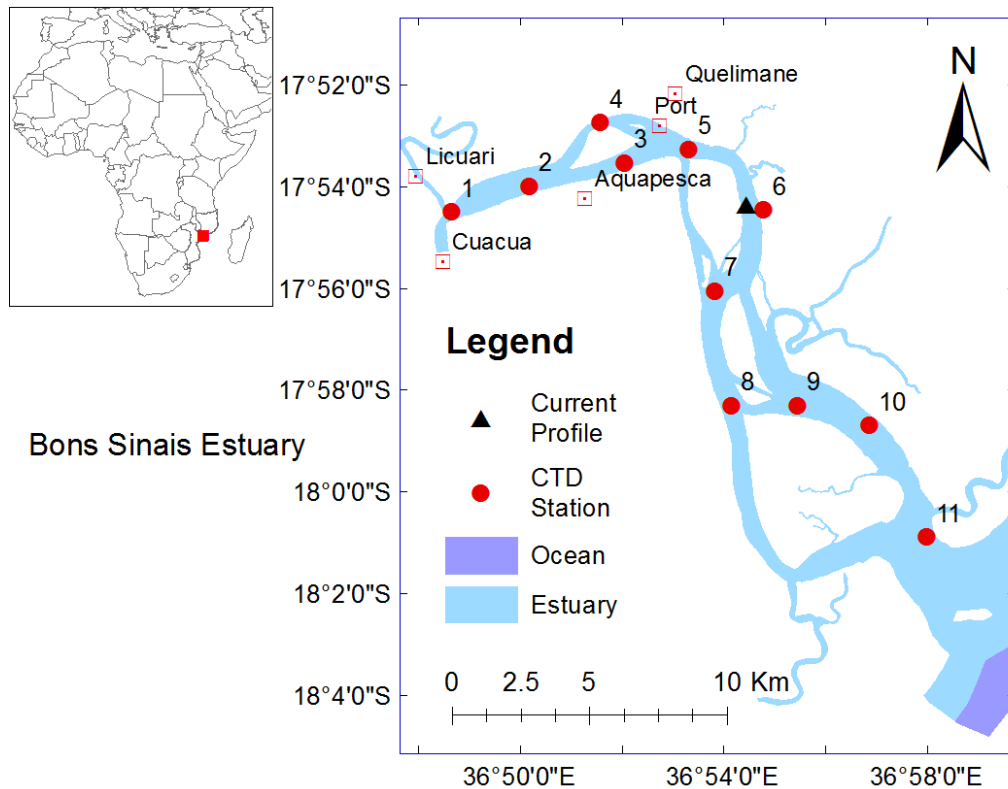


Figure 1. The study area and the location of sampling stations, denoted by red circles. The black triangle at Station 6 is where water current velocities were measured.

tributaries (Mazzilli, 2015). The estuary is fringed by dense mangrove vegetation dominated by *Avicennia marina* (white mangrove) and is linked to extensive freshwater wetlands and tidal creeks that contribute to the mass transport of water to the mangroves. The tides are semi-diurnal, with average amplitudes of 1.2 m and 3.8 m for neap and spring tides respectively and a maximum spring tide of 4.5 m (INAHINA, 2012). Water masses over the Sofala Bank are characterized by low salinity (<26) and high temperature near the estuary mouth; a salinity of 34.8 to 35.5 in open sea water; and high salinity of 35.5 to 37 over the southern Sofala Bank (Sætre and Jorge da Silva, 1984; Gammelsrød and Hogueane, 1995; Nehama *et al.*, 2015).

started at the beginning of the flood cycle, proceeding upstream from the estuary mouth. The CTD data were used to determine the longitudinal density profile using Matlab-software.

The vertical velocity profile at station 6 (see Fig. 1) was measured every 0.5 h over a 13 h period, which covered a full tidal cycle between two low tides. The recording frequency was once every 10 seconds, for 10 minutes at each 1 m depth interval between the surface and bottom (0.5 m offset from surface or bottom observed). To determine the residual currents, average currents over a tidal cycle were calculated. Profiles were obtained for the dry- (30 November 2012), wet- (6 March 2013) and transition seasons (28 April 2013).

Circulation model

The analytical solution of Hansen and Rattray (1965) was used to determine the residual currents. The basic equations (MacCreary and Geyer, 2010; Geyer and MacCready, 2014) consisted of the Reynolds-averaged equations for salinity and along-channel momentum, in hydrostatic form and subject to the Boussinesq approximation. The momentum advection and Coriolis forces were excluded and only the along-channel gradients were considered. Thus, the equations were as follows:

$$\frac{\partial S}{\partial t} + u \frac{\partial S}{\partial x} = \frac{\partial}{\partial z} \left(k \frac{\partial S}{\partial z} \right) \quad [1]$$

$$\frac{1}{\rho} \frac{\partial p}{\partial x} = \frac{\partial}{\partial z} \left(A \frac{\partial u}{\partial z} \right) \quad [2]$$

Where S is the salinity, x (m) is along-channel distance, measured from the estuary's head, z (m) is the water level in the water column measured from the surface, and negative downwards, ρ (kg m^{-3}) is the water density, p (N m^{-2}) is the pressure obtained from the hydrostatic equation, k is the eddy diffusion coefficient (constant at $0.006 \text{ m}^2 \text{ s}^{-1}$; Hogue et al., 2020), u (m s^{-1}) is the along-channel velocity, and A is the eddy viscosity. By tidally and width averaging all the variables and assuming a constant longitudinal salinity gradient and constant tidally averaged eddy viscosity, the vertical profile of the subtidal along-channel velocity without wind effects was obtained as follows (MacCreary and Geyer, 2010; Geyer and MacCready, 2014):

$$U = U_r (1.5 - 1.5\xi^2) + U_g (1 - 9\xi^2 - 8\xi^3) \quad [3]$$

Where U (m s^{-1}) is the observed velocity with depth, positive for upstream velocity (flood), U_r (m s^{-1}) is the residual velocity, U_g (m s^{-1}) is the gravitational velocity, $\xi = \frac{z}{h}$ is the normalized depth, and h (m) is the local depth. The equation [3] was calibrated by regression analysis using the observed velocity, to estimate U_r and U_g .

Results

Longitudinal variation in water temperature, salinity and density

The observed longitudinal temperature profile during the dry season (Fig. 2a) showed slightly cooler water (21°C) input from the ocean and warmer water ($22.4 - 22.6^\circ\text{C}$) at the surface in mid-estuary, but the water column appeared to be thermally mixed (left panel in Fig. 2a). Surface and bottom salinity did not

differ (middle panel in Fig. 2a), but a strong longitudinal gradient was visible, with salinity decreasing from 29 at the mouth to 23 in the upper estuary. Similarly, density was not stratified by depth, but decreased longitudinally from 1020 kg m^{-3} near the estuary mouth to 1015 kg m^{-3} in the upper estuary (right panel in Fig. 2a), with a gradient of about $0.2 \text{ kg m}^{-3} \text{ km}^{-1}$.

During the wet season (Fig. 2b) water temperature was higher in the upper estuary than near the mouth (left panel in Fig. 2b) but the water column was thermally mixed. Salinity increased from 12 in the upper reaches to 22 at the estuary mouth (middle panel in Fig. 2b) indicating freshwater input. The water column was partially mixed, suggesting that freshwater input was not sufficient to oppose the strong tidal mixing, with little vertical stratification observed. The density (right panel in Fig. 2b) profile displayed a similar pattern to salinity, by increasing from 1005 kg m^{-3} in the upper estuary to 1012 kg m^{-3} near the mouth with a gradient of $\sim 0.3 \text{ kg m}^{-3} \text{ km}^{-1}$.

Tidally averaged vertical profiles

Tidally averaged temperature, salinity, density and velocity profiles measured at Station 6 during the dry- (30 November 2012), wet- (6 March 2013) and transition seasons (28 April 2013) showed uniform temperature irrespective of depth during all three seasons (Fig. 3). Salinity was uniform irrespective of depth during the dry and intermediate seasons, but depth-stratified during the wet season, with higher salinity near the bottom. The tidally averaged density profiles were uniform during the dry and transition seasons, with higher density during November $\sim 1022 \text{ kg m}^{-3}$, dry season, marine influence) and with lower density during April $\sim 1014 \text{ kg m}^{-3}$, transition season, freshwater influence). The density profile was lowest and stratified during the wet season (March $1000 - 1009 \text{ kg m}^{-3}$).

The velocity profile showed a classical two-layer circulation model, with downstream (ebb) net flow at the surface and upstream (flood) net flow at the bottom. During the wet season, the residual flood currents were $\sim 0.14 \text{ m s}^{-1}$ upstream in the bottom layer and $\sim 0.25 \text{ m s}^{-1}$ downstream in the surface layer. The intensification of downstream flow at the surface is attributed to enhanced river discharge into the estuary. During the dry season, there was seldom much residual current ($<0.05 \text{ m s}^{-1}$) reflecting a strong tidal influence. During the transition season, the residual flood currents reached 0.24 m s^{-1} near the bottom and the ebb current reached $\sim 0.30 \text{ m s}^{-1}$ near the surface.

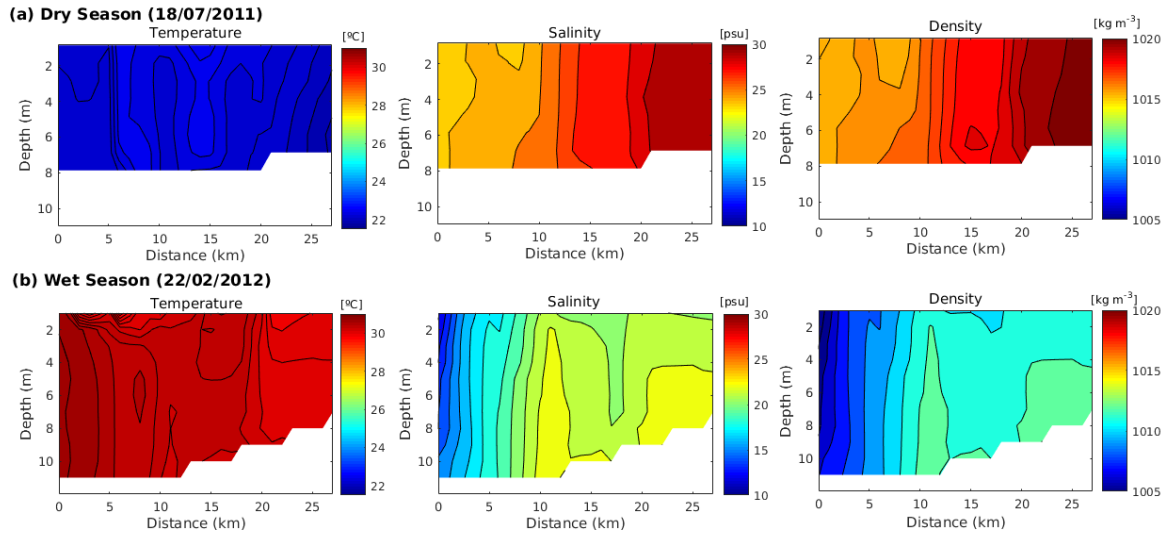


Figure 2. Longitudinal distribution of water temperature, salinity and density in the Bons Sinais Estuary during: (a) dry season (measured 18 July 2011) and (b) wet season (measured 22 February 2012). The estuary mouth is to the right of each panel.

Residual flow applying Hansen and Rattray equations

The modelled flow velocities fitted the observed data well with high coefficient of goodness of fit (r^2) (Table 1) confirming that the simplified model described the residual flow of the estuary well. During the dry season, the small residual- ($U_r = 0.04 \text{ m s}^{-1}$) and gravitational flows ($U_g = 0.03 \text{ m s}^{-1}$; Table 1) reflected reduced freshwater input and a tidally dominated estuary state, with net seawards flow

attributed to freshwater stored in upper estuary wetlands or ground water sources. During the wet season, the residual- ($\sim 0.05 \text{ m s}^{-1}$) and gravitational flow ($\sim 0.19 \text{ m s}^{-1}$; Table 1) increased during ebb tide, because of increased longitudinal density and salinity gradients. During the transition season, residual flow decreased (0.02 m s^{-1}) during ebb tide but gravitational flow increased to 0.30 m s^{-1} , possibly because of freshwater drainage from wetland reservoirs filled up during the wet season.

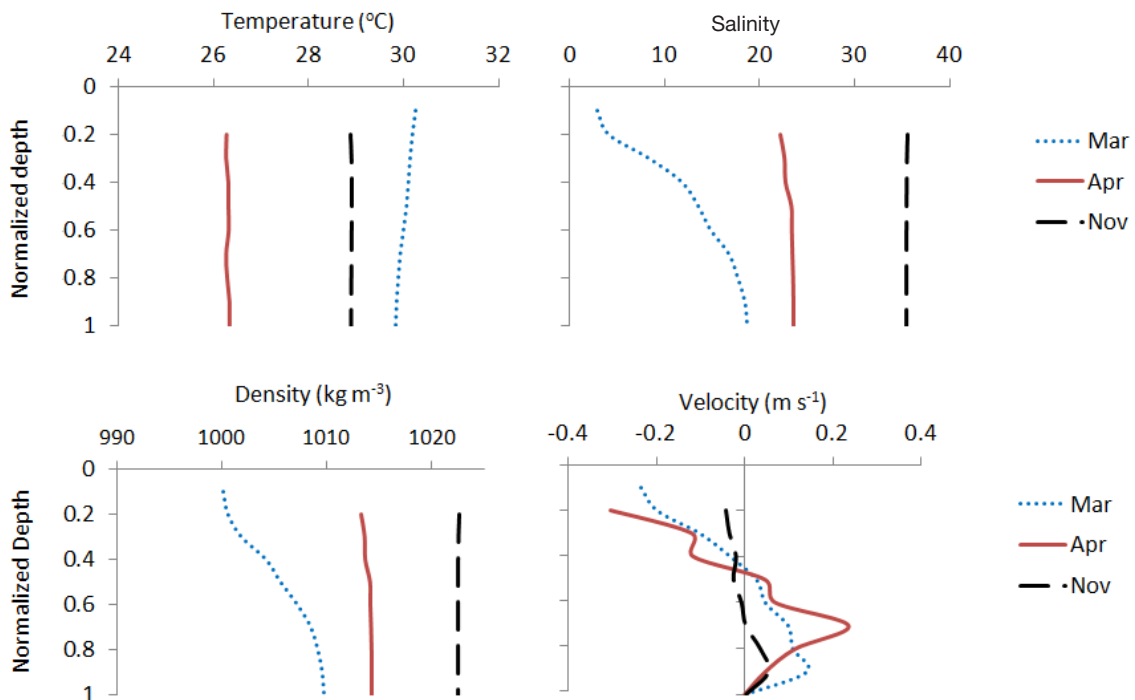


Figure 3. Tidally averaged temperature, salinity, density and velocity profiles with normalized depth, measured at Station 6 during the dry (30 November 2012), wet (6 March 2013) and transition (28 April 2013) seasons.

Table 1. Estimates of residual flow (U_r) and gravitational flow (U_g) based on the fit of the Hansen and Rattray model to the current velocity data collected at Station 6; where SS is the sum of squared differences from the mean, MS is mean square, F is F-Test, P-value is the level of statistical significance, and r^2 is the goodness of fit coefficient.

Period	Coefficients			SS	MS	F	P	r^2 (%)
	Const (m/s)	U_r (m/s)	U_g (m/s)					
Dry season (Nov)	0.02	-0.04	-0.03	0.006	0.003	9.5	0.014	76
Wet season (Mar)	0.02	-0.05	-0.19	0.143	0.071	101.7	0.000	97
Transition (Apr)	0.34	-0.02	-0.30	0.178	0.089	26.3	0.001	90

Simulated vertical flow velocities (U) were decomposed into components for residual velocity (U_r) and gravitational velocity (U_g) (Fig. 4; Equation 3). Strong gradients in vertical velocity profiles were apparent during the wet and transition seasons, when the surface layer was dominated by seaward flow and the bottom layer by upstream flow. The vertical profile during the dry season showed minimal residual flow.

Discussion

Observed vertical profiles of temperature, salinity and velocity

The empirical data and model outputs confirmed a change-over from a well-mixed water column during the dry season to a stratified water column during the wet season (see also Mazzilli, 2015). Nevertheless, throughout most of the year, the vertical profile remained mixed to partially mixed, thus justifying

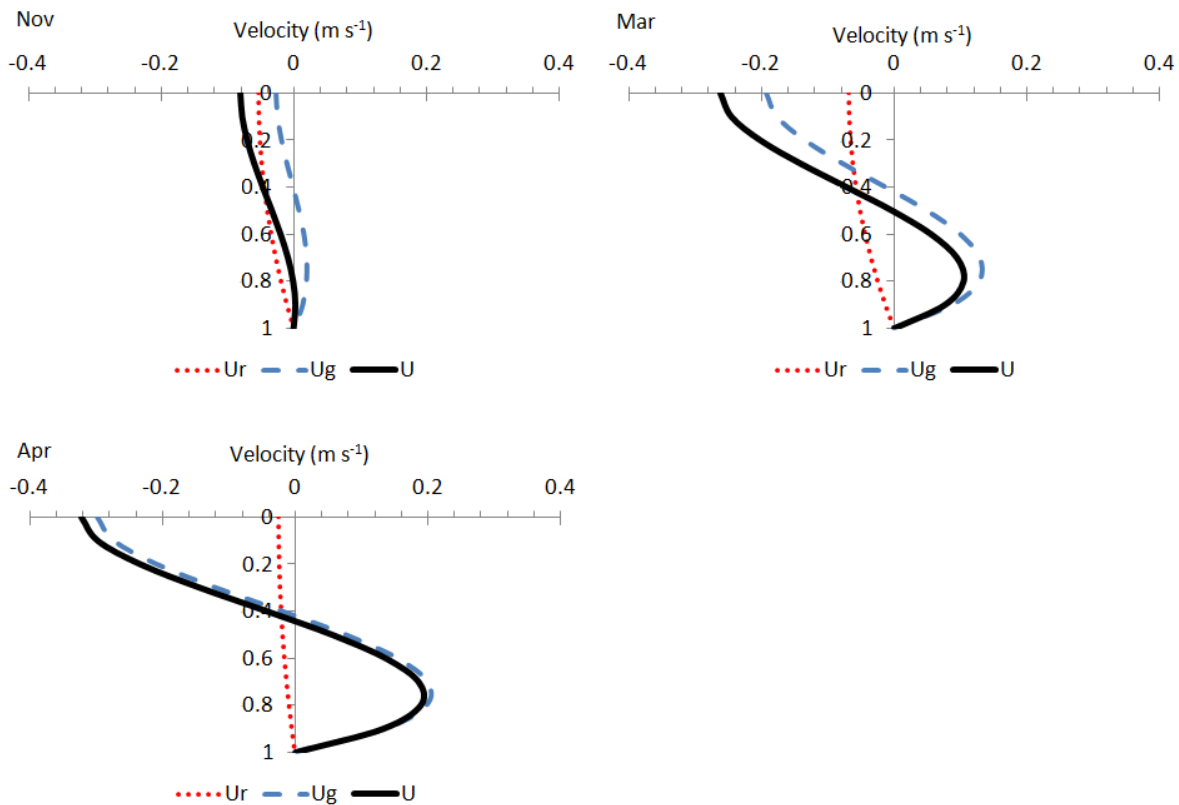


Figure 4. Simulation of the vertical flow velocity. The curves represent tidally averaged flow velocities with normalized depth, assuming constant longitudinal salinity and eddy viscosity. U_r is residual flow; U_g is gravitational flow; U is the sum of U_r and U_g . Nov = dry season; Mar = wet season; Apr = transition season.

the application of a Hansen and Rattray (1965) model (Priya *et al.*, 2012). The residual velocity at Station 6 was dominated by freshwater input during the wet and transitional seasons and tidal flow during the dry season. The finding agrees with Bernardes and Miranda (2001) who found major forcing agents to be the longitudinal density gradient and the river flow (with wind effect excluded) in mixed to partially mixed estuaries. The weak residual flow during the dry season can be explained by tidal straining (Burchard *et al.*, 2014; Geyer and MacCready, 2014). Several authors have shown that estuarine residual circulation weakens when tidal importance increases (Li, 1997; Shiraki and Yanagi, 2007; Cheng *et al.*, 2011) as is the case in the Bons Sinais Estuary, where the tidal amplitude reaches ~ 4 m during spring tide.

Comparison between the observed and modelled vertical velocity profiles

The modelled velocity profiles compared well with the observed data for the dry- (Fig. 5a) and wet seasons (Fig. 5b) but underestimated the maximum velocities during the transition season (Fig. 5c). An increased run-off during the April transition season, shortly after the rainy season can be explained by precipitation from

more remote catchment areas reaching the estuary. The run-off increases the water level at the estuary head, causing a pressure force because of the surface tilt which drives surface water seawards hence increasing observed surface maximum velocities compared to modelled maxima. This increases the upstream pressure force in the lower layer (and increases the bottom velocity above model estimates) because of the increased density gradient. This effect is clearly seen when comparing the observed and modelled vertical velocities between seasons (Fig. 5 a-c). The prominent velocity peaks during the transition season is potentially exacerbated by freshwater drainage from wetland reservoirs filled up during the rainy season. Geyer and MacCready (2014), among others, suggested that U_g is directly proportional to the density (or salinity) gradient, indicating that the salinity at the head of the estuary was lower in April than in March. Furthermore, the depth of the modelled zero-velocity estimate (a measure of the depth of the boundary between the directional surface and bottom layers) reproduced the observed values well during all three seasons (Fig. 5), allowing for management applications in which dispersal patterns can be associated with vertical positioning in the water column.

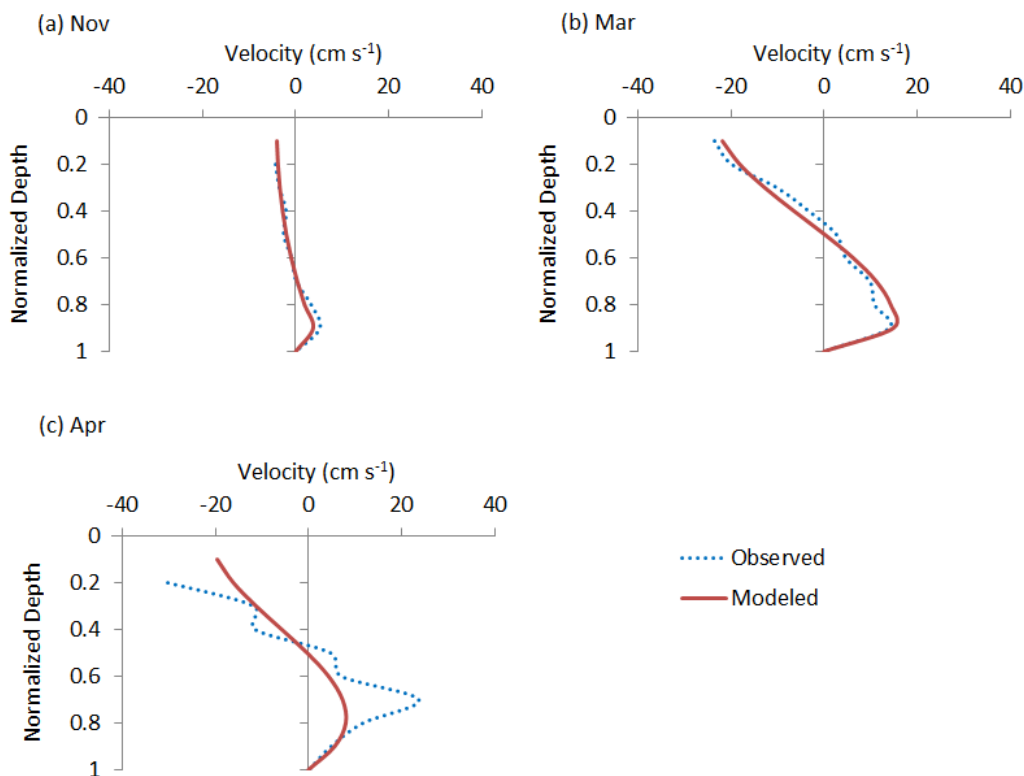


Figure 5. Comparison of the modelled and observed current profiles for a) the dry season (November) b) the wet season (March), and c) the transition season (April). Model-estimated zero-velocities compare well with the observed data in all three seasons.

Model evaluation

The model performance was evaluated by comparison between the observed and modelled result (Fig. 6). The model represented observations well with high goodness of fit ($0.90 < r^2 < 0.97$) for the wet and transition season, but a weaker fit to dry season data ($r^2 = 0.76$) because the latter observations overlapped with a neap tide - i.e. the model had to be fitted to narrow range of observed velocity data.

The residual circulation model developed here may contribute to understanding larval distribution patterns in the Bons Sinais Estuary. Most fish and crustacean larvae can position themselves in the water column to facilitate directional transport by currents - distribution patterns are therefore likely to match residual currents at different depths (Epifanio, 1988; Thiebault *et al.*, 1992; Lazarrri *et al.*, 1993; Katz *et al.*, 1994; Garrison, 1999; Robins *et al.*, 2013; Teodósio and Garel, 2015). For example, in this study, seaward transport would be associated with high river runoff and landward transport with low runoff seasons, which matches with the life cycle of penaeid prawns. Female prawns spawn in coastal waters during the dry season with larvae entering the estuary during a period of weak and tidally-driven estuarine circulation (Gammelsrød, 1992). The estuary is a productive and sheltered nursery area where larvae grow into juveniles,

before returning to offshore mudbanks – facilitated by a seawards residual flow during the wet season.

In conclusion, the classical two-layer Hansen and Rattray model provided a simple analytical tool which succeeded in quantifying fundamental residual circulation in a way that makes model simulations of dispersal and connectivity easier to interpret. Model simulations can provide a tool for predicting the outcomes of environmental and fisheries management decisions. The location of the estuary adjacent to the important Sofala Bank fishing grounds makes it a spatially well-placed location for *in situ* studies of changes in estuary circulation and its effects on the distribution and recruitment of estuary-dependent fish and prawns.

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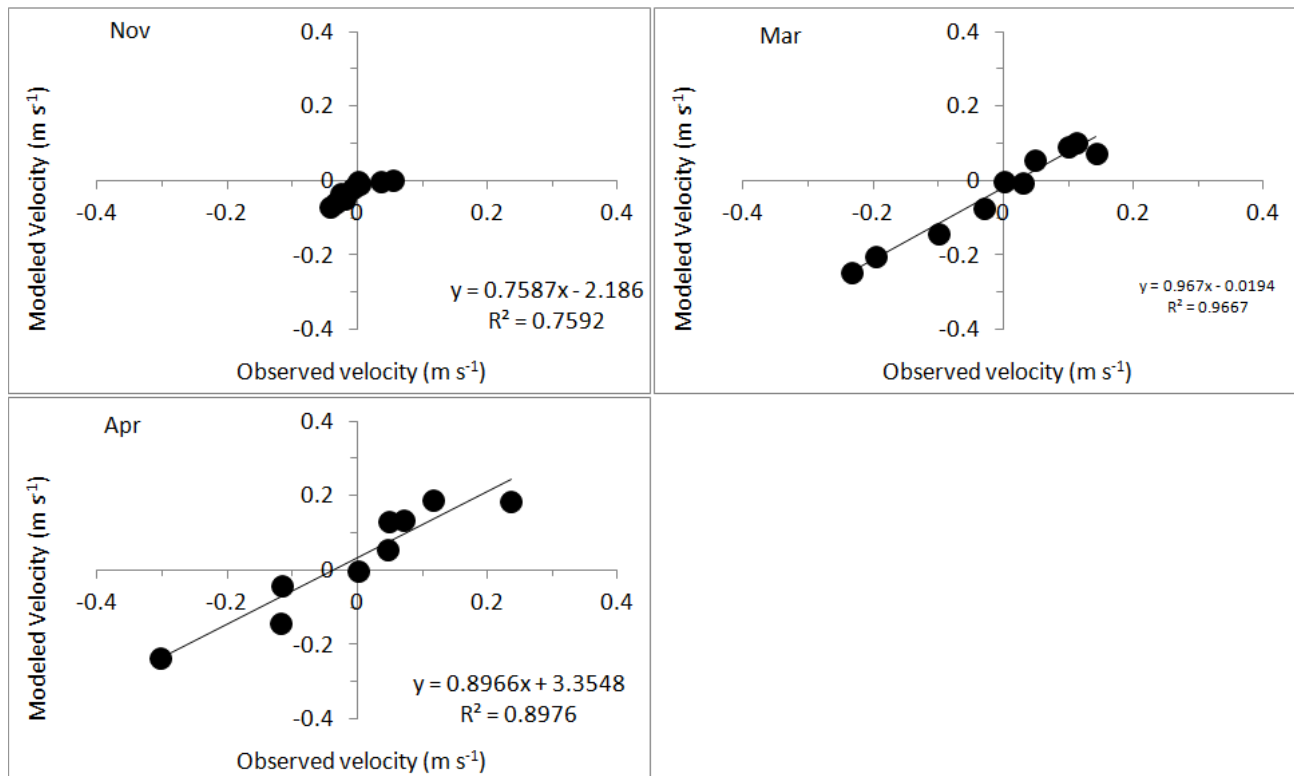


Figure 6. Model performance gauged by comparison of observed and modelled flow, as estimated by the Hansen and Rattray approach and measured at Station 6.

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