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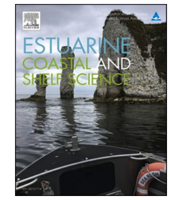

Water renewal and stratification modelling in small estuaries

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ABSTRACT

Water renewal and flushing in small, intermittently open or closed estuaries is receiving increasing attention particularly in light of the climate change induced alterations in run-off, wave and sediment transport conditions along coasts. The challenges of predicting the stratification-circulation state and the balance between tidal or freshwater flushing in response to the mouth dynamics of small, wave-dominated estuaries is the focus of the paper. Such predictions are required for determining estuary freshwater requirements or establishing an estuary's capacity to maintain sound water quality under pollutant discharges. Advances in simulating changes in stratification-circulation over long time scales are limited. Instead attention has focused on generating indices of stratification or water quality state using heuristic methods. In this paper, systems dynamics modelling is applied to simulate the non-linear response of the estuary to changes in river and marine water fluxes. The estuary is modelled as a basin with a specified water volume to water level relationship, connected to the sea by a channel with variable sill height, but fixed width. The direction and magnitude of the flow through the mouth determines whether the sill height erodes or accretes and hence the mouth dynamics (see Slinger, 2017). The tidal flux through the mouth co-determines the volumetric exchange of salt, influencing both the stratification state of the estuary and the degree of tidal or freshwater flushing. This is also influenced by run-off. The resulting dynamic balance is captured in two bulk indices, the Estuarine Richardson number and the bulk densimetric Froude number. Using measured data from the Great Brak Estuary, South Africa, the model is calibrated. Model simulations demonstrate the importance of tidal flushing and concomitant mouth breaching for water renewal as freshwater flushing declines under scenarios of increased water abstraction. Although the estuary remains partially mixed, there is increased average salinity and a more uniform the water column. Water releases and mouth breaching bring about a more natural stratification-circulation state, but these effects are short-lived.

1. Introduction

Small, intermittent closed/open lakes and lagoons (ICOLLs), also termed temporarily open/closed estuaries (TOCEs) or low-inflow estuaries (LIEs), are prevalent on microtidal coasts in temperate zones such as along the coasts of South Africa, Australia, west Africa, California and Mexico (McSweeney et al., 2017; Largier, 2023). These estuaries are subject to variability in freshwater flows and wave conditions, leading to a high incidence of mouth closure (Haines et al., 2006; McSweeney et al., 2017). Closure commonly occurs when sediment accumulates in the mouth channel under high wave conditions (Harvey et al., 2023) and the ebb tidal flows are insufficient to expel this sediment. The channel becomes choked and a bar builds across the mouth. These dynamics have been modelled by a variety of authors (Slinger, 1997, 2017; Ranasinghe et al., 1999; Tung et al., 2009; Fortunatoa et al., 2014; Behrens et al., 2015; Duong et al., 2015). Some have focussed attention on longshore sediment supply versus cross-shore sediment supply via onshore-directed swells in their modelling. Others have explored the role of the ebb tidal prism, or have focussed at the process level of individual closure events. Yet others have undertaken century-scale simulation using Escoffier's co-efficient as a measure of propensity for closure. Few of these attempts have explored the corresponding effects on the stratification-circulation state and the flushing of the estuary (Harvey et al., 2023). Where this has received attention, it has been via hydrodynamic model simulation on relatively short event time scales e.g. van Ballegooyen et al. (2004). It is intriguing to explore whether the stratification-circulation state and the balance between tidal or freshwater flushing in response to the mouth dynamics of small, wave-dominated estuaries can be simulated over long time scales in association with parametric modelling of the mouth dynamics. Such a

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capability opens the door to investigating the effects of alterations in run-off, wave and sediment transport conditions along coasts on the flushing and renewal of small estuaries. It could also support conservation efforts aimed at restoring connectivity between rivers and coasts, such as in the REST-COAST project (see Caiola and Ibáñez, 2022; Sanchez-Arcilla et al., 2023).

The aim of this paper, therefore, is to formulate a systems dynamics model and apply it in simulating the non-linear response of small, intermittent estuaries to changes in river and marine water fluxes. Drawing on the work of Slinger (1997, 2017), an estuary is modelled as a basin with a specified water volume to water level relationship, connected to the sea by a channel with variable sill height, but fixed width. The direction and magnitude of the flow through the mouth then determines whether the sill height erodes or accretes and hence the mouth dynamics. The tidal flux through the mouth co-determines the volumetric exchange of salt, fundamentally influencing both the stratification state of the estuary and the degree of tidal or freshwater flushing.

Core to the development and application of such a model is an established understanding and relevant measurements of flushing and water renewal processes in these estuaries. In a recent publication on flushing and water renewal in the Great Brak Estuary, South Africa, long term research and monitoring insights (garnered over thirty-five years) are synthesized into a schematic to indicate the relative efficacy of flushing and renewal of the water body by a minor freshwater release and a major flood each followed by breaching of the mouth and subsequent tidal intrusion (see Slinger et al., 2017: Fig. 6). The Great Brak Estuary therefore provides an ideal case study in which to test such an approach.

Accordingly, the formulation of a model of flushing and stratification-circulation state is undertaken in Section 2. This is followed by the application of the model to the Great Brak Estuary in Section 3 and a discussion of the results in Section 4. The paper concludes with a discussion of the potential value of the approach in relation to the management challenges facing small, intermittent estuaries in Section 5.

2. Model development

Where the water volume and mouth condition are fundamental to a description of the morphology and hydrology of small, intermittently open estuaries, the frequency and extent of flushing and characteristics such as the stratification-circulation regime (i.e. partially mixed, highly stratified) are fundamental to a description of the hydrodynamic environment. Therefore, the time dependent state variables deemed essential in modelling the physical dynamics of an estuary are.

- the water volume, from which a representative water level is derived,
- the sill height at the mouth, from which the extent of mouth closure/openness is derived,
- the freshwater flushing of the water body,
- the tidal flushing of the water body
- the salt content of the water within the estuary,
- an index of stratification, and
- an index of circulation.

2.1. Freshwater and tidal flushing

The equations for the rates affecting the estuary water volume (x_1) and the sill height at the mouth (x_2) have been formulated in Slinger (2017, Appendix 1). These parameters are essential in determining the degree to which the water body of an estuary is flushed at any time. Indeed, the rate at which water is flushed from an estuary has been indicated to be the most important physical influence on water quality (Sandford et al., 1992), and this fundament has only been affirmed by subsequent studies (Behrens et al., 2013; Taljaard et al., 2017). Initially, flushing time was defined as the time required to replace the existing freshwater in an estuary at a rate equal to the river discharge. According to Dyer (1997), this concept was introduced to calculate the flushing time of the New York Bight under different river discharges based on the fraction of freshwater present in the basin. This definition considers the dominant flushing mechanism to be freshwater flow, whereas the dominant flushing mechanism in an estuary may be the tide (Slinger et al., 1994; Slinger et al., 2017). A tidal flushing time or residence time specified in terms of the tidal cycle is calculated as the ratio of the high tide volume to the intertidal volume or tidal prism (Dyer, 1997). The assumptions of this simple tidal prism method, are (i) that complete mixing of freshwater and salt water inputs occurs in the basin within a tidal cycle (mixing is rapid and thorough), and (ii) the nearshore receiving water body is itself well flushed and vigorously mixed so that there is no return flow of estuary water. Because these assumptions do not hold for long or stratified estuaries where internal mixing is incomplete, nor for large estuaries or those on sheltered coasts where external mixing is incomplete, the simple tidal prism method delivers a flushing time that is lower than that found in practice. The modified tidal prism method accounts for incomplete longitudinal mixing by dividing the estuary into longitudinal sections corresponding in length to the average excursion of a water particle on the flood tide, determining a flushing time for each section as the inverse of a volume exchange ratio, and then calculating the total flushing time for the estuary as the sum of the flushing times of the individual segments (Dyer, 1997). In similar vein, the fraction of freshwater method has been modified to accommodate incomplete longitudinal mixing and forms the basis of many box model assessments of flushing times (Crossland et al., 2005; Swaney et al., 2008). More recently, Lemagie and Lerczak (2015) compared three methods for estimating bulk estuarine turnover timescales using particle tracking measurements, namely the modified tidal prism method, the fraction of freshwater method, and a newer total exchange flow method (see MacCready, 2011). The calculated timescales were similar under high river run-off, differed substantially under low run-off, and varied with tidal amplitude. They indicate that the total exchange flow timescale may be more representative of the turnover time in the lower reaches of the estuary they studied, whereas the fraction of freshwater method is more representative in the upper reaches where river forcing is dominant. Most commonly, longitudinal and vertical dispersion coefficients are determined from field data or via analytical formulae and used in standard 1D, 2D or 3D hydrodynamic models to simulate transport and dispersion within an estuary and enable calculation of the volume exchange with the sea (e.g. van Ballegooyen et al., 2004). This facilitates accurate prediction of the tidal and freshwater flushing of an estuary under the prevailing mouth condition and tidal cycle. The simulation of this level of hydrodynamic detail over long periods of time, under changing mouth, tidal, wave and river flow conditions remains a daunting and computationally intensive task (see Fortunatoa et al., 2014; Behrens et al., 2015; Duong et al., 2015). Moreover, the data required for calibrating such models is often not readily available for small, intermittently open estuaries (see Taljaard et al., 2017). Herein, lies both the argument and the need for a parametric modelling approach that is conceptually sound, can simulate across changing mouth, tide, wave and inflow conditions and yet has low data needs. Accordingly, in this parametric model, and in line with the findings of Lemagie and Lerczak (2015), we choose to calculate bulk numbers indicative of both the freshwater flushing and the tidal flushing with the idea that variations in these two state variables will enable us to simulate the balance between the different flushing mechanisms over time under changing conditions.

A first order exponential delay of the inflow rate provides an estimate of the **freshwater flushing**:

$$\frac{dx_3}{dt} = \left(\frac{x_{11}}{x_{11r}} - x_3\right) \Big/ t_1 \tag{1}$$

where x_3 = freshwater flushing (unitless), x_{11} = freshwater inflow rate (m^3. yr^{-1}), x_{11r} = reference freshwater inflow rate (m^3. yr^{-1}), and t_1 = time delay constant 1 (yr). The formulation as a first order exponential delay means that the freshwater flushing response of the estuary to a change in freshwater inflow is not instantaneous, but is shifted later or delayed in time (on average by the value of the time delay constant 1). This is a standard formulation in System Dynamics modelling (Forrester, 1961; Albin, 1998) and can be applied in groundwater modelling as a generic method for formulating a material delay (see Jurgens et al., 2016). In an estuary, it accommodates the time needed for the freshwater to enter the water body and effect change, or for a pulse of freshwater to pass through the system.

For the tidal exchange rate of the water body, the lack of longitudinal definition in the parametric approach means that the modified tidal prism method cannot be adopted. Instead the simple tidal prism method is used, yielding a flushing time the inverse of the tidal exchange rate. The instantaneous fractional tidal exchange rate is then defined as the ratio of the tidal flow through the mouth ($|x_{14}|$) to the water volume of the estuary (x_1). The **tidal flushing** frequency is given by a first order exponential delay of the instantaneous fractional tidal exchange rate:

$$\frac{dx_4}{dt} = \left(\frac{|x_{14}|}{x_1} - x_4\right) \Big/ t_2 \tag{2}$$

where x_4 = tidal flushing (yr^{-1}), tidal flow, x_{14} = tidal flow (m^3. yr^{-1}), x_1 = water volume (m^3) and t_2 = time delay constant 2 (yr). Mouth constriction and closure lead to lower values for the tidal flushing as the tidal exchange is reduced. Accordingly, this state variable is indicative of the flushing frequency of the water body, for instance whether it is tidally flushed an average of 365 times or more per year or much less. In contrast, the freshwater flushing variable provides an indication of the freshwater influence on the renewal of the water body.

2.2. Salt content of the estuary

Now that the equations for the rates affecting the estuary water volume (x_1), the sill height at the mouth (x_2), the freshwater flushing (x_3), and the tidal flushing frequency (x_4) are established, it is necessary to develop the equations for the salt content of the water body. First, we assume that the contribution of salt to the estuary via freshwater inflow is negligible and then we invoke the principle of the conservation of mass to define the rate of change of the **salt content of the estuary** as a conservative co-flow associated with the tidal flux (Gambardella et al., 2017):

$$\frac{dx_5}{dt} = x_{51} + x_{52} \tag{3}$$

where x_5 = salt (kg), x_{51} = salt import (kg. yr^{-1}) and x_{52} = salt export (kg. yr^{-1}) and both x_{51} and x_{52} depend on x_{14} the tidal flux. The quantity of salt entering an estuary on the flood tide therefore depends on both the volume and the salinity of the water flowing into the system from the sea. When there is active turbulent mixing in the nearshore zone, the inflowing water has sea salinity. However, in a highly stratified system, multi-layer flow may persist through the tidal cycle. The effect of multi-layer flow during flood tide is modelled by reducing the average salinity of the inflowing water according to the degree of stratification and density-induced circulation in the estuary. The quantity of salt entering an estuary is then the product of the flood tidal flux and the reduced salinity where the reduced salinity is a function of the stratification-circulation in the estuary. It takes on a value equal to ocean salinity when the system is vertically mixed, a slightly lower value when the system is partially stratified and the ebb tidal outflow may not have completely mixed with the sea water, and a still lower value when the estuary is highly stratified and there is a continuous outflow of low salinity water at the surface. The salt import rate is given by:

$$x_{51} = \begin{cases} x_{14} RS(x_6, x_7), & x_{14} > 0 \\ 0, \mathit{otherwise} \end{cases} \tag{4}$$

where x_{51} = salt import (kg. yr^{-1}), x_{14} = tidal flow (m^3. yr^{-1}), $RS(x_6, x_7)$ = reduced salinity (kg. m^{-3}), x_6 = stratification index (unitless), and x_7 = circulation index (unitless). Here $x_{14} > 0$ indicates that water is entering the estuary, and it is flood tide. The formulation of the equations for the stratification-circulation state of an estuary are developed after those related to the salt content.

The export of salt from an estuary generally occurs during ebb tides, although highly stratified systems are characterised by a continuous outflow of low salinity surface water and inflow of high salinity bottom water (Fischer, 1979; Largier and Taljaard, 1991; Dyer, 1997). Flooding or periods of high river flow may expel all salt from an estuary (Slinger et al., 2017; Coates and Guo, 2003; Coates and Mondon, 2009). Accordingly, the quantity of salt lost to a system depends on the magnitude of the outflowing volume and the saline concentration of the water.

For a uniformly mixed estuary, the salt export rate is the product of the outflowing volume flux and the average concentration, that is the ratio of the salt content to the water volume of the estuary. Most well mixed estuaries and partially stratified systems, however, exhibit a longitudinal gradient in salinity with fresher riverine water located near the head of the estuary and sea water near the mouth (Dyer, 1997). This axial variation in salinity means that under average flow conditions the concentration of the effluent water is higher than the average salinity of the estuary, because the higher salinity water located near the mouth is expelled from the estuary first. This effect is heightened under low river flow conditions when tidal exchange usually only affects the lower reaches of an estuary. Under high river flow conditions the concentration of the outgoing water approaches the average salinity of the estuary because more effective flushing occurs. This observation holds true even when a freshwater flood flushes the entire system, expelling water of zero salinity (the average concentration under these conditions) through the mouth.

Vertical gradients in salinity and density-induced circulation influence the salt export rate. In highly stratified estuaries, the flushing of saline water is less effective than in well mixed and partially stratified estuaries despite the continual outflow of surface water. Salt is flushed from these systems through entrainment of the saline bottom layer by the outflowing surface layer (Coates and Guo, 2003; Coates and Mondon, 2009). The process of entrainment increases the volume of estuarine water entering the coastal sea above that ascribable to river discharge alone (Fischer, 1979). Yet, it is not as effective a mixing mechanism as turbulent diffusion which is the predominant process in well mixed estuaries and is active in partially stratified estuaries (Dyer, 1997; Whitney et al., 2012). The bar at the estuary mouth or the presence of sills elsewhere in the system may cause topographic blocking of the downstream movement of saline bottom water on the ebb tide (Largier and Slinger, 1991; Largier et al., 1992; Slinger et al., 2017) and reduce the rate at which salt is exported from such stratified systems even further. This effect on the salt export rate is included through a stratification export function (*SEF*), a function of x_6 and x_7, that moderates the product of the average saline concentration and the ebb tidal flux. The salt export rate is given by:

$$x_{52} = \begin{cases} \frac{x_5}{x_1} x_{14} SEM(x_3, x_4) SEF(x_6, x_7), & x_{14} < 0 \\ 0, \mathit{otherwise} \end{cases} \tag{5}$$

where x_{52} = salt export (kg. yr^{-1}), x_1 = estuary water volume (m^3), x_{14} = tidal flow (m^3. yr^{-1}), *SEM* = salinity export multiplier (unitless), x_3 = freshwater flushing (unitless), x_4 = tidal flushing frequency (yr^{-1}), *SEF* = stratification export function (unitless), x_6 = stratification index (unitless), and x_7 = circulation index (unitless).

2.3. Stratification and circulation

There have been many attempts to characterize estuary stratification and circulation accordingly to universally applicable principles. Historically, the first stratification index used the ratio of river flow per tidal cycle to the tidal prism to reflect the density stratification in an estuary. Pritchard (1956) was the first to pinpoint the role of hypsometry in determining the stratification-circulation of an estuary, and examples where the first index fails in the Mersey Estuary and Southhampton water were indicated by Dyer (1973). Ippen and Harleman's (1966) ratio of tidal energy dissipation to potential energy gain per unit mass of water measures the amount of energy lost by the tidal wave relative to that used in mixing the water column. This stratification number is analogous to the inverse of a Richardson number (Dyer, 1973) and requires fairly accurate data on river flow and tidal elevation along an estuary for its calculation.

As early as 1966, Hansen and Rattray (1966) defined two non-dimensional parameters of stratification and circulation, that have subsequently been applied extensively in the classification of estuaries (Jay and Smith, 1988; Largier et al., 1992; Scott, 1993; Slinger, 1997; Dyer, 1997; Weisberg and Zheng, 2003). The stratification parameter is defined as the ratio of the difference between the bed and surface tidally averaged salinity to the depth mean salinity ($\Delta S/\overline{S}$). The circulation parameter is defined as the ratio of the residual velocity at the surface to the depth mean value (u_s/u), and measures the strength of the baroclinic circulation. Four types of estuary can then be distinguished using these parameters. Type 1 estuaries are dominated by diffusive processes rather than gravitational circulation and are generally well mixed, with net seaward flows and little to no vertical structure. Type 2 estuaries are partially mixed exhibiting gravitational and longitudinal circulation with advective and diffusive processes contributing to the landward transport of salt. Type 3 estuaries are stratified with strong gravitational circulation and advective processes predominating in the landward transport of salt. Type 4 are salt wedge estuaries with limited vertical mixing (Fig. 1). For all but the salt wedge estuaries sub-types a and b are distinguished with type b more stratified than type a. Hansen and Rattray related their stratification-circulation parameters theoretically to an analysis of estuarine motion and empirically to two bulk parameters: the ratio of river flow to tidal flow and a bulk densimetric Froude number based on the river flow. The bulk densimetric Froude number is given by:

$$F_m = \frac{q_f}{BD\sqrt{\frac{\Delta\rho_H}{\rho} gD}} \tag{6}$$

where F_m = bulk densimetric Froude number (unitless), q_f = freshwater inflow rate (m^3. s^{-1}), B = channel width (m), D = mean depth (m), $\Delta\rho_H$ = head to mouth density difference (kg. m^{-3}), ρ = ocean density (kg. m^{-3}), g = gravitational acceleration (m. s^{-2}).

The circulation parameter depends primarily on the value of the bulk densimetric Froude number, but the stratification parameter depends on both of the bulk parameters. So, Hansen and Rattray established that a stratification-circulation diagram could be used to classify estuaries according to their circulation and salinity structures, but they failed to determine two independent bulk parameters to characterie estuaries. Fischer (1979) addressed this inadequacy by defining a non-dimensional number, known as the Estuarine Richardson number (R_E), which compares the stabilizing forces of density stratification to the destabilizing forces of velocity shear. R_E is defined as the ratio of the input of buoyancy per unit width of channel to the mixing power available from the tide:

$$R_E = g\,\frac{\Delta\rho_H}{\rho}\,\frac{q_f}{B}\Big/u_{rt}^3 \tag{7}$$

where R_E = Estuarine Richardson number (unitless), g = gravitational

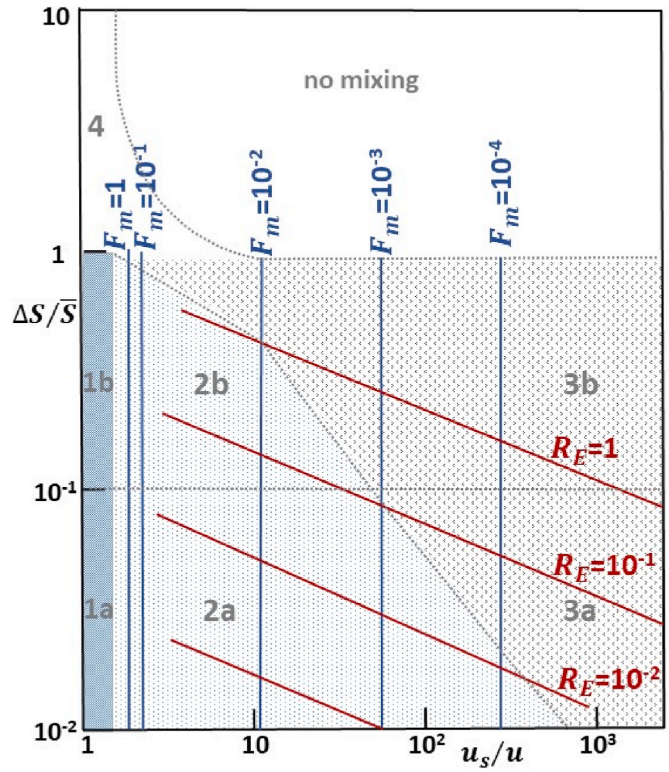

Fig. 1. Stratification-circulation in estuaries (after Hansen and Rattray, 1966) in relation to the two bulk parameters, the estuarine Richardson number and the bulk densimetric Froude number. Four general types of stratification-circulation state are indicated, namely: well mixed estuaries (1a, b), partially mixed estuaries (2a,b), highly stratified estuaries (3a,b), and salt wedge estuaries (4), with the b sub-type indicating the presence of more stratification than the a sub-type.

acceleration (m. s^{-2}), $\Delta\rho_H$ = head to mouth density difference (kg. m^{-3}), ρ = ocean density (kg. m^{-3}), q_f = freshwater inflow rate (m^3. s^{-1}), B = channel width (m), and u_{rt} = root mean square tidal velocity (m. s^{-1}). The stratification parameter of Hansen and Rattray depends primarily on R_E, indicating that the two independent bulk parameters needed to characterize the stratification-circulation state of an estuary are the Estuarine Richardson number (providing an index of stratification) and the bulk densimetric Froude number (providing an index of circulation). After a deep mathematical analysis, the suitability of these bulk parameters for characterizing estuaries in terms of stratification and circulation was affirmed by Scott (1993). The dependence of the stratification and circulation parameters of Hansen and Rattray on the bulk parameters F_m and R_E is depicted in Fig. 1.

Nowadays high-precision measurements from acoustic Doppler current profilers and moored continuous data loggers are used to estimate gradient Richardson numbers for diverse positions within an estuary. However, where such data are not available, the bulk version of the Richardson number is still used. The interpretation of the bulk Richardson number is similar to that of the gradient Richardson number, except that it is a single stability metric for the entire water column. When the bulk Richardson number is small, the water column is turbulent, and when it is large, the water column is stable. However, no universal or clearly defined critical value has been determined (Wells and Troy, 2022).

Accordingly, dynamic bulk parameters analogous to the Estuarine Richardson number and the bulk densimetric Froude number are formulated from model variables as indices for stratification and circulation. Following Scott (1993), a function of the mean salinity of the system is used to represent the ratio $\Delta\rho_H/\rho$ of the head to mouth density difference to the ocean density. The ratio of freshwater discharge to the estuary width is represented in turn by the ratio of the freshwater inflow rate (x_{11}/c to express it in $m^3.\ s^{-1}$) to a characteristic width B. The depth is represented by the water level h. When the estuary mouth is open, the tidal velocity in $m.s^{-1}$ is $|x_{14}|/ca$, where a is the mouth cross-sectional area. When the mouth is closed, a tidal velocity that is likely to have occurred immediately prior to the closure of the mouth is used ($|x_{min}|/ca$). This ensures that the model-generated Estuarine Richardson number will then only change in response to changes in the freshwater discharge rate. Finally, first order exponential delays are applied to represent the tidal mean formulation of Hansen and Rattray (1966). Therefore the model-based **stratification** and **circulation indices** are:

$$R_{model} = g\ DF\left(\frac{x_5}{x_1}\right)\frac{x_{11}}{cB} \bigg/ u_t^3 \tag{8}$$

$$u_t = \begin{cases} \dfrac{|x_{14}|}{ca}, \left|x_{14}\right| > x_{min} \\ \dfrac{x_{min}}{ca}, otherwise \end{cases} \tag{9}$$

$$F_{model} = \frac{x_{11}}{cBwl\sqrt{DF\left(\frac{x_5}{x_1}\right)gwl}} \tag{10}$$

$$\frac{dx_6}{dt} = (R_{model} - x_6) \bigg/ t_3 \tag{11}$$

$$\frac{dx_7}{dt} = (F_{model} - x_7) \bigg/ t_3$$

where R_{model} = analogue Estuarine Richardson number (unitless), g = gravitational acceleration ($m.\ s^{-2}$), DF = density anomaly function (unitless), x_5 = salt (kg), x_1 = water volume (m^3), x_{11} = freshwater inflow rate ($m^3.\ yr^{-1}$), $c = 3{,}1536 \times 10^7$ ($s.\ yr^{-1}$), B = characteristic estuary width (m), u_t = tidal velocity ($m^3.\ s^{-1}$), x_{14} = tidal flow ($m^3.\ yr^{-1}$), a = mouth cross-sectional area (m^2), x_{min} = minimum tidal flow ($m^3.\ yr^{-1}$), F_{model} = analogue densimetric Froude number (unitless), wl = water level (m), x_6 = stratification index (unitless), x_7 = circulation index (unitless), and t_3 = time delay constant 3 (yr).

This completes the formulation of the state variables for the salt content of the estuary, the stratification and circulation indices, and the freshwater and tidal flushing.

3. Applying the model to the Great Brak

Numerous field measurements over a thirty-five year period led to a synthesized understanding of the flushing and water renewal mechanisms at play in the Great Brak Estuary in South Africa (Slinger et al., 2017). This knowledge base, together with the ongoing need to address mouth management, water quality and freshwater requirements issues (Taljaard et al., 2017; van Niekerk et al., 2021), contributed to the decision to apply the model to this system. The Great Brak Estuary is a small (7 km in length), wave-dominated estuary subject to intermittent mouth closure, with an Escoffier criteria for inlet stability in the range 'normally closed' to 'unstable' (see Goodman, 1996). A combination of high waves and low river flows, influenced by the presence of a large dam 3 km upstream of the estuary, leads to frequent and sometimes prolonged closure of the mouth (van Niekerk et al., 2021). River floods, freshwater releases from the dam, or mechanical breaching are required to open the mouth again and restore the exchange of water with the marine environment. Of interest is the simulation of the characteristic salinity distribution and stratification-circulation states known to be associated with the different mouth conditions and river flows (CSIR, 1990, 1992, 2003; DWAF, 2008; Slinger et al., 1994, 2017).

System dynamics modelling (Forrester, 1961, 2007; Slinger, 1997, 2017) was applied to formulate the equations of the parametric model. The model applies a hypsometric curve to parametrize the water level to volume relationship of the estuary basin (derived from survey measurements), and comprises two differential equations for the water volume and sill height at the mouth (see Slinger, 2017), and five differential equations for the tidal and freshwater flushing, the salt content, and the stratification and circulation indices (Section 2). The model is coded in Fortran and simulated using a double precision variable step numerical method with error bound set to 0,01%. Results from applications to both the Great Brak and Kromme Estuaries in South Africa were compared with routines from the IMSL Fortran Numerical Library and were found to agree within the error bound (Slinger, 1997). A version of the model coded in Vensim DSS (www.vensim.org) was simulated with a time step of 12,5 min to the same level of numerical accuracy and was used to simulate the water volume and mouth dynamics of the Slufter in the Netherlands (D'Hont, 2014; D'Hont et al., 2014).

3.1. Model calibration

The calibration of the water volume, sediment transport and sill height at the mouth and the subsequent simulation of the water volume and associated alterations in the mouth sill height dynamics are reported in Slinger (2017, specifically in Section 3.2 and Table A1, A2 and A3). Here, the calibration of the freshwater and tidal flushing, the salt sector and the stratification-circulation are reported. Details of the parameter values of the calibrated model are provided in Table 1.

The freshwater and tidal flushing sectors are calibrated by choosing values for the reference freshwater inflow rate and the delay times (Table 1). The reference freshwater inflow rate (x_{11r}) is set to the flow that would have occurred in the driest month under natural conditions, and the freshwater time delay constant (t_1) is selected to reflect the 5.5 days that would be required to replace the estuary volume at 0,6 m to

Table 1
Parameter values for the calibrated model.

Parameter	Symbol	Value
reference freshwater inflow rate	x_{11r}	$4.5 \times 10^6\ m^3\ yr^{-1}$
time delay constant 1	t_1	0.015 yr, 5.5 days
time delay constant 2	t_2	0.009855405 yr, 7 *x* the semi-diurnal tidal period
reduced salinity	*RS*	Formulated to yield values between 35 and 34.5 when an estuary is well mixed, gradually decreasing to values of 14 when an estuary is strongly stratified (Slinger, 1997: p91-93)
salinity export multiplier	*SEM*	Formulated as a two-dimensional table function with a maximum value of 1.5 under high freshwater flushing, an intermediate value of 1,25 when tidal flushing is high but freshwater flushing limited and a minimum value of 1.1 when both the freshwater and tidal flushing are low (Slinger, 1997: p87-88)
stratification export function	*SEF*	Formulated as a two-dimensional table function with a maximum value of 1.008 under vertically mixed conditions and a minimum value of 0.92 when an estuary is highly stratified (Slinger, 1997: p91-93)
time delay constant 3	t_3	0.004223745 yr, 3 *x* the semi-diurnal tidal period
density anomaly function	*DF*	Monotonic decreasing function, with a maximum of 0.034 when mean salinity is 0, and a minimum of 0 at mean salinity 40. Interim values are 0.0025 at 30, 0,018 at 20, 0.031 at 10 and 0,033 at 5.
constant	c	$3{,}1536 \times 10^7\ s\ yr^{-1}$
characteristic estuary width	B	55 m, the average width at 0.6 m to MSL
gravitational acceleration	g	$m.\ s^{-2}$
mouth cross section	a	m^2
water level	wl	m to MSL

MSL (mean sea level) under this flow regime. The tidal flushing time delay constant (t_2) is set to seven times the semi-diurnal tidal period as this is the time period over which successive tidal intrusions are inferred to have renewed bottom water in the upper reaches under open mouth conditions (see Slinger et al., 2017).

The calibration of the salt content of the estuary is complex. For this the salinity structure measured on November 30, 1988 is selected as representing an open mouth situation accompanied by low freshwater flows (CSIR, 1990) that is characteristic of the small, intermittent Great Brak estuary (see DWAF, 2008; Slinger et al., 2017). Under this situation, freshwater is confined to the head reaches of the estuary, the estuary is predominantly saline and there is slight vertical stratification. Tidal exchange is active in the lower reaches, while renewal of water in the middle reaches is limited. The following values are assigned: a base freshwater flow averaging 0.2 m^3 s^{-1}; no high waves; rainfall, evaporation groundwater and semi-diurnal and spring-neap tidal variation as in Slinger (2017); initial mean salinity of 29 to accord with measurements; an *RS* value of 34.5 (equivalent to sea salinity) and a *SEF* value of unity because the stratification-circulation sector is still not calibrated. The salinity export multiplier (*SEM*) is then formulated as a two-dimensional function of similar form to the table functions of classical system dynamics (Forrester, 1961). Preliminary simulations are then conducted using initial values for this function and the simulated values are compared with measurements in the estuary under low freshwater flows and open mouth conditions. This step is repeated with adjustments to the *SEM* function values until reasonable agreement between simulated and characteristic mean salinities is obtained (see DWAF, 2008; Slinger et al., 2017). With the parametrisation listed in Table 1, the simulated mean salinities range from 21 to 30 in the estuary when there is the lowest freshwater flow in April, May and June, whereas the mean salinities range from around 10 and 12 to 28 during November and September when freshwater inflow is stronger. These salinity ranges are representative of the Great Brak estuary when the mouth is open and freshwater flows are relatively low (approximating 18,5 % of the natural mean annual run-off or below). The spring-neap variation in mean salinities concurs with observed behaviour.

Both the stratification and circulation indices are dependent on the density anomaly function, which depends in turn on the mean salinity. The form of this function (Table 1) is determined using empirical knowledge of the average salinity conditions and associated density differences characteristic of the relatively shallow and small estuaries common in South Africa (Largier, 1986; MacKay and Schumann, 1990; Slinger et al., 2017). The authenticity of these choices of parameter values for the Great Brak Estuary is established by simulating a freshwater flow similar to the minor flood release of 29–November 30, 1990. This involved the release of 3.8×10^5 m^3 of freshwater into the estuary over 13 h. A maximum efflux of 15.5 m^3 s^{-1} through the open mouth is simulated. This agrees reasonably well with the maximum outflow rate of 16.6 m^3 s^{-1} calculated from hourly measurements of the actual event. The simulated salinities range from 22 to 32 prior to the release (reflecting conditions with 0.1 m^3 s^{-1} freshwater flow and an open mouth), but decline steeply when the freshwater released from the dam enters the estuary exhibiting a minimum salinity of about 6. One and a half weeks later the average salinities range from 22 to 32, once again agreeing with measurements (Slinger et al., 1994). The indices of stratification and circulation attain their maximum values about a day and a half after the release commenced. The stratification-circulation state is that of a partially mixed system with top to bottom salinity differences about 16% of the depth mean salinity. The delay between the start of the release and the maximum simulated stratification-circulation state arises because the indices are formulated as first order exponential delays of the analogue Estuarine Richardson number and bulk densimetric Froude number, respectively. However, it is reflective of the real situation in which buoyant freshwater spreads over the more saline layers at depth in the estuary with turbulence-induced flushing limited to the upper reaches, leading to a stratification state that is at a maximum one to two days after a strong freshwater influx. The stratification-circulation state returns to a less stratified, yet still partially mixed situation characteristic of the Great Brak under low inflow and open mouth tidal conditions (see CSIR, 1990, Slinger et al., 1994) within ten days. In these circumstances, the top to bottom salinity differences are usually less than 5% of the mean salinity. Although the stratification in isolated deep holes in the Great Brak Estuary is not reflected by the model, the simulations of the stratification-circulation state of the water body are considered representative of the real situation of a freshwater flow event as the deep holes contribute less than 9% to the volume of the Great Brak Estuary at 0.6 m to MSL.

The reduced salinity function is formulated to ensure that salinities lie between 35 and 34.5 when the estuary is well mixed, gradually declining to 14 when the estuary is strongly stratified. The stratification export function is a two-dimensional table function with a maximum value of 1.008 under vertically mixed conditions and a minimum value of 0.92 when the estuary is highly stratified. The greatest influence of the stratification-circulation state on mean salinities occurs during the freshwater release and neap tides as expected, because stratification is enhanced when the freshwater input increases and/or the tidal influence decreases. Accordingly, the peaks in mean salinity occur at neap tides in Fig. 2. The deviation in salinities arising when the stratification-circulation state is taken into account is less than 20% at the time of the release and less than 12% at neap tides, once again reflecting that the Great Brak is a partially mixed estuary.

3.2. Simulation runs

Multiple simulation runs were executed with the calibrated model, four of which are reported here. These are selected to highlight the effects of reductions in freshwater flows on the estuary, from the **natural situation**, to the **pre-dam situation** in which 30% of the mean annual run-off is used in the catchment and does not reach the estuary, to **two post-dam situations** in which the supply of freshwater to the estuary is reduced by 94% following the construction of the Wolwedans Dam in 1988 (Table 2). A further effect of reduced freshwater flows lies in the increased sensitivity of the estuary to mouth closure in response to high wave events, as demonstrated in Slinger (2017). The increased frequency of mouth closure is incorporated in the reported simulation runs with the mouth only closing in June under the natural situation and in late April/early May (remaining closed over June) and December in the pre-dam situation (Table 2). In the post-dam situation the mouth closes in November/December, February, late April/early May (remaining closed over June) and mid-July. The associated breaching policies are selected to represent current and historical interventions to open the mouth of the estuary (CSIR, 1990; Slinger, 2017).

4. Results

Under **natural run-off conditions**, spring tidal fluxes through the mouth vary from 12 m^3 s^{-1} on the flood to 9 m^3 s^{-1} on the ebb. The higher magnitude of the flood tidal flux reflects the flood tidal dominance of this small, shallow estuary even under pristine conditions with substantial freshwater flows. Over neap tides, no seawater penetrates the estuary, although estuarine water continues to flow out through the shallow mouth. Tidal exchange ceases entirely when the mouth closes in June and the salinity in the estuary declines from an average of 22.5 to less than 2.5 immediately before the mouth breaches as only freshwater is entering the system. With the mouth open, strong tidal intrusion occurs and the mean salinities reach an overall maximum of 25 once again. In general, the mean salinities lie between 18 and 25 on spring tides, decreasing to near zero at low water neap tides. These dynamics are illustrated in Fig. 3, while the water levels in the estuary and the height of the sill at mouth are depicted in the Supplementary Material. Note that the simulation year begins on 1 October in all cases in accordance with the austral hydrological year.

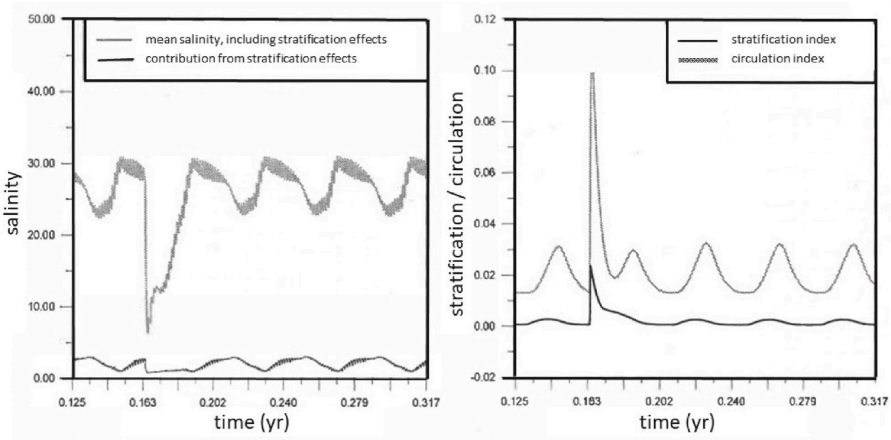

Fig. 2. Simulated mean salinity (left) and stratification-circulation (right) in response to a minor flood release on 29–November 30, 1990. The difference in the mean salinity occasioned by stratification-circulation effects is distinguished.

The stratification index ranges from 4×10^{-3} to about 3×10^{-2} and the circulation index varies between 2×10^{-2} and 6×10^{-2}, indicating that the Great Brak Estuary is partially mixed (type 2a) under the natural run-off scenario. The stratification index shows sensitivity to seasonality in freshwater inflows, exhibiting higher maxima during the stronger freshwater inflows in Nov and March (Fig. 3). The effect of the spring-neap tidal variation is evident throughout the year, with bi-monthly maxima and minima in the stratification index occurring about four days after the neap and the spring tides, respectively. The more vigorous tidal mixing associated with spring tide de-stratifies the water column, whereas this effect is negligible on the neap tide when the inflowing freshwater acts to intensify stratification of the water column. This influence is felt during and immediately after neap tide until the onset of spring tide. The role of freshwater in intensifying the stratification is clearest in June when the mouth is closed and the estuary gradually fills with freshwater over the more saline bottom water. The stratification index increases from just under 2×10^{-2} to above 3×10^{-2}. After mouth breaching, the stratification index shows values similar to after neap tide, indicating that the effects of freshwater still linger in the system. Thereafter, the stratification index declines below 2×10^{-2}, showing values characteristic of stronger tidal influence and low freshwater flows in the Great Brak estuary. In short, the estuary remains in a partially mixed state (type 2a) throughout.

The annual freshwater flushing maximum of 11.5 in late November and the smaller peaks late in March and September reflect the accumulated effects of sustained slightly higher freshwater flows, while the annual minimum of 3.5 in later June to early July reflect the low inflows over the preceding month. The tidal flushing frequency is reduced during the period of mouth closure with a near zero minimum in June. This contrasts with the maximum of 500 yr^{-1} in November and March when the mouth is open, freshwater flows are higher, and tidal exchange is active.

Under the pre-dam run-off scenario, the mouth closes in May and Dec and water levels rise to 1.82 and 1.63 m to MSL, respectively, before breaching occurs. During both mouth closures, the mean salinities in the estuary decline to below 2, but rise to maxima of 27 on the spring tide after the mouth breaching (Fig. 3). The spring-neap tidal variation strongly influences the mean salinities when the mouth is open. As in the natural run-off situation, the bi-monthly maxima reflect the intrusion of highly saline water through the mouth over the spring tide and the bi-monthly minima represent the continuous inflow of freshwater at the head and the slow efflux of estuarine water through the mouth during the neap tides.

The stratification and circulation indices range from 3×10^{-3} to near 3.2×10^{-2} and 3×10^{-3} to 4.4×10^{-2}, respectively, indicating that the Great Brak Estuary remains partially mixed under the pre-dam run-off scenario. However, the stratification index shows higher sensitivity to tidal influence under reduced freshwater inflows when compared with the natural run-off scenario. This is most noticeable in April–May, before the mouth closes, when the stratification index ranges from minima of 3×10^{-3} after spring tides to maxima of 3.1×10^{-2} after neap tides. Such variations also occur after mouth breaching, but they are ascribed to two effects combining. First, the stratifying influence of the freshwater entering the closed system has not dissipated, but lingers on, and second, the lower freshwater inflows in the months of Jan–Feb and July–Aug mean that there is enhanced sensitivity to tidal influence. Thus, the amplitude of variation in the stratification state of the estuary under the pre-dam run-off scenario increases over periods of lower freshwater flow compared with the natural run-off scenario, with the lower over the periods of higher flow such as Nov, March and Sep. The circulation index shows a decreased range of variation and has a lower maximum value compared with the natural situation. Increased mouth closure also leads to reduced baroclinic circulation, although the estuary remains partially mixed throughout (type 2a). This stratification-circulation response indicates that the capacity of the water body to buffer changes in the riverine and marine forcing is reduced in comparison with the natural situation.

The freshwater flushing of the system is substantially reduced under the pre-dam situation compared with the natural situation, and shows less variability with a maximum of 8 and a minimum near 3. The tidal flushing is also less vigorous than under the natural run-off scenario, reaching a maximum of about 475 yr^{-1} in November and March compared with 500 yr^{-1} and a minimum near zero twice a year rather than once a year when the mouth is closed.

In the post-dam freshwater flow situations, the mouth of the estuary closes four times per year in early Nov, late Feb, late April and mid-July. With the mouth open, the tidal fluxes vary from a maximum of 12 $m^3 s^{-1}$ on the flood to a minimum of 8 $m^3 s^{-1}$ on the ebb. The mean salinities under the post-dam with base flow situation reach a maximum of 28 on the spring tide and show minima of between 6 and 12.5 depending on the seasonality in the freshwater inflow (Fig. 3). Salinities generally decrease to less than 3 when the mouth is closed. An exception occurs in Feb when the mouth closes at spring tide when salinities in the estuary are high, and mouth closure is not prolonged. The post-dam freshwater releases are timed to coincide with periods of mouth closure and cause mean salinities to decrease below 10 three times per year. However, when the mouth is open, the salinities in the estuary generally are higher than under post-dam base flow conditions.

Comparing the stratification-circulation states of the Great Brak Estuary under the post-dam scenarios reveals that when the limited freshwater allocation is delivered to the estuary as base flow, there is a strong reduction in the amplitudes of variation and the average values of

Table 2
Freshwater inflow and mouth breaching conditions for the Great Brak Estuary model.

Freshwater flow	Total annual volume	Seasonal variation in freshwater flow	Mouth closure	Breaching policy
Natural	34×10^6 m^3 yr^{-1}	Seasonal variation typical of the southern Cape coast i.e. least run-off during June (50% of MAR) with high run-off in Sep, Nov and March (between 133% and 151% of the MAR). The average flow in October is slightly lower than in Sep and Nov	High waves in June cause mouth closure	Natural breaching, or mechanical breaching at water levels of 1.95 m to MSL after 15 days at a rate of - 1870 m. yr^{-1} for 2 h
Pre-dam	24×10^6 m^3 yr^{-1}	Seasonal variation typical of the southern Cape coast, but with 30% reduced amplitude of variation	High waves in late April/early May and Dec cause mouth closure	Mechanical breaching at water levels between 1.85 and 1.62 m to MSL. The breaching rate is −0.2 m per hour for 2 h
Post-dam with base flow	2×10^6 m^3 yr^{-1}	Average annual volume released as a base flow throughout the year. The base flow has slight seasonal variation (96% reduction in amplitude of variation)	High waves in Nov/Dec, Feb, late April/early May and mid-July cause mouth closure	Mechanical breaching at water levels between 1.85 and 1.62 m to MSL. The breaching rate is −0.2 m per hour for 3.5 h
Post-dam with releases	2×10^6 m^3 yr^{-1}	3 flood releases of 5×10^5 m^3 each on 29 November, 27 February, 15 September respectively, and a base flow of 5×10^5 m^3 throughout the year. The base flow has slight seasonal variation (96% reduction in amplitude of variation)	High waves in Nov/Dec, Feb, late April/early May and mid-July cause mouth closure	Mechanical breaching at water levels between 1.85 and 1.62 m to MSL. The breaching rate is −0.2 m per hour for 2 h

both the stratification and circulation indices. The maximum in the circulation index decreases to 2.6×10^{-2}, while that of the stratification index is 2.4×10^{-2}. However, under the post-dam with releases situation, the stratification index tri-annually attains values exceeding 7×10^{-2} and the circulation index tri-annually exceeds 6.5×10^{-2}. Between such flood events, the stratification in the system remains minimal (stratification index values lower than 5×10^{-3}) and the circulation index is always lower than 5×10^{-3}. These figures indicate that the Great Brak Estuary remains partially mixed and that the minor flood releases are not sufficient to thrust the estuary into a highly stratified state. However, the contribution of the density-driven circulation to the landward transport of salt does increase during flood events (see Slinger et al., 2017), as indicated by the maxima in the circulation index. The strategy of releasing freshwater floods as opposed to only continuous base flows, therefore, causes the estuary to exhibit partially mixed states more typical of the variability found under natural run-off conditions interspersed with periods in which the estuary remains partially mixed but the water column is fairly uniform. The latter condition is less characteristic of the estuary under natural conditions. So, the strategy of releasing floods goes some way towards alleviating the change in stratification-circulation state towards a persistent, more uniform water column, but the effect is extremely short-lived.

The freshwater flushing in the post dam situation with base flow exhibits a substantial reduction in the amplitude of variation and the average value compared with the pre-dam and natural freshwater flow conditions. This sharp decline associated with decreasing freshwater supply indicates a severe reduction in the capacity of the estuary to flush older water from the system by the turbulence-induced mixing associated with high velocity freshwater flows. The post-dam with releases scenario, tries to re-introduce such effects. Under this situation, the freshwater tri-annually attains levels characteristic of the pre-dam freshwater flow situation, but shows little freshwater flushing at times other than during and immediately after such a water release.

The tidal flushing of the Great Brak estuary under the post-dam base flow situation achieves maxima of about 450 yr^{-1} (compared with 475 yr^{-1} under the pre-dam situation) and minima of zero when the mouth is closed. When the mouth is open to tidal exchange, the tidal flushing minima are only about 100 yr^{-1}, indicating that there is a substantial reduction in the efficacy of tidal flushing between the pre-dam and the post-dam with base flow situations. In the post-dam with releases situation, the tidal flushing bears this out, exhibiting a maximum of 430 yr^{-1}, and minima of 50 yr^{-1} when the mouth is open. Clearly, the tidal flushing of the Great Brak Estuary is severely impacted by the reduction in freshwater flow to the system and water releases do not appear to exert an ameliorating effect.

5. Concluding discussion

This study explores whether the stratification-circulation state and the balance between tidal or freshwater flushing in small, wave-dominated estuaries can be simulated over long time scales in association with parametric modelling of the mouth dynamics. The answer is a resounding Yes!

Diverse freshwater flow and mouth closure and breaching scenarios have been simulated for the Great Brak Estuary in South Africa, varying from near natural conditions to highly modified situations in which 94% reduction in freshwater flow occurs and the mouth is breached mechanically at least 4 times per year. Time horizons of 5 years and more were simulated with ease. Results indicate that mean salinities can be simulated with acceptable accuracy, and that the balance between freshwater and tidal flushing alters as the estuary is starved of freshwater. However, the overall character of the estuary does not alter. It remains a partially mixed system, as indicated by the simulation outputs. Although the model cannot reflect the difficulty in flushing old water from deep scour holes (forming only 9% of the water volume at 0.6 m to MSL), it does accurately determine the stratification-circulation state as type 2a throughout.

A unique aspect of this system dynamics simulation approach that could form a limitation to its wider application is the requirement to specify the hypsometry of the estuary basin as a relation between water level and water volume. In our case, bathymetric survey data were use to determine this relationship for the Great Brak Estuary. However, such data may not be readily available for other small, wave-dominated and intermittent estuaries. Similarly in determining the characteristic width at the mouth (the inlet throat), for instance, we used survey data. We drew on a deep understanding of the hydrodynamics of the chosen case study in calibrating the model and interpreting the outcomes. As such, the applicability of the model to systems other than small, intermittent estuaries in the micro-tidal range is not yet established.

It would be of interest, however, to simulate some of the alternative stratification-circulation indices deriving from the work of Guha and Lawrence (2013), and Dijkstra and Schuttelaars (2021), for instance, and to cross-compare outcomes against existing measurements for

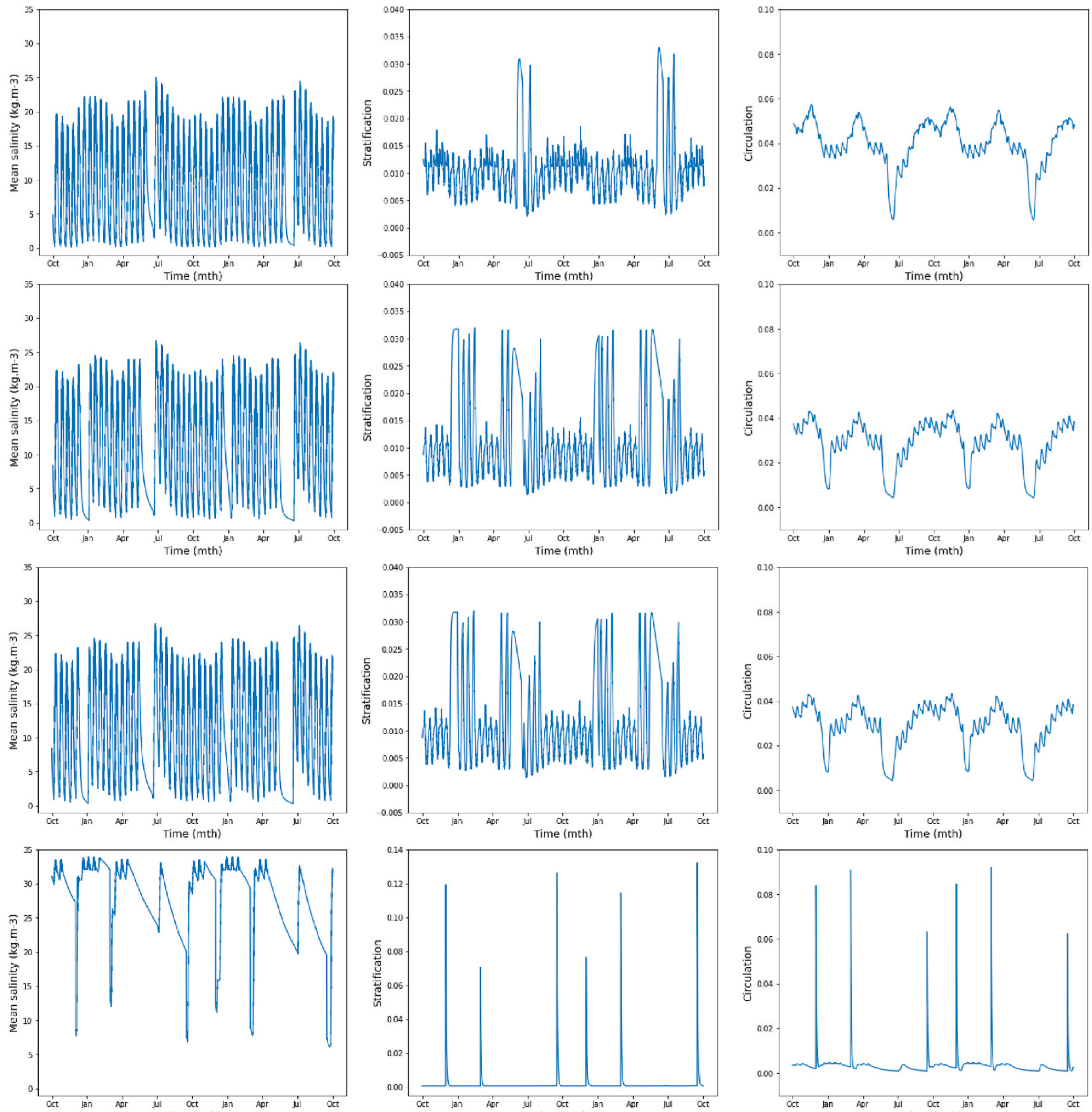

Fig. 3. Simulated mean salinity (left), stratification (centre) and circulation (right) from year 3–5 under: natural run-off conditions, with the mouth closing once per year (top); pre-dam run-off conditions, with the mouth closing twice per year (upper middle); low post-dam freshwater base flow conditions, with the mouth closing four times per year (lower middle); the post-dam condition with freshwater releases and the mouth closing four times per year (bottom).

systems other than the Great Brak. The true potential of such a simulation capability lies in investigating the effects of alterations in run-off, wave and sediment transport conditions along coasts on the flushing and renewal of small estuaries (cf. Shen et al., 2022). This could aid in determining their freshwater or e-flow requirements, and assist coastal practitioners in designing mouth breaching strategies. Moreover, the combined effects of low freshwater run-off, and increased flooding and high wave events could be investigated over decadal time periods. The insights gained regarding adaptive management could assist estuary managers in increasing climate resilience and addressing the many challenges these small, intermittent estuaries face.

CRediT authorship contribution statement

Jill H. Slinger: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2024.108720.

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