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The Calculation of Estuarine Turnover Times Using Freshwater Fraction and Tidal Prism Models: A Critical Evaluation

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ABSTRACT: Freshwater fraction and tidal prism models are simple methods for estimating the turnover time of estuarine water. The freshwater fraction method prominently features flushing by freshwater inflow and has sometimes been criticized because it appears not to include flushing by seawater, but this is accounted for implicitly because the average estuary salinity used in the calculation reflects all the processes that bring seawater into the estuary, including gravitational circulation and tidal processes. The model relies on measurable salinity differences among water masses and so must be used for estuaries with substantial freshwater inflow. Tidal prism models are based on flushing by flood tide inflow and ignore seawater inflow due to gravitational circulation. These models should only be applied to estuaries with weak or nonexistent gravitational circulation, which are generally those with little freshwater inflow. Using a framework that is less ambiguous and more directly applicable to the estimation of turnover times than those used previously, this paper critically examines the application of tidal prism models in well-mixed estuaries with complete tidal exchange, partial ebb return, or incomplete flood mixing and in partially mixed estuaries. Problems with self-consistency in earlier versions of these models also apply to the budgeting procedure used by the LOICZ (Land-Ocean Interactions in the Coastal Zone) program. Although freshwater fraction and tidal prism models are different approaches to estimating turnover times in systems with very different characteristics, consistent derivation shows that these models have much in common with each other and that they yield equivalent values that can be used to make comparisons across systems.

Introduction

Time scales that describe the mixing, transport, or escape of estuarine water are often used to characterize estuaries and to make general comparisons among them. Metrics such as turnover time, transit time, age, and residence time all describe different aspects of the rate of replacement of estuarine water and dissolved constituents. There are also various models or equations for quantifying these mixing time scales, some of which take differing approaches to quantifying the same time scale. This variety of mixing time scales and equations, combined with overlapping terminology, has led to some confusion in the literature (Monsen et al. 2002; Sheldon and Alber 2002). In spite of the confusion, a general estimate of the rate of replacement of estuarine water can be useful for determining the sensitivity of a particular system to the introduction of pollutants or other materials, or as a baseline against which to evaluate the rates of other estuarine processes. Estuaries that flush slowly can be expected to have different characteristics than those that flush quickly, especially with regard to the rate of introduction of water and associated materials, such as nutrients and sediments, and the extent of within-estuary processing of those materials. For example, the extent of nutrient retention within estuaries versus transport through them has been related to various measures of mixing time in North Atlantic estuaries (Nixon et al. 1996), and the growth rate of phytoplankton relative to the rate of physical flushing of water can determine if blooms are likely to occur (Malone 1977; Vieira and Chant 1993; Vallino and Hopkinson 1998; Howarth et al. 2000). The rate of water replacement can be an important descriptor of an estuary that may be useful in the development of an estuarine typology (Jay et al. 2000; National Research Council 2000; Bricker et al. 2003).

Characteristic mixing time scales are usually calculated for periods long enough to assume an overall steady state, so that simple models with tidally (or longer-term) averaged variables may be employed. With any given model, interannual scale mean (or median) estimates are often made using typical values for an estuary, but if conditions relevant to the model can be defined during a shorter time period of interest (such as a season or sampling period), then mixing time scales specific to that period may also be calculated. Many of the estuary salt and water budgets developed for the Land-Ocean Interactions in the Coastal Zone (LOICZ) project have used annual average or quasi-steady-state seasonal average values (e.g., Gordon et al. 1996; Smith 1996; Dupra et al. 2000; Smith et al. 2000; Dupra et al. 2002). Given that the inflow of new water can vary seasonally and interannually in response to changes in streamflow, rainfall, and

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*Corresponding author; tele: 706/542-1283; fax: 706/542-5888; e-mail: jsheldon@uga.edu nearshore circulation patterns, estimates of the range of mixing time scales exhibited by a system can be at least as useful as mean or median estimates for characterizing estuaries (Alber and Sheldon 1999; Jay et al. 2000).

It is also possible to calculate mixing time scales under time-varying conditions. The date-specific flushing time method (Alber and Sheldon 1999) is a steady-state approximation for variable freshwater inflow conditions. Steady-state salinity is often considered one of the most unrealistic assumptions of simple models, and several attempts have been made to address this shortcoming. Hagy et al. (2000) used a box model that included rates of salinity change to estimate mixing time scales for the Patuxent River estuary, Maryland. The LOICZ modeling guidelines (Gordon et al. 1996) include terms for nonsteady-state estuary volume and salinity in a model similar to those presented here, although few applications of that method have used the nonsteady-state terms (but see Smith and Hollibaugh 1997). At coarse time scales (months, seasons), the choice of a value for a model variable (such as salinity) to represent a time period during which that value is changing can present a conundrum, so finer time scales (and more frequent field observations) are generally needed to approximate continuously changing conditions. The main arguments of this paper can be made using the simpler steady-state formulations, although the consequences of applying them when flow rates and salinity are changing can be important (Vallino and Hopkinson 1998).

The turnover or flushing time of estuarine water is one mixing time scale that is relatively easy to calculate using simple, steady-state models. Turnover time (τ) is estimated by dividing the volume of water in a specified region by the rate of throughput. Assuming that the volume of water is constant, the rate of throughput (or volume transport) is equal to the rate of input (or output) of water.

$$\tau = \frac{\text{Water Volume (m}^3\text{)}}{\text{Water Inflow or Outflow (m}^3\text{ time}^{-1}\text{)}} \quad (1)$$

Flushing of an estuary is usually considered from the point of view of inflow; that is, replacing the water present at some initial time with inflows of new freshwater and new seawater. Sources of freshwater include river flow, groundwater, and precipitation directly on the estuary. Evaporation represents a loss of freshwater that should be subtracted from the sources, but if net precipitation-evaporation is much smaller than the other sources of freshwater, they can both be ignored (Solis and Powell 1999; Hagy et al. 2000). The source of new seawater is the coastal ocean, but water entering the estuary from the ocean inlet(s) on the flood tide can be composed of a mixture of seawater and returning estuarine water from the previous ebb tide. In addition, not all of the seawater necessarily mixes into the estuary before the next outgoing tide. Since neither returning estuarine water nor unmixed seawater actually contributes to flushing, using the total inflow of water from the ocean in the denominator of Eq. 1 can underestimate the flushing time, perhaps severely. In many cases, such as when turnover time is used to evaluate the potential flushing of pollutants, a more conservative estimate would be preferred (Sanford et al. 1992). Determination of the actual contribution of seawater to flushing is essential.

It is also important to consider whether the flushing analysis is focused on the replacement of water molecules themselves or on the removal or retention of particular constituents, such as pollutants, nutrients, and phytoplankton. In most cases, flushing of the component of interest is accomplished only by the escape of estuarine water to the ocean as opposed to evaporation. Consider a body of water in which water inputs exactly balance evaporation: although water molecules move into the atmosphere and are replaced by inputs, nonvolatile constituents within the water body are not removed. Since many of the dissolved or suspended constituents that are the real focus of most flushing analyses are not lost via evaporation, evaporation and the portion of inflows that replace it do not usually contribute to flushing. For positive estuaries (where freshwater sources exceed evaporation), net freshwater inflow + net seawater inflow may be used successfully in Eq. 1, as evaporation and replacement freshwater have already been taken into account. In these cases, it is assumed that a volume of estuarine water equal to the net input volumes escapes to the ocean. The models presented here include this assumption except as noted. In negative estuaries (where evaporation exceeds freshwater inputs), a portion of the net seawater inflow makes up for this volume deficit and does not count toward flushing. For this reason, the rate of outflow of estuarine water is preferable in the denominator of Eq. 1, and its use is critical in negative estuaries.

In this paper, we critically evaluate two types of simple, steady-state models that estimate the turnover time of estuarine water: freshwater fraction models and simple tidal prism models. Freshwater fraction models (e.g., Dyer 1973), often called flushing time or freshwater replacement time models, have been developed for estuaries with substantial freshwater input and salinities that are measurably less than that of the coastal ocean, such as riverine estuaries. They calculate turnover time by relating the rate of freshwater inflow to the amount of freshwater in the estuary (the freshwater volume). Although they can treat the estuary as a series of compartments or boxes, we focus on the 1-box formulation for comparison with simple tidal prism models, which use a single box to describe short, longitudinally well-mixed estuaries with low or negligible freshwater inflow, such as lagoons and marinas. Simple tidal prism models (e.g., Sanford et al. 1992; Luketina 1998) rely primarily on tidal action to estimate flushing by relating the volume of the tidal prism (the intertidal volume) to the volume of the estuary. They are routinely modified to include the effects of returning estuarine water from the ebb tide (Sanford et al. 1992), and attempts have been made to account for incomplete mixing of the flood flow as well (Pritchard 1960; Guo and Lordi 2000). Both types of models have relatively modest data requirements and have been widely applied to estimate estuarine mixing times. We found that the underlying assumptions and mathematics of both these methods warrant a careful reevaluation, as they have not always been applied properly and there are mathematical inconsistencies in the literature. We identify an appropriate formulation for simple tidal prism models that includes only those components of the tidal prism that contribute to flushing of well-mixed estuaries, and we recast some earlier methods to incorporate partial in-estuary mixing into a new framework that is less ambiguous and more directly applicable to the estimation of turnover times.

Model Evaluation

Freshwater Fraction Models

The freshwater fraction method estimates the flushing time (τ_{FW}) by dividing the freshwater volume of the estuary by the freshwater inflow rate (Q_{FW}) averaged over a given period of time. Freshwater volume is calculated by multiplying the estuary volume (V) by the freshwater fraction, which is calculated by comparing the average estuarine salinity (S_{AVG}) to the salinity of seawater (σ) (Dyer 1973).

$$\mathrm{Frac}_{FW} = \frac{\sigma - S_{AVG}}{\sigma} \tag{2}$$

The freshwater inflow rate is usually expressed in standard time units (s, d, yr), but throughout this paper we use tidal periods (T) as the time scale for all models and all flow parameters in order to facilitate comparisons. Flushing time is then:

$$\tau_{FW} = \frac{V\,\mathrm{Frac}_{FW}}{Q_{FW}} \tag{3}$$

A reliable estimation of flushing time can be made only if S_{AVG} is significantly different from σ. If it is not, then Frac_{FW} approaches zero. This by itself is not problematic, but Frac_{FW} can be expected to covary with Q_{FW} so that the ratio in Eq. 3 will be poorly constrained at very low flows. This model is applicable only to estuaries with sufficient freshwater inflow to measurably dilute the enclosed body of seawater.

Equation 3 appears to calculate only the turnover time of the freshwater in the estuary, and freshwater fraction models have been criticized for not including flushing by seawater and overestimating the turnover time (Knoppers et al. 1991; Guo and Lordi 2000; National Research Council 2000). We have stated that flushing time is specific to freshwater (Sheldon and Alber 2002), in the sense that it can be interpreted as the average transit time of freshwater (or a constituent dissolved in it) from the head to the mouth of an estuary (Zimmerman 1976). Although this interpretation is valid, the calculation does not ignore flushing by seawater. As we demonstrate below, the freshwater fraction reflects the net balance between seawater and freshwater inflows.

Flushing of the estuary is accomplished by inflows of both freshwater (Q_{FW}) and seawater (Q_{SW}). A generalized estuarine turnover time equation based on flow inputs would take the form:

$$\tau = \frac{V}{Q_{FW} + Q_{SW}} \tag{4}$$

Assuming a steady state for both volume and salt over some time frame, the inflows of freshwater (with salinity 0) and seawater (with salinity σ) must balance to produce an equivalent volume of water of average estuarine salinity (S_{AVG}).

$$Q_{FW}0 + Q_{SW}\sigma = (Q_{FW} + Q_{SW})S_{AVG} \tag{5}$$

Rearranging terms, seawater flow can be expressed as a function of freshwater inflow and salinity measurements:

$$Q_{SW} = \frac{Q_{FW}S_{AVG}}{\sigma - S_{AVG}} \tag{6}$$

and this can be substituted into Eq. 4 and simplified.

$$\tau = \frac{V}{Q_{FW} + \dfrac{Q_{FW}S_{AVG}}{\sigma - S_{AVG}}} = \frac{V}{Q_{FW}\left(\dfrac{\sigma}{\sigma - S_{AVG}}\right)} \tag{7}$$

The term in parentheses on the right side is the reciprocal of Frac_{FW} (Eq. 2), so that Eq. 7 reduces to Eq. 3. The calculation of the freshwater fraction incorporates the seawater inflow necessary to balance the freshwater inflow and maintain the average estuarine salinity. The inference that the method does not take flushing by seawater into account is a misleading consequence of the simplification of terms in the usual presentation of the model.

τ also represents the turnover time or average transit time of seawater, as can be demonstrated by solving Eq. 5 for Q_{FW}, substituting into Eq. 4, and simplifying in terms of Q_{SW} and the seawater fraction. The average transit time of seawater is often a less useful concept than that of freshwater because of the relative positions of estuary inlets and outlets. In many cases the freshwater inlet and outlet are at opposite ends of the estuary so there is some minimum-distance path that freshwater (and dissolved constituents) must travel. This provides a spatial context for the freshwater transit time, and the transit times of individual freshwater parcels may be expected to have a bell-shaped distribution with the turnover time as a likely value (i.e., the average transit time is near the mode). The seawater inlet is usually the same as the outlet, so that much of the seawater may enter and exit quickly, whereas any seawater that intrudes far up-estuary may have a long transit time. The distribution of transit times of seawater parcels is generally skewed, so the turnover time represents the average but it is not a likely value for any individual parcel (Takeoka 1984).

An important feature of this model, which will be contrasted with the tidal prism model, is its treatment of the typical gravitational circulation that occurs in a partially or fully stratified estuary (Pritchard 1967). As freshwater flows seaward from the head of a riverine estuary, the saltier underlying water becomes entrained in the upper layer, causing a compensatory net landward flow in the lower layer. An increase in the freshwater flow rate would usually be expected to increase the entrainment and compensatory seawater flow (e.g., Sheldon and Alber 2002). In the case of the freshwater fraction model, upstream seawater flow is related to freshwater inflow (Eq. 6), although it is not immediately clear what effect a change in freshwater inflow would have on seawater inflow because the average estuarine salinity would also be altered. The freshwater fraction model has the potential to reflect enhanced gravitational circulation if it is indicated by an estuary's particular freshwater inflow-salinity relationship.

SIMPLE TIDAL PRISM MODELS-WELL-MIXED ESTUARY

Complete Tidal Exchange

In their simplest form, tidal prism models calculate the turnover time of estuarine water by dividing the estuary volume (V) by the tidal prism volume (V_{TP}), the difference between high and low tide volumes.

$$\tau = \frac{V}{V_{TP}} \tag{8}$$

The implicit time scale is tidal periods (T) because V_{TP} represents the volume change over T. V_{TP} is usually assumed to be constant and is calculated using the average tidal range for the estuary, so that periodic variations in tidal range are not considered. V can be the volume at low tide (Zimmerman 1988), high tide (Luketina 1998), or mid tide (Sanford et al. 1992; Solis and Powell 1999); we recommend the latter for comparability with other models.

Freshwater inflow is not explicitly taken into account in this simple model. This important drawback makes it impossible to use Eq. 8 to assess the effects of changing freshwater inflow to estuaries, a topic that is of considerable current interest (see Montagna et al. 2002 and other papers in that issue). This limitation can be corrected, because the tidal prism actually includes any freshwater inflow that accumulates during the flood tide (Fig. 1). This can be approximated as half the freshwater inflow during a tidal period ($0.5Q_{FW}$), as it has been shown that asymmetries in the durations of flood and ebb flows have a minimal effect on model results (Luketina 1998). The remainder of the tidal prism is inflow from the ocean during flood, represented as an average flow rate Q_{FL} over time T, so that:

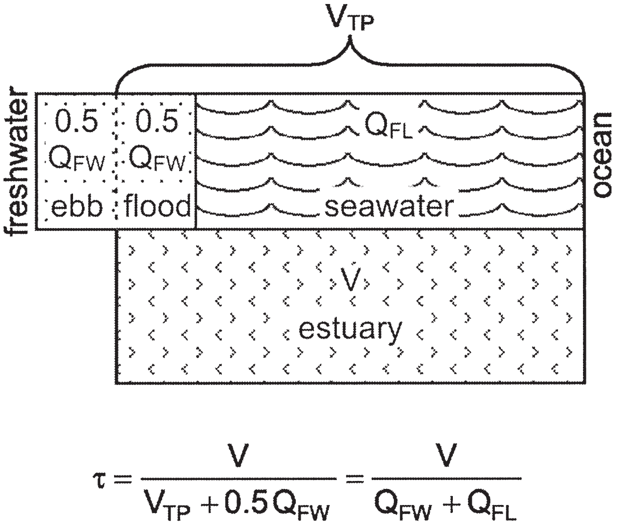
$$V_{TP} = 0.5Q_{FW} + Q_{FL} \tag{9}$$

Since the freshwater inflow during ebb (the remaining $0.5Q_{FW}$) also contributes to flushing, a correct assessment of turnover time in cases involving freshwater inflow should include $V_{TP} + 0.5Q_{FW}$ (Fig. 1), although this may be a small correction.

This formulation of the tidal prism model assumes that the estuary is well mixed at high tide and that there is complete exchange of the tidal prism volume on every tidal cycle. None of the water that exits during ebb returns; it is replaced by new water that mixes completely into the estuary during flood. These assumptions, which represent maximum flushing, are not always met; in such cases, the tidal prism model should be adjusted to include only those components that contribute to flushing. Neglecting these adjustments will usually lead to an underestimate of the turnover time (Sanford et al. 1992; Koutitonsky et al. 2004).

PARTIAL EBB RETURN

Except in the complete tidal exchange case described above, some portion of the tidal prism is



$$\tau = \frac{V}{V_{TP} + 0.5Q_{FW}} = \frac{V}{Q_{FW} + Q_{FL}}$$

Fig. 1. Conceptual representation of a simple tidal prism model of a well-mixed estuary with complete tidal exchange. Q_{FW} is the combined inflow of freshwater over both flood and ebb tides, and Q_{FL} is seawater inflow on the flood tide. V_{TP}, the tidal prism volume, includes seawater and freshwater inflow during flood tide, but all of Q_{FW} and Q_{FL} contribute to the turnover time (τ) of the estuary volume (V).

usually water returning from the previous ebb tide (return flow), which does not contribute to flushing. In order to represent this, we can divide the flood flow into a portion R_OQ_{FL} that is seawater and a portion $(1 - R_O)Q_{FL}$ that is return flow (Fig. 2). The components of the tidal prism that should be included in the turnover time estimate, as shown in Fig. 2, can be represented as:

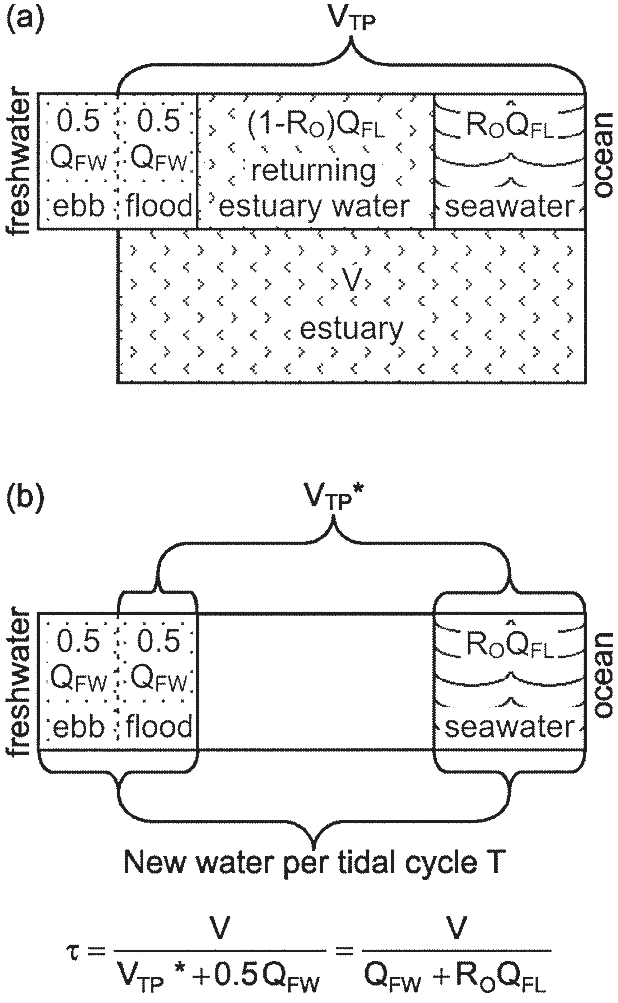
$$V^*_{TP} = 0.5Q_{FW} + R_OQ_{FL} \tag{10}$$

As in the previous case, the freshwater inflow during ebb tide should be included as well (Fig. 2), so the correct turnover time equation based on the simple tidal prism model should be:

$$\tau = \frac{V}{0.5Q_{FW} + V^*_{TP}} = \frac{V}{Q_{FW} + R_OQ_{FL}} \tag{11}$$

If V_{TP} and Q_{FW} are known, then Q_{FL} can be calculated by subtraction using Eq. 9.

The tidal prism model includes seawater inflow due only to oscillatory tidal flow. The tidal prism volume, V_{TP}, which is used as an estimator of the total inflow of water, does not include the net nontidal seawater inflow due to gravitational circulation (Parker et al. 1972). This is in contrast to the freshwater fraction model, wherein the observed estuarine salinity S_{AVG} reflects net seawater inflow from all processes. In the tidal prism model, Eq. 9 shows that an increase in freshwater inflow (Q_{FW}) would result in a decrease in the estimated inflow through the ocean inlet (Q_{FL}) if V_{TP} is treated as a constant. Even if the equation is adjusted to account for return flow (Eq. 11), there is rarely more than one estimate of R_O for an estuary so an increase in freshwater inflow usually leads to a decrease in estimated seawater inflow. These models have no additional mechanism to reflect gravitational circulation and allow for increased seawater inflow in response to increased freshwater inflow. Their application should be limited to estuaries with



$$\tau = \frac{V}{V_{TP}* + 0.5Q_{FW}} = \frac{V}{Q_{FW} + R_OQ_{FL}}$$

Fig. 2. (a) Conceptual representation of a simple tidal prism model of a well-mixed estuary with partial ebb return. Q_{FW} is the combined inflow of freshwater over both flood and ebb tides, $(1 - R_O)Q_{FL}$ is that portion of the ocean flood water that is estuary water returning from the previous ebb tide, and R_OQ_{FL} is that portion of the ocean flood water that is seawater. V_{TP}, the tidal prism volume, includes all of the ocean flood water and the freshwater inflow during flood tide. V is the estuary volume. (b) Components of inflow that consist of new water and contribute to the turnover time (τ) of the estuary volume V (not shown). V^*_{TP}, the adjusted tidal prism volume, excludes returning estuary water, but the total inflow of new water consists of all the freshwater inflow (Q_{FW}) plus seawater (R_OQ_{FL}).

weak or nonexistent gravitational circulation, which generally means estuaries with little or no freshwater inflow.

If freshwater inflow is negligible then it can be ignored in Eq. 11, but the return flow is an important feature of the model that can have a large effect on the calculated turnover time (Sanford et al. 1992). The return flow factor, $(1 - R_O) = b$, is the ratio of the inflow of returning ebb water to the total flood flow from the ocean (Sanford et al. 1992). The complementary fraction, R_O, is the ratio of seawater inflow to total flood flow, as described above. This has been called the tidal exchange ratio (Parker et al. 1972; Fischer et al. 1979), ocean tidal exchange ratio (Guo and Lordi 2000), and mixing efficiency (Solis and Powell 1999). Van de Kreeke (1988) calculated an ebb escape fraction (our term), ϵ, that is the fraction of the ebb volume (Q_E) not returning on the next flood. This can be related to the tidal exchange ratio R_O but is not numerically equivalent to it. If van de Kreeke's ebb volume is corrected to include the remaining half of the freshwater inflow in addition to the tidal prism (Eq. 9), so that a steady-state water balance is maintained, then

$$Q_E = V_{TP} + 0.5Q_{FW} = Q_{FW} + Q_{FL} \qquad (12)$$

At steady state, the escaping volume must be replaced by freshwater and seawater inflows.

$$\epsilon Q_E = \epsilon(Q_{FW} + Q_{FL}) = Q_{FW} + R_O Q_{FL} \qquad (13)$$

From Eq. 13, $\epsilon > R_O$ for any positive values of Q_{FW} and Q_{FL}, although there are examples where the two have been treated as equivalent (van de Kreeke 1988; Solis and Powell 1999). ϵ has also been used to describe the fraction of the incoming tidal prism that mixes within the estuary (Koutitonsky et al. 2004). Due to the similarity in concepts, it is essential to note the details of calculations when comparing literature values for any sort of mixing efficiency for estuarine waters.

The tidal exchange ratio (R_O) is governed mainly by processes occurring outside the estuary that affect the fate of the ebb plume (Sanford et al. 1992), so it can be difficult to estimate. Sanford et al. (1992) described a method to estimate return flow (b) based on the tidal period, tidal prism volume, entrance channel cross-sectional area, coastal water depth, magnitude of the coastal tidal current, and the distance down coast to where the ebb plume enters open water. Signell and Butman (1992) pointed out the importance of bottom friction, in addition to embayment entrance geometry, on the formation and fate of vortices generated during ebb flow through a narrow entrance. Persistent vortices may propagate away from the entrance, tending to decrease the return flow on the following flood.

If a suitable tracer is available to differentiate between water sources, then a much simpler estimation of tidal exchange can be made from the relative concentrations of tracer in freshwater, seawater, and flood and ebb waters (Parker et al. 1972; Sanford et al. 1992). An obvious potential tracer is salt (or freshwater), and it has been suggested that the tidal exchange ratio can be calculated based on salinity differences in flood and ebb flows (Parker et al. 1972; Fischer et al. 1979):

$$R_O = (1 - b) = \frac{S_{FL} - S_E}{\sigma - S_E} \qquad (14)$$

where S_{FL} and S_E are the average salinities of the flood and ebb flows, respectively. These can still be difficult to estimate because both salinity and current speed at a sampling location (such as the estuary mouth) will vary throughout the flood and ebb flows. A different method for estimating b using Q_{FW}, V_{TP}, σ, and high tide salinity is given by Luketina (1998). Regardless of the formula used, a measurable salinity difference between water masses may indicate that freshwater inflow is substantial, which could violate the assumption of weak gravitational circulation.

INCOMPLETE FLOOD MIXING

Just as water that exits the estuary late in the ebb cycle may not escape the coastal zone, water that enters the estuary late in the flood cycle may not mix completely within the estuary before the tide turns. In cases where there is both partial ebb return and incomplete flood mixing, water mass bookkeeping becomes even more complex as the tidal prism model must be modified to incorporate the degree to which flood flows mix with the water already in the estuary. In the following analysis, we assume for the sake of simplicity that freshwater inflow primarily occurs at the head or inland edge and mixes into the estuary completely, and we focus only on cases where a fraction of the seawater exits unmixed as the tide turns. The model could be extended to include partial mixing of freshwater if necessary.

Guo and Lordi (2000), building on earlier work by Pritchard (1960), attempted to account for incomplete escape of the ebb flow and incomplete mixing of the flood flow by considering both the ocean tidal exchange ratio (R_O above), defined by them as the fraction of water that enters from the ocean on the flood tide that did not flow out of the estuary on the previous ebb tide, and the estuary or bay tidal exchange ratio, R_B, defined as the fraction of water leaving on the ebb tide that did not enter

TABLE 1. Constituent water masses of the ebb and flood flows in the tidal prism model of Guo and Lordi (2000) and the revised model introduced here. nth time refers to $n > 1$. Q_B? and Q_O? refer to parcels of water that may or may not be considered parts of Q_B and Q_O, respectively. All other symbols as defined in text.

Line	Water mass	Entered previous flood?	Fate after leaving	Contributes to flushing via outflow	Component of water mass (Guo and Lordi)	Component of water mass (current study)
Ebb						
1a	Estuary water leaving 1st time	No	Escapes	Yes	Q_B	$\varepsilon R_B Q_E$
1b	Estuary water leaving 1st time	No	Returns	No	Q_B?	$(1 - \varepsilon) R_B Q_E$
2a	Estuary water leaving nth time	Yes	Escapes	Yes	$(1 - R_B) Q_E$	$\varepsilon R_B Q_E$
2b	Estuary water leaving nth time	Yes	Returns	No	$(1 - R_B) Q_E$	$(1 - \varepsilon) R_B Q_E$
3a	Unmixed seawater	Yes	Escapes	No	$(1 - R_B) Q_E$	$(1 - R_B) Q_E$
3b	Unmixed seawater	Yes	Returns	No	$(1 - R_B) Q_E$	$(1 - R_B) Q_E$

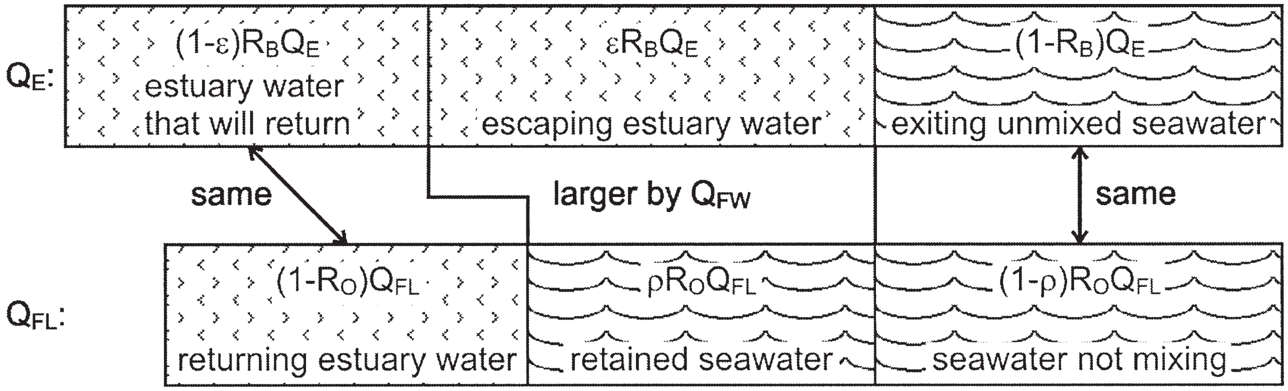
Line	Water mass	Exited previous ebb?	Fate after entering	Contributes to flushing via inflow	Component of water mass (Guo and Lordi)	Component of water mass (current study)
Flood						
4a	Seawater entering 1st time	No	Retained	Yes	Q_O	$\rho R_O Q_{FL}$
4b	Seawater entering 1st time	No	Exits	No	Q_O?	$(1 - \rho) R_O Q_{FL}$
5a	Seawater entering nth time	Yes	Retained	Yes	$(1 - R_O) Q_{FL}$	$\rho R_O Q_{FL}$
5b	Seawater entering nth time	Yes	Exits	No	$(1 - R_O) Q_{FL}$	$(1 - \rho) R_O Q_{FL}$
6a	Returning estuary water	Yes	Retained	No	$(1 - R_O) Q_{FL}$	$(1 - R_O) Q_{FL}$
6b	Returning estuary water	Yes	Exits	No	$(1 - R_O) Q_{FL}$	$(1 - R_O) Q_{FL}$

the estuary on the previous flood tide. The corresponding quantities of water are then $Q_O = R_O Q_{FL}$ and $Q_B = R_B Q_E$. Taken individually, these definitions are clear, but if both effects are occurring in a given estuary, these definitions become equivocal as they apply to the flushing of the estuary. Water exiting with the ebb outflow (Table 1) may be composed of estuary water parcels exiting for the first time; estuary water parcels that have exited previously, returned, and are exiting again; and unmixed seawater from the previous flood tide. According to a strict reading of the definition above, estuary parcels exiting for the first time would qualify as Q_B whether they escaped or returned (Lines 1a and 1b in Table 1) whereas both estuarine water and unmixed seawater that had entered with the previous flood would be designated together as $(1 - R_B)Q_E$ (Lines 2a–3b). The flood flow may be composed of seawater parcels that enter for the first time (Q_O, Lines 4a and 4b), seawater entering again after exiting unmixed, and returning estuary water (together designated $(1 - R_O)Q_{FL}$, Lines 5a–6b). These definitions are couched in terms of the recent histories of the water parcels involved and ignore their fates.

The fact that Guo and Lordi (2000) estimated turnover time using Q_B suggests instead that it is supposed to represent the volume of estuary water that escapes (Lines 1a and 2a in Table 1), which is at odds with the definition above. One might be able to exclude Line 1b from Q_B if water leaving on the ebb tide is assumed to mean that which leaves permanently (i.e., escapes), but excluding water that did not enter the estuary on the previous flood tide would improperly exclude any estuary parcels that recirculate prior to escape (Line 2a). If water entering from the ocean means that which is retained, this would exclude Line 4b from Q_O but the definition also excludes any seawater parcels that recirculate prior to retention within the estuary (Line 5a). The confusion over which quantities are included in Q_B and Q_O is not merely semantic. Even if we assume that Q_B represents the volume of escaping estuary water (Lines 1a and 2a in Table 1), then the equations that Guo and Lordi used to derive it are internally inconsistent. These differences are described in the context of our own derivation below.

We propose to clarify the situation by redefining the parameters R_O and R_B in terms of the types of water parcels that make up the flood and ebb flows rather than their recent histories. The history of a water parcel (e.g., entering the ebb or flood for the first or nth time) is difficult to determine and is irrelevant to the question of flushing; new water that successfully enters the estuary is contributing to flushing whether it took 1 or more tidal cycles to arrive. We redefine R_O as the fraction of the flood inflow that is seawater, $(1 - R_O)$ as the fraction that is returning estuarine water, R_B as the fraction of the ebb outflow that is mixed estuarine water, and $(1 - R_B)$ as the fraction that is unmixed, recirculated seawater. Using these fractions of the flood and ebb flows, we can proceed to define subfractions that will be important for flushing according to their fates rather than their histories.

We divide the estuarine water in the ebb flow, ($Q_B = R_B Q_E$), into a fraction ε that escapes the coastal area and a fraction $(1 - \varepsilon)$ that returns to the estuary on the next flood tide (Fig. 3). The ebb outflow is then composed of three water masses: estuarine water that will escape, estuarine water that



$$\tau = \frac{V}{\varepsilon R_B Q_E} = \frac{V}{\rho R_O Q_{FL} + Q_{FW}}$$

Fig. 3. Conceptual representation of ebb (Q_E) and flood (Q_{FL}) tide volumes in an estuary with partial ebb return and incomplete flood mixing. R_BQ_E is that portion of the ebb outflow that is estuary water, and $(1 - R_B)Q_E$ is the portion that is unmixed seawater. R_BQ_E is further divided into a portion ε that escapes the estuary and a portion $(1 - \varepsilon)$ that returns on the next flood tide. R_OQ_{FL} and $(1 - R_O)Q_{FL}$ are as defined in Fig. 2. ρ is that portion of R_OQ_{FL} that mixes into the estuary, and $(1 - \rho)$ is the portion that exits unmixed. Identical water masses in Q_E and Q_{FL} are indicated by arrows; εR_BQ_E is larger than ρR_OQ_{FL} by the freshwater inflow during a tidal cycle, Q_{FW}, which is assumed to mix into the estuary before and during the ebb tide. Turnover time (τ) of the estuary volume V (not shown) can be calculated using either εR_BQ_E or $\rho R_OQ_{FL} + Q_{FW}$.

will return, and unmixed seawater.

$$Q_E = \varepsilon R_B Q_E + (1 - \varepsilon)R_B Q_E + (1 - R_B)Q_E \quad (15)$$

We also divide the seawater inflow ($Q_O = R_OQ_{FL}$) into a fraction ρ that is retained within the estuary and a fraction $(1 - \rho)$ that exits unmixed on the next ebb tide (Fig. 3). The flood inflow is composed of seawater that will be retained and mix into the estuary, seawater that will exit unmixed, and returning estuarine water.

$$Q_{FL} = \rho R_O Q_{FL} + (1 - \rho)R_O Q_{FL} + (1 - R_O)Q_{FL} \quad (16)$$

Some notable relationships exist among the expressions in Eqs. 15 and 16. The returning estuarine water appears in both equations, and the two different expressions must represent the same quantity. Likewise, the recirculating unmixed seawater must be the same in both equations (Fig. 3). Combining the equivalent expressions for both these water masses from each of these equations and setting them equal to each other:

$$(1 - \varepsilon)R_B Q_E + (1 - R_B)Q_E = (1 - \rho)R_O Q_{FL} + (1 - R_O)Q_{FL} \quad (17)$$

In Guo and Lordi's terminology, the left side of this expression would represent the fraction of ebb flow that is unmixed flood water and would be assigned the average salinity of the flood flow, S_{FL}, whereas the right side would represent the fraction of flood flow that is returned bay water and would be assigned the average salinity of the ebb flow, S_E. Our formulation shows that these quantities represent the same water masses in both equations, so they are the same in both volume and salinity. The assignment of the salinities S_{FL} and S_E by Guo and Lordi led to a fortuitous, but erroneous, expression for Q_B as a function of only measured flow and salinity data at the ocean inlet (Q_E, Q_{FL}, S_{FL}, S_E) and the seawater salinity σ (see Eq. 12 in Guo and Lordi 2000). As we will show, it is impossible to parameterize this type of model completely using only these measurements.

Beginning with the gross water balance represented in Eq. 12, substituting for Q_E and Q_{FL} using Eqs. 15 and 16, and eliminating recirculating water masses using Eq. 17, the water mass balance between net estuarine outflow and net inflow of new water is:

$$\varepsilon R_B Q_E = \rho R_O Q_{FL} + Q_{FW} \quad (18)$$

Turnover time may be estimated by dividing the estuary volume V by either the escaping estuarine water (εR_BQ_E) or the sum of the retained seawater plus freshwater inflow ($\rho R_OQ_{FL} + Q_{FW}$). We develop expressions for εR_B and ρR_O below.

A suitable tracer would be useful for differentiating between water masses in the equations above. Previous methods have assumed that salinity differences among water masses may be used. We proceed with this approach using salinity as a proxy for any suitable tracer although we recognize that large salinity differences may indicate appreciable freshwater inflow, with implications as discussed above. The salinities of the defined subfractions are as follows: the fractions that are seawater have the salinity of the coastal ocean, σ; average salinity of the escaping estuarine water is defined as S_B; and the returning estuarine water has some, possibly different, salinity, S_β. Salt balance equations for the ebb and flood flows (Eqs. 15 and 16) are then:

$$Q_E S_E = \varepsilon R_B Q_E S_B + (1 - \varepsilon) R_B Q_E S_\beta + (1 - R_B) Q_E \sigma \quad (19)$$

$$Q_{FL} S_{FL} = \rho R_O Q_{FL} \sigma + (1 - \rho) R_O Q_{FL} \sigma + (1 - R_O) Q_{FL} S_\beta \quad (20)$$

As above, the equivalent recirculating water masses in these two equations also have identical salinities. The salt balance for these water masses is:

$$(1 - \varepsilon) R_B Q_E S_\beta + (1 - R_B) Q_E \sigma = (1 - R_O) Q_{FL} S_\beta + (1 - \rho) R_O Q_{FL} \sigma \quad (21)$$

Following the pattern of the water balance analysis above, the gross salt balance is:

$$Q_E S_E = Q_{FL} S_{FL} \quad (22)$$

Substituting using Eqs. 19 and 20 and eliminating recirculating water masses using Eq. 21, the net salt balance between escaping water and new inflows is:

$$\varepsilon R_B Q_E S_B = \rho R_O Q_{FL} \sigma \quad (23)$$

Solving Eq. 17 for $\rho R_O Q_{FL}$ and substituting in Eq. 23 yields an expression for εR_B in terms of flow and salinity variables:

$$\varepsilon R_B = \frac{(Q_E - Q_{FL})\sigma}{Q_E(\sigma - S_B)} \quad (24)$$

The flow variables may be eliminated by substituting for Q_E using Eq. 22:

$$\varepsilon R_B = \frac{(S_{FL} - S_E)\sigma}{(\sigma - S_B) S_{FL}} \quad (25)$$

Repeating the procedure but using Eq. 17 to substitute for $\varepsilon R_B Q_E$ yields comparable expressions for ρR_O:

$$\rho R_O = \frac{(Q_E - Q_{FL}) S_B}{Q_{FL}(\sigma - S_B)} = \frac{(S_{FL} - S_E) S_B}{(\sigma - S_B) S_E} \quad (26)$$

Using Eq. 24, the quantity of water escaping during each ebb tide is:

$$\varepsilon R_B Q_E = \frac{(Q_E - Q_{FL})\sigma}{\sigma - S_B} = \frac{Q_{FW}\sigma}{\sigma - S_B} \quad (27)$$

Note the similarity in form to the denominator of freshwater fraction model Eq. 7. The final use of these expressions in the calculation of turnover time will depend on the salinity of the escaping estuary water, S_B, which we discuss below.

Previous authors (Pritchard 1960; Guo and Lordi 2000) asserted that the salinity S_B of the escaping estuary water Q_B would be higher than the average estuary salinity S_{AVG} and difficult to measure directly, which is why Guo and Lordi set out to develop a model that used different variables. In contrast to Guo and Lordi's model, our expressions for the ebb and flood exchange ratios still require S_B (Eqs. 25 and 26) and there are too many unknowns in the system of unique water and salt balance equations that constitute the model (Eqs. 17, 19, 20, and 22) to eliminate it. Our model derivation shows that S_{FL} and S_E are not necessary for the estimation of turnover time, but that either gross ebb and flood volumes (Q_E, Q_{FL}) or freshwater inflow (Q_{FW}) are necessary, along with S_B and σ (Eq. 27).

The preceding formulations of the tidal prism model assume that all of the water that does mix into the estuary over the course of a tidal cycle is mixed into the entire estuarine volume. If the estuary is not at steady state, the salinity of the escaping water S_B at a given time might be higher or lower than the average estuary salinity S_{AVG}. On the other hand, if the whole-estuary volume V is used to estimate turnover time at steady state, then the implicit assumption is that the estuary is acting as one well-mixed box, and the escaping water must have salinity $S_B = S_\beta = S_{AVG}$. In this case, the turnover time equation based on a tidal prism approach is identical to the freshwater fraction equation.

$$\tau = \frac{V}{\varepsilon R_B Q_E} = \frac{V(\sigma - S_{AVG})}{Q_{FW}\sigma} \quad (28)$$

The more complex tidal prism models presented here begin to stray from the tidal prism character of the simpler models: ebb and flood volumes (Q_E, Q_{FL}) or freshwater inflow (Q_{FW}) must be measured directly instead of relying on V_{TP} (Eq. 27), and salinity may be the only practical way to distinguish among water masses (Eqs. 25 and 26). Field observations of many of these variables, especially salinity, will reflect gravitational circulation and other processes, which would allow the model to be used under conditions with higher freshwater inflow. When V_{TP} is no longer used as an estimator of flow then the model ceases to be a tidal prism model in the classic sense. The minimum required variables become those of the freshwater fraction method, and the two models become mathematically equivalent.

SIMPLE TIDAL PRISM MODELS-PARTIALLY MIXED ESTUARY

The assertion that S_B must be greater than S_{AVG} even in steady-state situations stems from an assumption that not all of the estuarine volume is involved in the mixing, so that S_B would be the salinity of some lower estuary water mass that is considered to be participating directly in tidal mixing processes (Pritchard 1960; Guo and Lordi 2000). If $S_B > S_{AVG}$ is used in Eq. 28, then we have the curious result that the assumption of a lower degree of mixing in the estuary appears to cause faster flushing than if the escaping water had salinity S_{AVG} (Guo and Lordi 2000). This non-intuitive result stems from an incorrect pairing of the escaping salinity S_B with the whole estuary volume V. Mixing must be taking place within some subvolume of the estuary, V_B, that has average salinity S_B. The assumption of a well-mixed estuary no longer applies and the model becomes, at minimum, a 2-box problem. The turnover time of V_B may be estimated, and this is expected to be shorter than the turnover time of V. To estimate turnover time of the entire estuary, the remainder of the system (volume $V - V_B$ and salinity $< S_{AVG}$) must be accounted for as well. Given that freshwater fraction flushing times for multiple segments of an estuary are additive (Dyer and Taylor 1973; Sheldon and Alber 2002) and that turnover times calculated from 1-box tidal prism models using salt as a tracer are numerically equivalent to those calculated from the freshwater fraction equation (as shown here), we offer without showing explicit proof that an expression for a whole-estuary turnover time calculated from a 2-box tidal prism model would reduce to the freshwater fraction model (Eq. 7). For a more explicit numerical modeling approach to partial mixing and escape of tidal flows, we refer the reader to Signell and Butman (1992).

IMPLICATIONS FOR LOICZ MODELS

The LOICZ approach has been used to develop biogeochemical budgets for many estuaries worldwide. In its simplest (and most commonly used) form, estimates of both the water and salt balance of an estuary are developed using a single-box model as outlined in the LOICZ guidelines (Gordon et al. 1996). This approach starts with a water budget that calculates the net (residual) estuary outflow or inflow (V_R) from a summation of the freshwater sources and sinks. For net outflow, V_R is negative, and for net inflow, it is positive. In both cases, the salinity of V_R is taken to be $S_R = (S_{AVG} + \sigma)/2$, which may be interpreted as the salinity at the lower estuary boundary. V_R and S_R are then both used to calculate a net exchange flow with the ocean (V_X), which exchanges water masses of salinity σ and S_{AVG} to maintain the average estuary salinity. The flows V_R and V_X are used to develop budgets of nonconservative materials such as nutrients. These quantities are also used to calculate water exchange time or turnover time as:

$$\tau = \frac{V}{V_X + |V_R|} \tag{29}$$

This characterization of net advective and exchange flows is very similar to a 1-box case of the classic box model (Officer 1980), but there are several problems with this formulation. In positive estuaries (where V_R is negative), the use of S_R rather than S_{AVG} as the salinity of the residual outflow causes problems similar to when $S_B > S_{AVG}$ is used in a well-mixed estuary. Box models assume that each box is well mixed and that flows out of a box have the average salinity of the box. The use of boundary salinities is inconsistent with the compartmentalization of the model; if S_R is not S_{AVG} then the box is not well mixed and should be subdivided. By using S_R, the amount of salt exported by V_R is too high and must be compensated by a higher exchange flow V_X, which leads to an underestimate of the turnover time (Eq. 29). Once V_X is corrected (i.e., S_{AVG} is used as the salinity of V_R), this model is analogous to those presented above in that V_X into the estuary represents net inflow of seawater and V_X out plus V_R represent net escape of estuary water.

In negative estuaries, V_R is positive and the salinity of that flow should be σ rather than S_{AVG} or S_R because net inflow is from the ocean. If the estuary salinity is higher than that of local seawater ($S_{AVG} > \sigma$), then use of S_R causes an overestimate of the salt transported in by V_R. This must be compensated by a higher exchange flow V_X with the less salty ocean, again leading to an underestimate of turnover time. An additional problem is that evaporation and the portion of inflows that replace it (V_R in this case) do not contribute to flushing. For negative estuaries, the denominator of Eq. 29 should be V_X alone. Including V_R results in an even larger underestimate of the turnover time.

The magnitude of these corrections depends largely on the difference between S_{AVG} and σ in any given case. As examples, we have used the publicly available data for four published LOICZ budgets, two where V_R is negative and two where it is positive. Sorsogon Bay, Philippines, is on average a net outflow system that is 3 psu less salty than the ocean (Dupra et al. 2000). The LOICZ estimate of turnover time is 61 d, which is barely different from our estimate of 62 d. Another net outflow system, Angaw Lagoon, Ghana, is 21 psu less salty than the ocean (Dupra et al. 2002) and in this case the turnover time estimates differ by 8 d (27 d versus our 35 d). The differences are larger in negative estuaries because of the additional error of including V_R in the denominator of Eq. 29. Canton Island lagoon, Kiribati, was only 2 psu saltier than the ocean during the study period (Smith 1996), but the turnover time correction is more than that calculated for Sorsogon Bay (45 d versus our 49 d). The salinity of Araruama Lagoon, Brazil, is 20.7 psu greater than that of the ocean on an annual average (Smith et al. 2000), and our turnover time, 1,830 d, is almost twice that calculated by the authors (985 d). Although turnover times are not generally used further for LOICZ nutrient budgeting, correcting the salinity of V_R (and hence V_X) will affect these additional calculations. The same arguments against using S_R could be applied by analogy to the use of estimated boundary concentrations of nutrients (Y_R) in LOICZ budgets, with implications that are beyond the scope of this paper.

Discussion

MODEL COMPARABILITY

The freshwater fraction and tidal prism approaches appear to calculate quite different estimates of turnover time using measurements of different aspects of the physical estuarine environment. This is due to a simplification of terms in the freshwater fraction model, and in fact, both models estimate the turnover time of estuarine water by dividing the estuary volume by the combined inflows of freshwater and seawater. A properly constructed tidal prism model includes both these flows while excluding return flow (Eq. 11) and unmixed flood flow (Eqs. 18 and 28). We have shown that the freshwater fraction method implicitly includes flushing by seawater, and it is inaccurate to assert that the calculation is limited in scope to flushing by freshwater (Knoppers et al. 1991; Guo and Lordi 2000; National Research Council 2000).

The fact that the freshwater fraction method accounts for the effects of seawater flushing processes on the freshwater distribution is difficult to glean from the literature. In an early description of the use of flushing times for predicting effluent dispersal, Pearson and Pearson (1965, p. 51–52) noted that the effects of tidal oscillation and ''apparent longitudinal diffusion'' were included in the model. Pilson (1985) implied that flushing times of Narragansett Bay calculated by the freshwater fraction method included both tidal and wind effects, but did not explicitly state that they would act, through the salinity distribution, on the freshwater fraction portion of the equation. Officer and Kester (1991) stated that the flushing rate, V/τ, represents the combined effects of nonadvective tidal exchanges and advective gravitational exchanges even though τ had been calculated using the freshwater fraction method. Our demonstration that the flushing times of freshwater and seawater are mathematically equivalent for a well-mixed system at steady state has also been alluded to in the literature. Pilson pointed out that, barring evidence of isolated water masses that do not participate in mixing processes, the average flushing times of both fresh and salt water would be roughly the same. Jay et al. (1997) also noted that turnover times for salt and freshwater are usually similar (except for fjords).

Because they include the same components of flushing, the results of freshwater fraction and tidal prism models are directly comparable. This has been suggested previously but not explained. Solis and Powell (1999, Eqs. 2–5) credit Zimmerman (1976, p. 182) for pointing out the approximate equality between freshwater fraction and tidal prism methods, but in that paper Zimmerman only made the point that the definitions of turnover time and flushing time are equivalent for the simple case of a basin exchanging matter with ''a reservoir of infinite volume'' (presumably the ocean); no specific conclusions were drawn regarding the equivalence of freshwater fraction and tidal prism methods for cases in which the basin exchanges material with both the ocean and a source of freshwater. We have demonstrated that even complex tidal prism models for partially mixed estuaries with incomplete escape of the ebb flow and incomplete mixing of the flood flow are identical to the freshwater fraction model if salinity is treated as a tracer common to both models.

CONSIDERATIONS FOR MODEL CHOICE

The evaluations above show that freshwater fraction and tidal prism models are based on different assumptions and are appropriate for estuaries with different physical characteristics: freshwater fraction models are appropriate for estuaries with relatively high freshwater inflow, and simple tidal prism models are applicable in situations such as well-mixed lagoons where freshwater inflow is low and gravitational circulation is weak.

Estuary characteristics and not data availability must dictate model choice: tidal prism models cannot properly be used to avoid quantifying freshwater inflow in those estuaries where it is important. It would be useful to develop guidelines to better define the limits within which each model should be applied.

A useful criterion for choosing between these two types of models should reflect the relative predominance of freshwater input versus tidal mixing in a given estuary. Luketina (1998) suggested that weak stratification reflects a predominance of tidal mixing over the effects of freshwater inflow (conditions favoring a tidal prism model), but stratification strength may not be a reliable criterion for choosing a model. Moderate tidal action actually strengthens gravitational circulation over that expected for a nontidal case (Pritchard 1967), so that, for a given freshwater inflow, greater tidal mixing would lead to an estuary with less stratification but greater gravitational circulation. The degree of stratification is not an indication of the strength of gravitational circulation, which is critical in choosing between freshwater fraction and tidal prism models.

A number of estuarine classification systems based on the relative strengths of tidal currents and river flow have been reviewed by Jay et al. (2000). Several methods classify estuaries according to two parameters that estimate degree of stratification and strength of gravitational circulation; using these criteria, estuaries tend to cluster in related groups, such as those without upstream bottom flow, partially mixed estuaries, fjords, and salt wedge estuaries. Such groupings could be useful in choosing an appropriate model to calculate turnover times: those without upstream bottom flow are likely candidates for tidal prism models, whereas freshwater fraction models are better suited for partially mixed estuaries. (Fjords and salt wedge estuaries, with poor mixing between well-defined water masses, would be better suited to independent analyses of the individual water masses.) The data necessary to estimate the classification parameters are not always available to those wishing to select a simple model to estimate turnover time.

The easiest and most relevant criterion for choosing an appropriate model might be whether there is a salinity difference between the estuary and the ocean (Eq. 2). In any situation where the salinities are measurably different and the freshwater fraction method can be applied, it is probably preferable. Although all the models presented here include flushing by both freshwater and seawater, the freshwater fraction method has more potential to include the combined effects of flushing from many physical processes because the salinity distribution can reflect all those processes, whereas the tidal prism model does not include gravitational circulation of seawater. The freshwater fraction model is also usually the easiest of the models to apply, as the data are often readily available or easily collected. In addition to salinities, an accurate estimate of freshwater inflow will be required.

If freshwater inflow is poorly quantified but a slight salinity difference suggests that it is low, a tidal prism model may be an acceptable alternative. Under these circumstances, it may be possible to parameterize the coefficients using salinity as a tracer. A time series of salinity measurements at the estuary mouth during several tidal cycles would be useful for detecting partial mixing and estimating the relative importance of the exchange ratios (Eqs. 25 and 26). The shapes of the peaks and troughs of the salinity fluctuation could indicate when lower-salinity water masses reach the mouth during ebb and whether they return during early flood or have been replaced by higher-salinity water from offshore (Koutitonsky et al. 2004).

If the salinity difference between estuary and ocean is negligible, then freshwater inflow must be low and relatively much less important than tidal mixing. In this case, a simple tidal prism model may be used but then it becomes impossible to use salinity as a tracer to estimate exchange ratios. It may be possible to use another tracer (such as dye) or Sanford et al.'s method (1992) to estimate return flow (Eq. 14). Numerical modeling (Signell and Butman 1992) or development of methods analogous to Sanford et al.'s may be necessary to estimate the more complex exchange ratios.

Utility of Simple Models

It is important to understand the limitations of applying simple models such as those presented here to real situations that are invariably more complex than a model. Models are averaged representations of the real system in both space and time, and both types of averaging may introduce errors or obscure important features of the system (Webster et al. 2000). Single-box steady-state models may be accurate enough for scaling or for gross comparisons, but these assumptions are not always reasonable. Small increases in complexity may yield a more accurate yet still tractable model, but model complexity must be increased consistently in order to avoid errors. We have discussed some of the consequences of trying to incorporate spatial heterogeneity in a single-box framework: volumes that are not well mixed should be divided into subvolumes that may be treated that way, with flow complexity increasing consistently with the compartmentalization scheme of the model. The freshwater fraction method can easily be extended to multiple zones, because turnover times from individual zones are additive. More complex mixing time scales can be derived from box models and hydrodynamic simulation models.

As models get increasingly complex, they have increasing data requirements and cost in terms of trained personnel and equipment. Models that are tailored to individual estuaries and highly useful for addressing localized questions may be difficult to generalize and compare. Simple models are still useful both as initial approaches for scaling larger projects and as easily accessible, widely applicable models that are comparable across systems. The LOICZ project and others addressing estuarine typology (Jay et al. 2000; National Research Council 2000; Bricker et al. 2003) are examples of the latter use. The simple freshwater fraction and tidal prism models described here, if applied appropriately, will yield comparable turnover times that can aid in the comparison of a wide variety of estuaries and will be useful in the larger context of developing an estuarine typology.

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