

# A stratification prediction diagram from characteristics of geometry, tides and runoff for estuaries with a prominent channel

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## Abstract

Accepting the premise that it should be possible to predict stratification within an estuary from the characteristics of its geometry, tide at the mouth and runoff, we use data from 14 estuaries with a prominent channel to develop an estuarine stratification prediction diagram. The data are taken from NOAA (1985) atlas of estuaries from USA. We then apply the diagram to a year long stratification record from the Mandovi, a monsoonal estuary, which during a year goes from being highly-stratified to partially-mixed to well-mixed due to change in runoff from wet to dry season. Using data from 16 estuaries around the world, we show that the diagram can be used to distinguish characteristics of stratification and of forcing functions between estuaries.

Keywords: prediction; stratification; tides; runoff; monsoonal estuary; India

## 1. Introduction

1 A number of studies in the literature on estuaries have discussed estuarine classification  
2 diagrams (see Valle-Levinson, 2010 for a review). The diagrams fall into two categories,  
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4 diagnostic and prognostic. A well known example of the former is the diagram proposed by Hansen  
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6 and Rattray (1966). The diagram, which uses information from within an estuary, provides insight  
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8 into relative contribution of advective and diffusive transport processes that determine the nature of  
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10 stratification in an estuary. An example of the prognostic diagram is Figure 2.7 of Geyer (2010),  
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12 reproduced here in Figure 1. The diagram predicts degree of stratification in an estuary from the  
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14 knowledge of two externally specified conditions, one related to tidal velocity and other to velocity  
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### Preferred position of Figure 1

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30 The diagram, besides providing a scheme for classifying estuaries, is useful because of its  
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32 potential ability to predict stratification in an estuary from externally specified conditions alone.  
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34 The diagram in Figure 1, however, needs to overcome the following limitations to achieve this  
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36 potential. First, the empirical data base on which it is based needs to be defined. Second, a  
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38 quantitative measure of stratification that the diagram is expected to predict needs to be spelled out.  
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40 Third, the most easily available information on tides at the mouth is not tidal velocity, but tidal  
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42 range; similarly it is the rate of runoff into an estuary that is usually available, not runoff velocity.  
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44 In this paper we describe an effort to overcome these issues leading to an estuarine stratification  
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46 prediction diagram.  
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55 In the next section we use dimensional analysis to address the second and the third of the  
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57 above issues and define the axes of an estuarine stratification prediction diagram. In Section 3 we  
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1 use an atlas on the estuaries of USA, NOAA (1985), to address the first issue. The data from the  
2 atlas on estuaries with a prominent channel with the sea at one end and a river at the other allow us  
3 to provide an empirical basis for separating from each other the regions in the diagram that  
4 represent the three states of stratification, i.e. well-mixed, partially-mixed and highly-stratified, in  
5 the estuarine stratification prediction diagram. In section 4 we use data from a monsoonal estuary  
6 to represent the states of stratification experienced by the estuary during a year. Monsoonal  
7 estuaries are known to exhibit all the three states of estuarine stratification during a year due to  
8 variation in runoff from season to season (Vijith et al., 2009). In section 5 we use the diagram to  
9 plot 16 estuaries around the world to examine the usefulness of the diagram. In section 6, the  
10 concluding section, we summarize the strengths and weakness of the stratification prediction  
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## 27 **2. Dimensional analysis**

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29 For carrying out the analysis in this section we will restrict our attention only to those  
30 estuaries that have a prominent channel with sea at the mouth and freshwater runoff at the head.  
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32 Additional runoff may enter the estuary along its length. We thus focus on estuaries with a  
33 geometry that is more commonly discussed in the literature. Let  $L$  be the length of the estuarine  
34 channel (m);  $h$ , the mean depth (m); and  $V_e$ , the volume of the estuary at mean sea level ( $\text{m}^3$ ).  
35 Let  $\Delta\rho$  be the difference in density in the channel from mouth to head ( $\text{kg m}^{-3}$ ). Our interest is to  
36 predict stratification in the estuarine channel averaged over a period  $\tau$ . It is logical to take  $\tau$  to  
37 be the period of the tide in the estuary, or about a day for mixed tides. We take  $t_r$  to be the tidal  
38 range at the mouth (m) and  $R$  the rate of total river runoff ( $\text{m}^3 \text{s}^{-1}$ ) into the estuary. Let  $g$  be the  
39 acceleration due to gravity ( $\text{m s}^{-2}$ ), the physical variable expected to play a dominant role in  
40 estuarine dynamics.  
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What is a good measure of stratification in an estuary? There is no clear answer to this question. One possibility is average vertical density gradient in the estuary. Another possibility could be the maximum density gradient because highly-stratified estuaries often have high vertical density gradient over a small length of the estuary, generally near its mouth. In this paper we will take  $\left(\frac{d\rho}{dz}\right)_{max}$ , i.e. maximum vertical density gradient in the estuary, as an indicator of stratification for prediction in the stratification diagram. We note, however, that we could have picked another variable that depends on vertical gradient of density in the estuary.

We thus have nine physical variables  $\left[\left(\frac{d\rho}{dz}\right)_{max}, L, h, V_e, \tau, t_r, R, \Delta\rho \text{ and } g\right]$  in three dimensions to describe the geometry, the state of stratification in an estuary, and its forcing functions. Hence Buckingham  $\Pi$  theorem implies we should be able to construct an equation  $f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6) = 0$ , where  $\pi_s, s = 1, 2, \dots, 6$  are the six non-dimensional parameters or

numbers constructed from the nine variables. We take the six numbers to be  $\frac{\left(\frac{d\rho}{dz}\right)_{max} h}{\Delta\rho}$ , a measure of stratification;  $t_r/h$ , tidal forcing;  $R\tau/V_e$ , runoff forcing;  $h/L$ , ratio of mean depth to length of the estuary;  $Lh^2/V_e$ , ratio of mean depth to width of the estuary; and  $L/(\tau\sqrt{gh})$ , ratio of the time taken by a shallow-water gravity wave to travel the length of the estuary to the chosen time-scale,  $\tau$ .

We thus get

$$\frac{\left(\frac{d\rho}{dz}\right)_{max} h}{\Delta\rho} = f\left(\frac{t_r}{h}, \frac{R\tau}{V_e}, \frac{h}{L}, \frac{Lh^2}{V_e}, \frac{L}{\tau\sqrt{gh}}\right). \quad (1)$$

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4 In order to convert this equation into an equation to construct a stratification prediction diagram, we  
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assume that the equation is most sensitively dependent on  $t_r/h$  and  $R\tau/V_e$ . We also assume that density variation in the estuary is due to variation in salinity. With these assumptions we get

$$\frac{\left(\frac{dS}{dz}\right)_{max} h}{\Delta S} = f\left(\frac{t_r}{h}, \frac{R\tau}{V_e}\right), \quad (2)$$

where  $\Delta S$  is change in salinity from head to mouth. The equation represents a surface in the space with  $t_r/h$  and  $R\tau/V_e$  as the two axes in the horizontal plane. The surface gives magnitude of the stratification number as a function of tidal forcing number (tidal range / mean depth) and runoff forcing number (runoff in a day / volume of the estuary). In the next section we use empirical data on the estuaries with prominent channel to determine characteristics of the relationship given in Equation (2).

### 3. Stratification in estuaries with a prominent channel

The empirical information on the state of stratification in estuaries with a prominent channel is derived from an atlas on estuaries in USA, NOAA (1985). This “National Estuarine Inventory: Data Atlas” gives a consistent description of physical and hydrologic characteristics of well over 60 estuaries in the USA. We decided to use this atlas because it followed a uniform procedure in all the estimates given in the atlas. Whenever doubts about an estimate arise, the authors of the atlas depended on consensus amongst informed experts. Of the data given in the atlas, the following are of interest to this paper in view of the physical variables discussed in the previous section: length, mean width, mean depth, tidal range at the mouth, stratification in the estuary and rate of daily freshwater runoff. The stratification in an estuary is assigned one of the following three states: highly stratified (salt-wedge); moderately stratified (surface salinity less than bottom salinity); and vertically homogeneous (surface salinity equals bottom salinity). In the nomenclature used in this paper we name these estuaries highly-stratified, partially-mixed and well-mixed, respectively.

1 Because the stratification in an estuary can differ with season due to variation in runoff, the atlas  
2 gives the state of stratification for each estuary twice a year, when the three month average runoff is  
3 highest and when it is lowest.  
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8 Of the sixty odd estuaries discussed in the atlas, only 14 conform to the estuarine geometry  
9 that we have restricted our attention to, i.e. to estuaries with a prominent channel. Geometrical  
10 configurations of the remaining estuaries fall in the following categories: estuaries with a large bay  
11 or lake having multiple rivers bringing freshwater and connected to the sea through one or more  
12 narrow channels (27 estuaries in the atlas); multiple channels that open into a large bay with a wide  
13 mouth (18 estuaries); and estuaries with a complex interconnected networks (7 estuaries). It is quite  
14 possible that these estuaries could be divided into sub-estuaries that have a prominent channel. But  
15 then we will need data on the variables listed in the Section 2 on each of the sub-estuaries. This is  
16 not possible with the data provided in the atlas.  
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### 32 Preferred position of Table 1

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37 The fourteen estuaries that are discussed here are listed in Table 1. The table also gives  
38 other data that have been picked from the atlas and used in our analysis. For each estuary we get  
39 two states of stratification once when the runoff is high and once when it is low. Hence if we  
40 construct a diagram with  $t_r/h$  and  $R\tau/V_e$  as x- and y-axis respectively, then we get two points  
41 with each point tagged with one of the three states of stratification described earlier.  
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### 52 Preferred position of Figure 2

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57 Figure 2 shows the plot with 28 points from the 14 estuaries. In the plot the degree of  
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stratification in an estuary is shown with the help of a symbol. From the plot it is seen that the points representing one particular degree of stratification tends to bunch together. In the plot we have shown two straight lines drawn by inspection to separate the symbols. One of these lines

separate the points  $\left(\frac{t_r}{h}, \frac{R\tau}{V_e}\right)$  corresponding to a well-mixed estuary from those corresponding to a partially-mixed estuary. The second line separates highly-stratified from partially-mixed.

In the earlier section we have noted that equation (2) represents a surface. The z-coordinate

of the surface equals  $\frac{\left(\frac{dS}{dz}\right)_{max} h}{\Delta S}$ . If we choose a constant  $C_1$  as the magnitude of stratification

that separates well-mixed estuaries from the partially-mixed ones, then the lower line in Figure 2

represents the projection of intersection of the plane  $\frac{\left(\frac{dS}{dz}\right)_{max} h}{\Delta S} = C_1$  on to the  $\frac{\left(\frac{dS}{dz}\right)_{max} h}{\Delta S} = 0$ , i.e.

$(x, y)$  plane. Similarly, if  $C_2$  separates partially-mixed estuaries from highly-stratified

estuaries then the upper line in Figure 2 is projection of  $\frac{\left(\frac{dS}{dz}\right)_{max} h}{\Delta S} = C_2$  on to the  $(x, y)$  plane.

#### 4. Application to a monsoonal estuary

How useful is the diagram in Figure 2 to study other estuaries? Can the plot be used to predict estuarine stratification quantitatively? To address these questions we use observed data from a monsoonal estuary which has earlier been shown to exhibit stratification that varies from

well-mixed to partially-mixed to highly-stratified due to variation in runoff (Vijith et al., 2009).

1 Can the transition from one of the three states of stratification to another be predicted from  
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3 knowledge of variation in runoff (and, of course, the tidal range) alone?  
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12 The monsoonal estuary we have chosen to examine the questions raised above is the  
13 Mandovi on the west coast of India. The estuary, shown in Figure 3, is a coastal plain estuary with  
14 a convergent channel with depth at the mouth of about 7m and about a meter at the head. The width  
15 at the mouth is 3.7 kilometers; at the head it is only a tenth of a kilometer. The catchment area of  
16 the estuary is about 1800 km<sup>2</sup>. The average annual precipitation over the catchment area is in  
17 excess of 2.5 m. Virtually all the precipitation occurs during the four months of the Indian Summer  
18 Monsoon, June – September. At times, during extreme rainfall events runoff in the Mandovi  
19 exceeds 1852 m<sup>3</sup> s<sup>-1</sup>, equaling 160×10<sup>6</sup> m<sup>3</sup> day<sup>-1</sup>, the volume of the Mandovi. The runoff into the  
20 Mandovi decreases rapidly following withdrawal of the monsoon in October.  
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42 The runoff at the head of the estuary, Ganjem, available from Central Water Commission ,  
43 India, from 23 June 2007 to 31 January 2008 is shown in Figure 4a (solid line). There is  
44 considerable intra-seasonal variability in the runoff due to similar variability in the monsoon  
45 precipitation. Rainfall sometimes can be so high that the daily runoff at Ganjem exceeds the  
46 volume of the estuary. The estuary also receives runoff from a number of tributaries that join the  
47 main channel of the Mandovi from head to mouth. The estimate based on hydrological model  
48 studies suggest that the contribution to runoff from the tributaries is of the same order as that at the  
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head (Suprit and Shankar, 2008). Due to negligible rainfall during November – May runoff at Ganjem decreases to about  $1 \text{ m}^3 \text{ s}^{-1}$  during the dry season (Suprit et al., 2011).

### Preferred position of Figure 5

The annual cycle of stratification in the main channel of the estuary was studied for a year during 1 June 2007 to 31 May 2008. Figure 5 is taken from Vijith et al. (2009) that summarized the findings from the study. Figure 5a shows the salinity field by early June, i.e. at the end of the seven-month long dry season (November – May) when salinity ingress into the estuary peaks. With the onset of the monsoon, runoff increases and saline waters gets pushed out of the estuary. Sometimes, when runoff is high, almost the whole estuary turns fresh (Figure 5b). Often a salt wedge forms near the mouth of the estuary at this time (Figure 5c and d). Following withdrawal of the monsoon, runoff into the estuary decreases rapidly and soon reaches negligible levels (Figure 4a). As a result, salinity starts migrating into the estuary and the stratification in the estuary decreases to levels similar to found in partially-mixed estuaries (Figures 5e). As the dry season progresses the stratification decreases further to the levels found in well-mixed estuaries (Figure 5f).

Tides in the Mandovi are mixed, predominantly semi-diurnal with a mean spring tidal range and mean neap tidal range of 2.3 m and 1.5 m, respectively at the mouth. Figure 4b shows the daily tidal range at Verem which is located close to the mouth of the estuary (see Figure 3 for location). The tidal range was computed from prediction of tide at Verem using tidal constituents computed from one-month long sea level data. During the 2007 – 2008 study of the Mandovi a vertical profile of temperature and salinity was collected at Panaji (see Figure 3 for location), 6.5 km upstream of the mouth, everyday during times of high and medium runoff (1 June 2007 – 14 January 2008) and once in two days during times of low and negligible runoff (16 January 2008 – 3

May 2008). The observation was made at 1100 hours Indian Standard Time. The profile was collected using a portable SeaBird CTD (SBE 19 Plus) from a boat in the middle of the channel. Figure 4c shows difference in salinity between bottom and surface, i.e. over a vertical separation of 6 m, using the vertical profile of salinity.

Using the data summarized in Figure 4c and taking  $h$  and  $\Delta S$  to be 5 m and 35 respectively we can compute the stratification number  $\left(\frac{dS}{dz}\right)_{max} \frac{h}{\Delta S}$  at Panaji. We assume that  $\frac{dS}{dz}$  at Panaji can be taken to be maximum  $\frac{dS}{dz}$  in the estuary. We make this assumption after noting in Figure 5 the region of maximum stratification is close to the point where the observation at Panaji were made. Time series of the stratification number computed each day is shown in Figure 4d. This time series shows the importance of tidal range: highs in stratification number coincide with lows in tidal range. During wet periods high stratification occurs during time of high runoff.

There are missing values in the runoff data (Figure 4a) from 1 February 2008 – 3 May 2008. We assume that a runoff of  $1 \text{ m}^3 \text{ s}^{-1}$ , occurs in the Mandovi from 1 March 2008, which is consistent with long-term average for dry season reported by Suprit et al. (2011). Runoff during February 2008 is interpolated using cubic-spline interpolation scheme. Interpolated runoff is shown using dots in Figure 4a. To estimate  $R\tau/V_e$ ,  $R$  is estimated as twice the value of runoff at the head of the estuary to account for runoff due to the tributaries,  $\tau$  is taken to be a day, and  $V_e$  to be  $160 \times 10^6 \text{ m}^3$ . The tidal forcing number,  $t_r/h$ , has been calculated using daily tidal range given Figure 4b and taking mean depth as 5 m.

## Preferred position of Figure 6

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4 In Figure 6 we plot the stratification number as a function of tidal range number and runoff  
5 number. In the figure we also reproduce the two dashed lines shown in Figure 2. Consistent with  
6 what is seen in Figure 5, Figure 6 shows that the stratification in the estuary varies from well-mixed  
7 to partially-mixed to highly-stratified. In this figure the two dashed lines can be assigned the value  
8 of 0.01 and 0.1, for separating, respectively, the well-mixed regime from the partially-mixed and the  
9 partially-mixed from the highly-stratified. The numerical values assigned to the two lines are, of  
10 course, dependent on the specific choice we have made to define the stratification number.  
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23 If we accept the premise that the state of stratification of an estuary is determined by the  
24 tidal forcing and runoff forcing then definition of the stratification number is not crucial. The  
25 definition merely provides a quantitative measure of stratification, the relative magnitude of which  
26 helps to separate the three classes of estuaries. Of crucial importance to construct the stratification  
27 prediction diagram is the empirical evidence in Figure 2 that made separation between the three  
28 classes of estuarine stratification possible. The dimensional analysis and definition of a  
29 stratification number used in Section 2 provides a physical and mathematical framework on which  
30 the prediction diagram can be built. Similar analysis can be carried out with another definition of  
31 stratification number. Henceforth we will not refer to any specific definition of the stratification  
32 number, but note that a point in the prediction diagram that is located farther towards the upper left  
33 corner on a line normal to the two dashed lines is expected to represent an estuary that has higher  
34 stratification.  
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## **5. Application to estuaries across the world**

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56 Noting that both the tidal- and runoff-forcing functions are time-dependent, an estuary in the  
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prediction diagram is better represented with a set of points that are representative of the states of stratification that the estuary is expected to exhibit during the course of a year. This set fits within a rectangle whose horizontal extent is determined by the variability of tidal range and the vertical extent is determined by variability of runoff. In Table 2 we define the minimum and maximum values for tidal range and runoff in 16 estuaries distributed around the world. We also define other parameters for each of the estuaries to compute the tidal- and the runoff-numbers. The resulting rectangle that represents the possible states that an estuary could exhibit during a year is shown in the stratification prediction diagram shown in Figure 7.

Preferred position of Table 2

Preferred position of Figure 7

The state of stratification predicted by each rectangle in Figure 7 is consistent with what is known from the literature on each estuary. The diagram could therefore be used to make a first guess about an estuary that has not been studied earlier. The diagram also helps to compare estuaries. The rectangle for an estuary helps to distinguish stratification in that estuary from that in another estuary.

## **6. Concluding comments**

The most important justification for the prediction diagram discussed here is the empirical evidence summarized in Figure 2. It is necessary to enlarge the database on which this figure is based, 14 estuaries with prominent channels. More estuaries need to be examined to ascertain robustness of the lines that separate the three categories of estuarine stratification regimes.

The importance of geometry to the processes inside an estuary has been noted earlier by

Prandle (2009). While working on the present study the role that estuarine geometry plays in determining the relationship between stratification and tidal- and runoff-forcing got highlighted. This, of course, is expected from Equation (1). When we used data from NOAA (1985) for estuaries that did not have a prominent channel, we found that it was not possible to separate the stratification regimes the way it was possible for estuaries with a prominent channel. It may be that sub-estuaries of estuaries with complicated geometry may still fit with the relationship shown in Figure 2 if information about the sub-estuaries becomes available. This possibility needs to be explored.

From Figure 7 we note that the prediction diagram helps to distinguish an estuary from others from the knowledge of its external forcing functions alone. The prediction diagram can thus serve as an exploratory tool to guess what could be going on in the estuary prior to making observations within it.

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## Figure Captions

1 Figure 1. The prognostic estuarine classification diagram given in Geyer (2010).  $u_T$  and  $u_R$  are  
2  
3 the forcing variables: tidal velocity and velocity due to river runoff respectively.  $\beta$ ,  $g$ ,  $s_0$ , and  $h$   
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5 are respectively, coefficient of saline contraction, acceleration due to gravity, average salinity at the  
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7 mouth and average depth. Note that the axes are in logarithmic scale.  
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13 Figure 2. Estuarine stratification diagram. Please refer to Table 1 for the names of the estuaries and  
14  
15 the data used to draw this diagram. The data were taken from NOAA (1985).  $t_r$  and  $R$  are the  
16  
17 forcing variables; tidal range at the mouth and total runoff into the estuary;  $h$ ,  $\tau$  and  $V_e$  are  
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19 mean depth, a time scale of interest (one day) and volume of the estuary at mean sea level,  
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21 respectively. NOAA (1985) gives the state of stratification in an estuary as highly-stratified,  
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23 partially-mixed and well-mixed. The symbols given in the upper left hand corner give the states of  
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25 stratification. Note that the axes use a logarithmic scale.  
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34 Figure 3. Map of the Mandovi estuary located in the state of Goa, west coast of India. Locations of  
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36 the runoff gauge (Ganjem), tide gauge (Verem) and daily sampling (Panaji) are shown with filled  
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38 circles. These are the locations where the time series measurements shown in Figure 4 were made.  
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44 Figure 4. (a) Daily runoff ( $\text{m}^3\text{s}^{-1}$ ) measured at the head of the Mandovi (Ganjem; see the map in  
45  
46 Figure 3 for location). The data were collected from the Central Water Commission, India. There  
47  
48 are missing values from 1 February 2008 – 3 May 2008. Interpolated values (shown with dots) are  
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50 used as substitute for missing values as discussed in Section 4. (b) Predicted tidal range (m)  
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52 estimated from the tide predicted at Verem (for location see Figure 3). (c) Difference in salinity  
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54 between the bottom and the surface, that is over a depth change of 6 m, in the middle of the channel  
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1 near Panaji (see Figure 3). (d) Stratification number,  $\left(\frac{dS}{dz}\right)h$ , computed using  $dS$  shown in (c),

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4  $dz=6\text{ m}$ ,  $h=5\text{ m}$  and  $\Delta S=35$ . The data presented in (a), (b) and (d) are used to construct  
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6 Figure 6.

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11 Figure 5. Observed sections of salinity along the Mandovi estuary during (a) 1 June 2007, (b) 10  
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13 August 2007, (c) 24 August 2007, (d) 19 October 2007, (e) 11 January 2008 and (f) 16 May 2008.

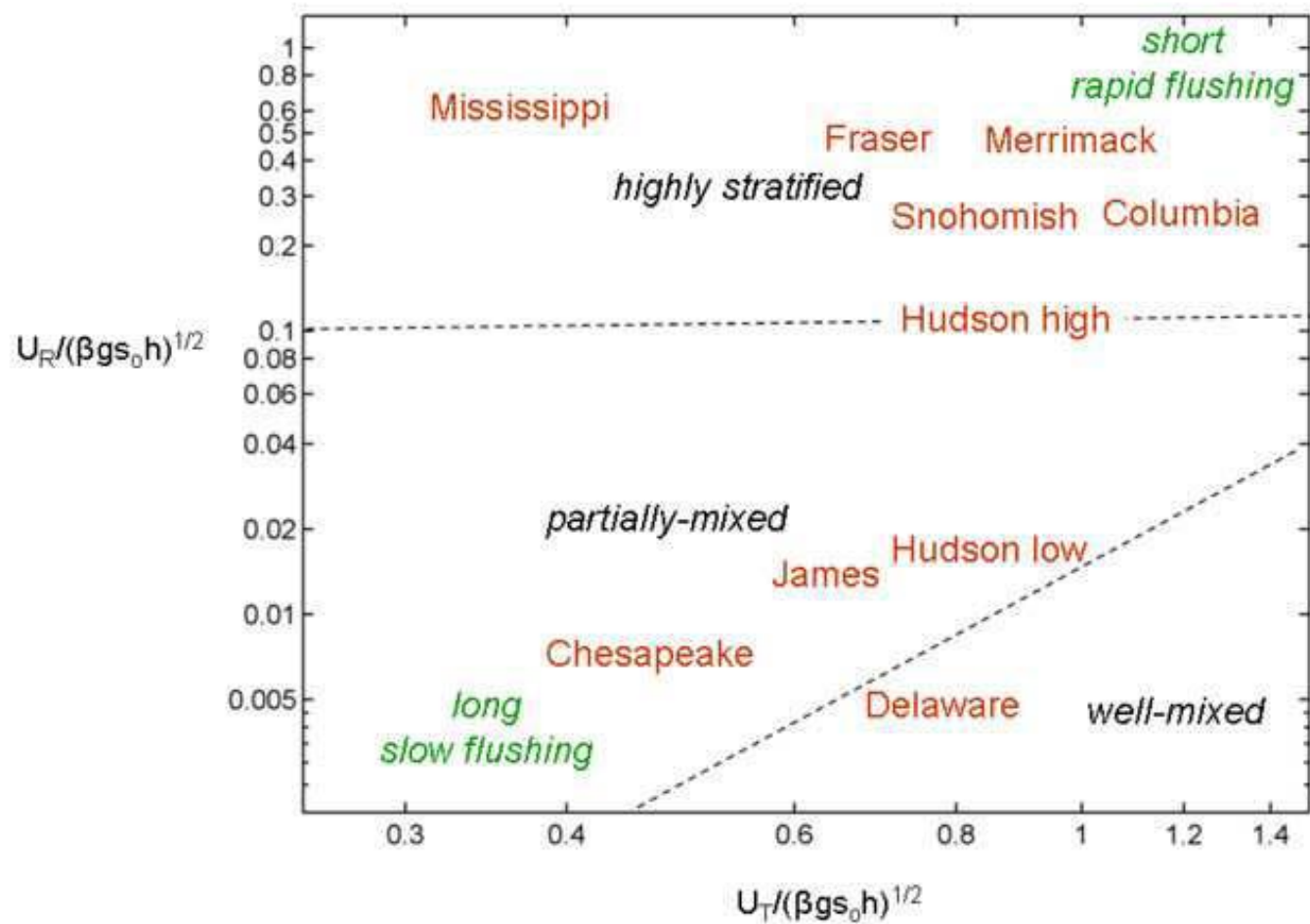
14  
15 River runoff at the head and tidal range near the mouth are given in lower right corner. The  
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17 Mandovi exhibits each of the three states of stratification (well-mixed, partially-mixed and highly-  
18  
19 stratified) in the course of an annual cycle. During heavy river runoff the estuary is completely  
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21 flushed as seen in (b).  
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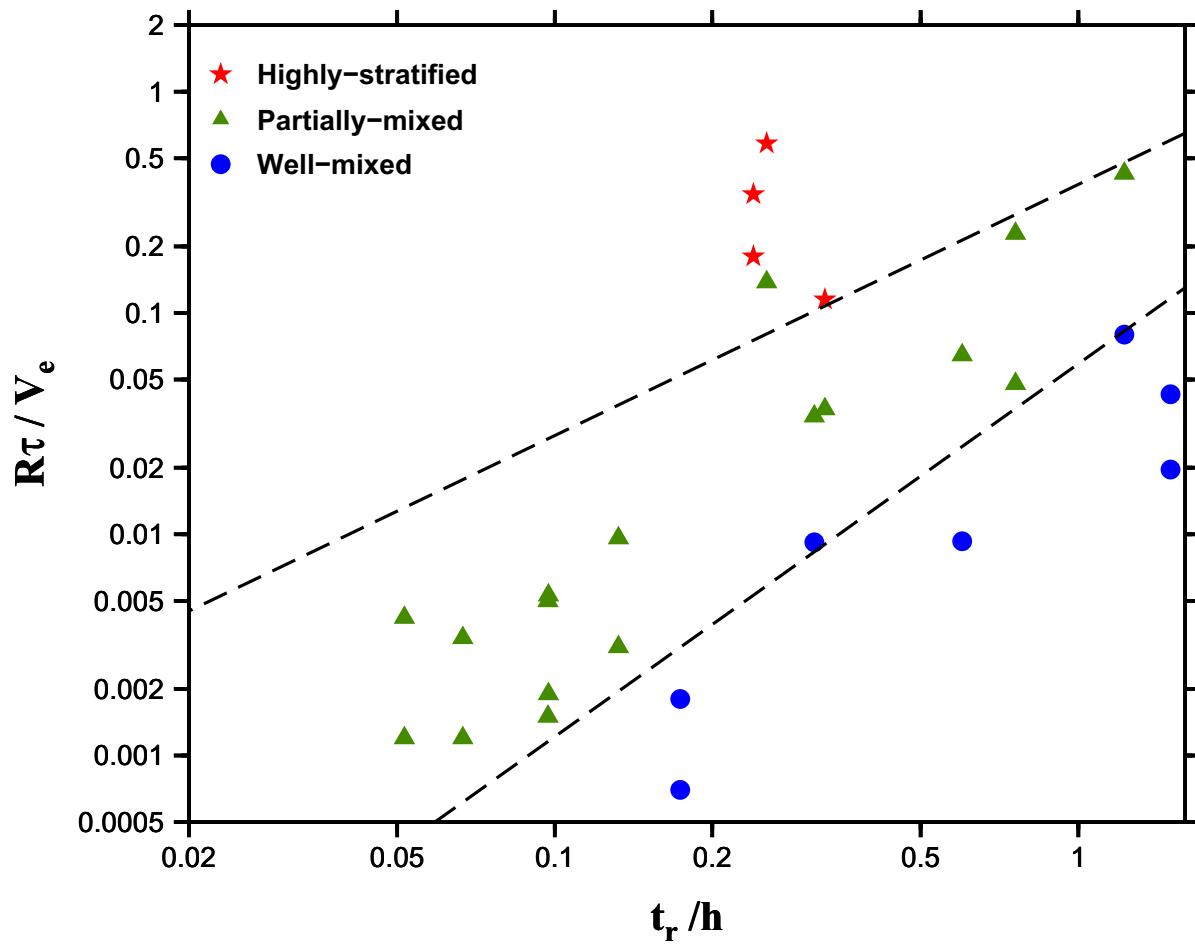
28 Figure 6. Stratification prediction diagram for the Mandovi. Section 4 describes how the tidal  
29  
30 range number, runoff number and stratification number are estimated. Axes are similar to those in  
31  
32 Figure 2. The lines separating different classes of mixing are also copied from Figure 2.

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34 Approximate values of the stratification number corresponding to the lines are given. Note that  
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36 when  $R\tau/V_e$  is greater than 1, volume of daily runoff exceeds the volume of the estuary. During  
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38 such times the estuary is completely flushed.  
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46 Figure 7. Each of the 16 estuaries listed in Table 2 is represented in the stratification prediction  
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48 diagram with a rectangle. The horizontal extent of the rectangle gives the range of values that the  
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50 tidal-forcing number ( $t_r/h$ ) takes in an estuary. The vertical extent of the rectangle is the range  
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52 of values that the runoff-forcing number ( $R\tau/V_e$ ) can take during a year. The rectangle thus  
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54 gives the set of states of stratification that an estuary can exhibit during a year. The name of the  
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56 estuary to which a particular diagram refers to is listed at the top of a diagram.  
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Figure 1





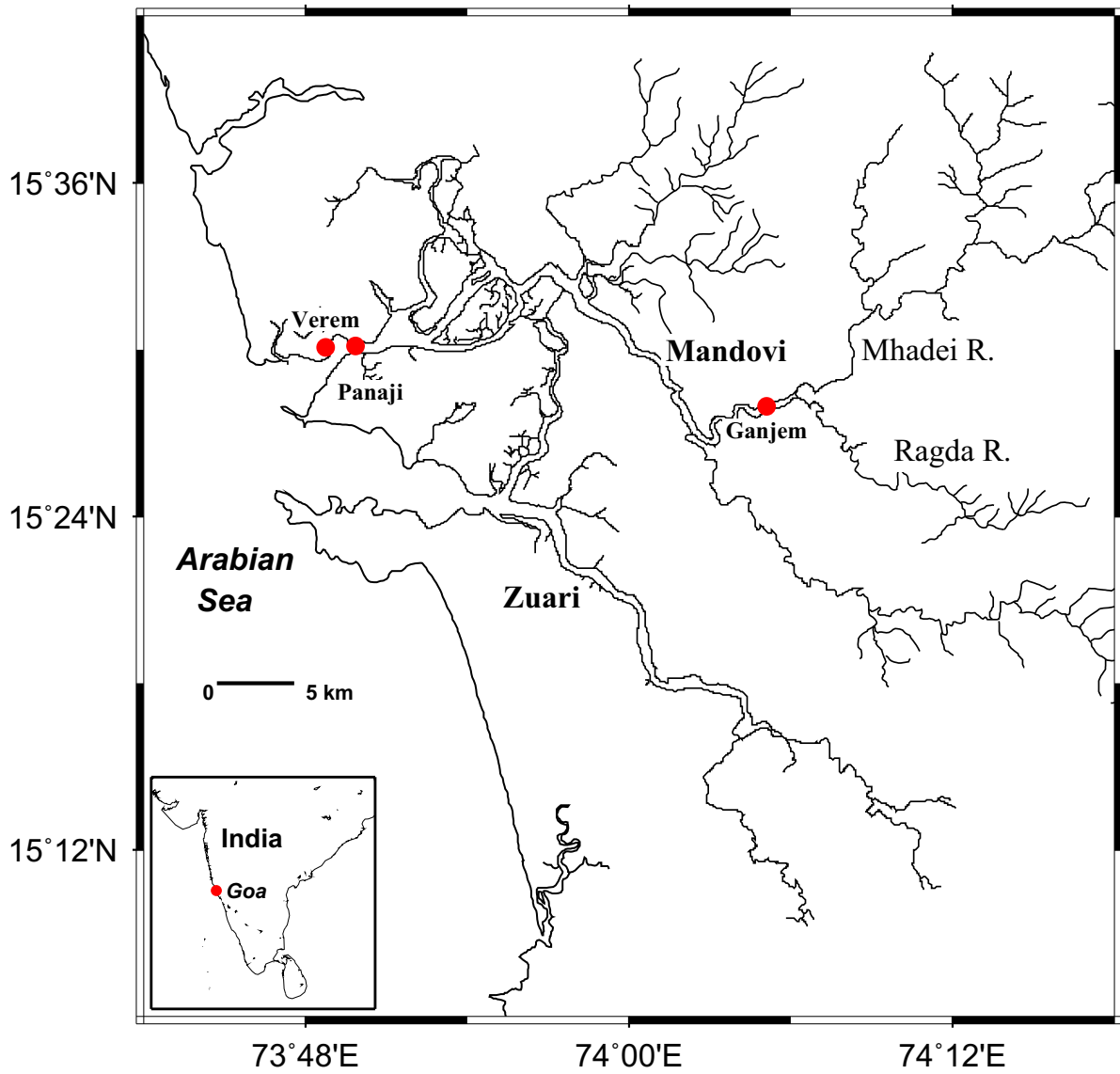
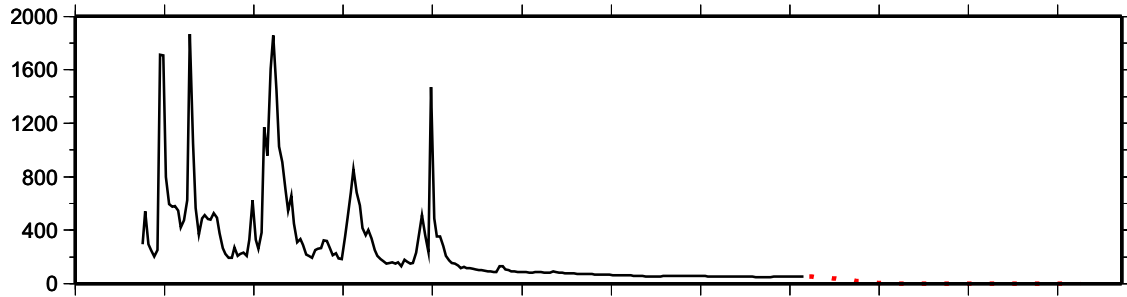
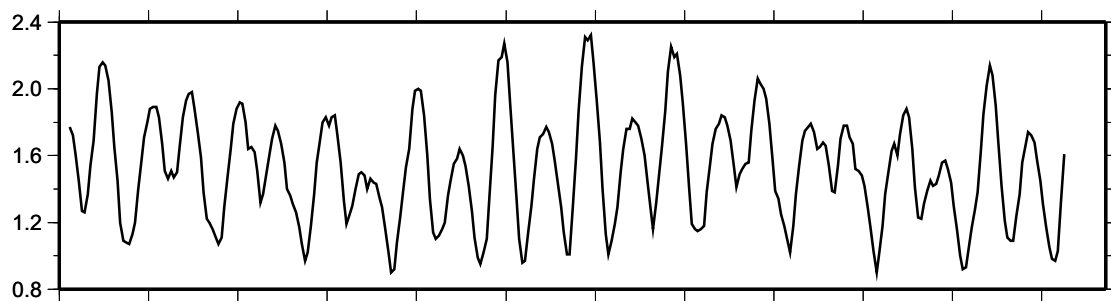


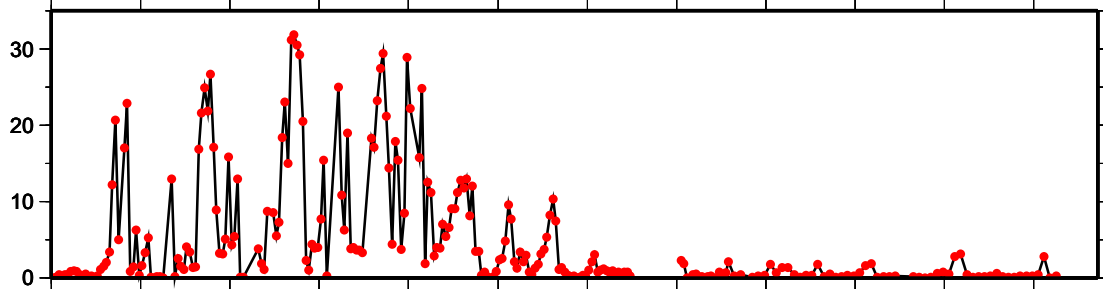
Figure **a**) Runoff ( $\text{m}^3\text{s}^{-1}$ )



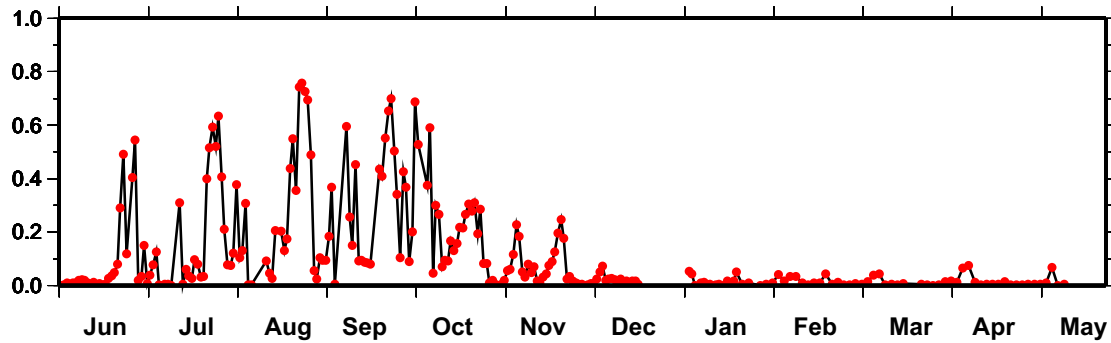
**b)** Tidal range (m)

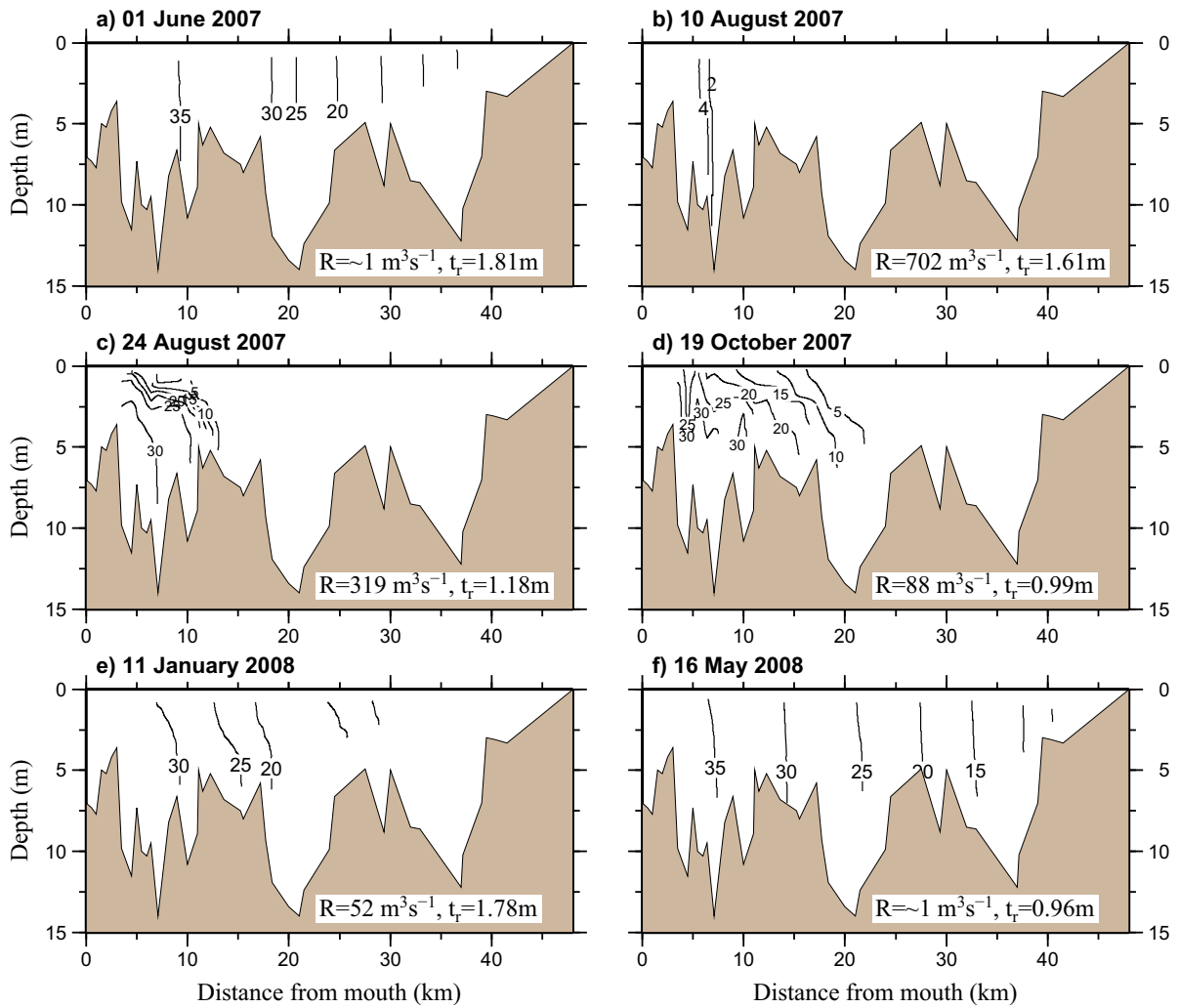


**c)** Salinity<sub>bottom</sub> - Salinity<sub>surface</sub>

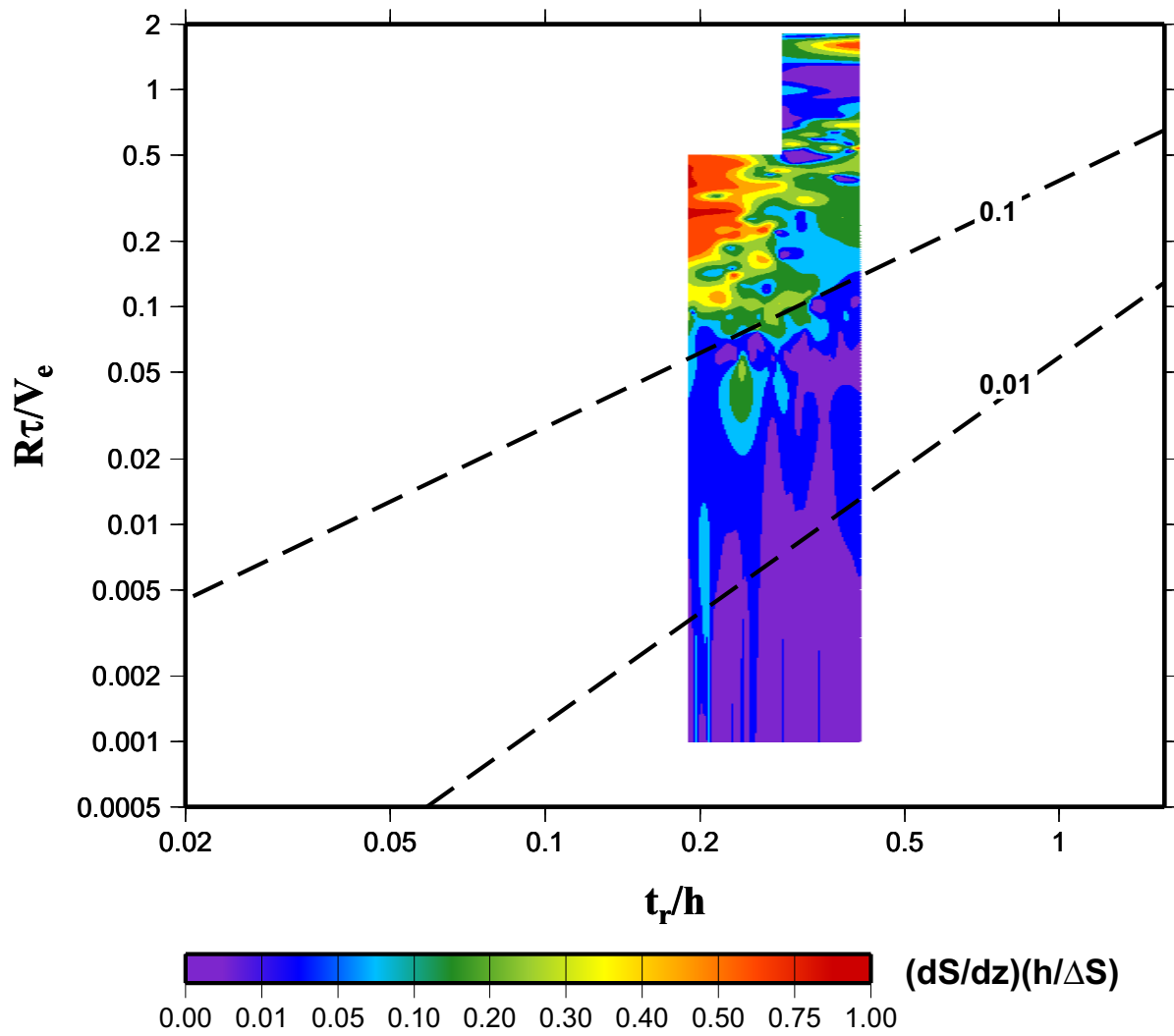


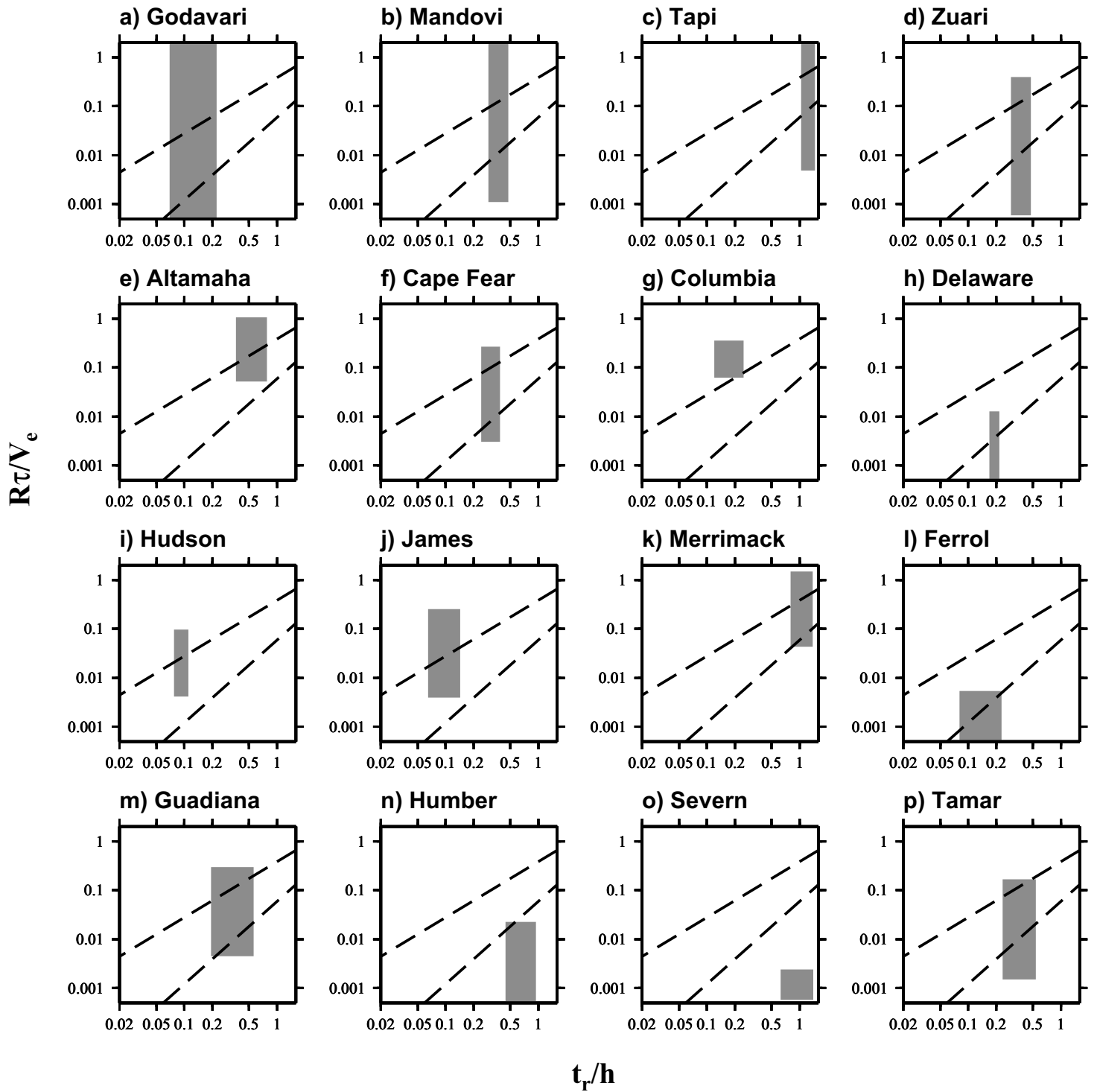
**d)** Stratification number











**Table 1**

Table 1. List of the name, length (km), mean width (km), mean depth (m), mean tidal range (m), runoff ( $\text{m}^3\text{s}^{-1}$ ) and classification of each of the 14 estuaries used in Figure 2. The code used to describe stratification is as follows: WM, Well-mixed; PM, Partially-mixed; HS, Highly-stratified. The volume of the estuary for computing the runoff-forcing number was taken to be the product of the length, mean width and mean depth.

Estuary	Length (km)	Width (km)	Depth (m)	Tidal range (m)	Runoff ( $\text{m}^3\text{s}^{-1}$ )		Classification	
					3-month low	3-month high	3-month low	3-month high
Merrimack River	40.9	1.1	2.0	2.5	86.8	464.4	WM	PM
Connecticut River	89.3	0.5	3.8	1.0	264.3	1119.5	PM	HS
Hudson River	257.5	2.7	4.6	1.4	343.6	1275.2	WM	PM
Delaware Bay	222.1	24.1	7.4	1.3	307.7	826.9	WM	WM
Chesapeake Bay	318.7	24.8	8.5	0.8	1131.7	3855.8	PM	PM
Potomac River	188.3	10.3	7.7	0.4	206.7	723.0	PM	PM
Rappahannock River	158.7	3.7	5.5	0.4	45.3	125.5	PM	PM
York River	78.9	3.4	6.6	0.6	37.8	108.5	PM	PM
James River	162.2	5.1	5.8	0.8	174.6	532.4	PM	PM
New River	39.9	2.7	0.6	0.9	15.1	33.0	WM	WM
Cape Fear River	83.7	1.1	4.0	1.3	160.5	502.2	PM	HS
North and South Santee Rivers	88.8	1.1	2.3	1.4	24.5	170.8	WM	PM
Altamaha River	43.5	2.7	2.7	2.0	174.6	833.5	PM	PM
Columbia River	64.4	5.1	7.3	1.7	5017.7	9587.1	HS	HS

**Table 2**

Table 2. The name, location,  $t_r$  during neap and spring tide,  $R$  during low and high runoff,  $h$ ,  $V_e$  and references for each of the estuaries included in Figure 7. '\*' in column 7 indicates that the volume of the estuary was estimated by integrating the cross-sectional area. '#' in column 7 indicates that the volume of the estuary was estimated as the product of the length, mean width and mean depth of the estuary.

Estuary	$t_r(m)$		$R(m^3 s^{-1})$		$h(m)$	$V_e(10^6 m^3)$	References
	Neap	Spring	Low	High			
Mandovi estuary, India	1.5	2.3	2	3900	5	160	Vijith et al. (2009)
Tapi estuary, India	4.3	5.7	10	8000	4	167	Bapardekar et al. (2004)
Zuari estuary, India	1.5	2.3	2	1156	5	270	Shetye et al. (2007)
Godavari estuary, India	0.5	1.5	1	11015	7	246	Sarma et al. (2009) and Sridevi Bobbili (personal communication)
Altamaha River estuary, U.S.A.	1.5	3.0	200	1800	4	157	Iorio and Kang (2007), Kang and Iorio (2006) and Alber and Sheldon (1999)
Cape Fear River estuary, U.S.A.	1.0	1.5	14	1100	4	375 <sup>#</sup>	Becker et al. (2010) and NOAA(1985)
Columbia River estuary, U.S.A.	0.9	1.8	3000	15000	7.25	3900	Jay and Smith (1990) and Sherwood et al. (1990)
Delaware Bay, U.S.A.	1.6	1.9	120	2600	8.8	18900	Cook et al. (2007) and Goodrich (1988)
Hudson River estuary, U.S.A.	1.2	1.6	100	2000	15	1925*	Geyer (2000) and Ralston et al. (2008)
James River estuary, U.S.A.	0.6	1.3	105	5946	9	2150*	Godfrey (1980)
Merrimack River estuary, U.S.A.	2.5	4.0	50	1500	3	94 <sup>#</sup>	Ralston et al. (2010) and NOAA (1985)
Ria of Ferrol, Spain	1.5	4.0	1.2	14.5	18	250	deCastro (2004)
Guadiana estuary, Portugal	1.3	3.5	8	463	6.5	143	Faria et al. (2006)
Humber estuary, England	3.2	6.4	4	475	7	1930	Uncles et al. (2006) and Townend (2005)
Severn estuary, England	6.5	13.5	30	110	10	4190	Uncles (2010), Manning et al. (2010) and Townend (2005)
Tamar estuary, England	2.2	4.7	3	290	9	160	Grabemann et al. (1997) and Miller et al. (1999)