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# Propagation of tides in the Mandovi-Zuari estuarine network

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**Abstract.** Located in Goa on the west coast of India and joining the Arabian Sea, the Mandovi and the Zuari are two estuaries, each about 50 km long, connected by a narrow canal. A number of small rivers join the two estuaries, forming a network of channels, whose cross-sectional area decreases rapidly in the upstream direction. They receive large freshwater influx during the southwest monsoon and little during the rest of the year. During April (dry season) and August (wet season) 1993, the water level and salinity at 15 locations in the network were monitored for 3 days to determine characteristics of tidal propagation in the network. Analysis of the data shows that the speed of propagation of both the diurnal and the semi-diurnal tide through the main channels of the network is approximately 6 m/s. Amplitudes of these tides in the channels remain unchanged over a distance of about 40 km from the mouth and then decay rapidly upstream over the next 10 km. The undamped propagation is a consequence of the balance between geometric amplification, due to decrease in the cross-sectional area in the upstream direction, and frictional dissipation. The rapid decay near the upstream end of the channels appears to result primarily from freshwater influx.

**Keywords.** Tides; estuary; freshwater influx; river runoff; tidal propagation.

## 1. Introduction

The Mandovi and the Zuari are two estuaries located in Goa on the west coast of India; they join the Arabian Sea (figure 1). The main channels of these estuaries are each about 50 km long and they are connected by a narrow channel, the Kumbarjua Canal. At the upstream end, both estuaries receive freshwater from rivers which originate in the Western Ghats mountain ranges. A number of rivers/rivulets join the two estuaries. The Mandovi, the Zuari, the Kumbarjua Canal and the rivers/rivulets form a network, which is used extensively for transport of goods (mainly iron ore), for fishing, and for dumping domestic and industrial waste. The increase in population and industrial activity in Goa during the last few decades has increased the dependence of the state on the network. Simultaneously, issues related to the health of the estuarine network and to its ability to absorb additional impacts have gained importance. Addressing these issues requires an understanding of the hydrodynamics of the network. A first step towards this goal is the understanding of propagation of tides because they dominate the advective field. Earlier studies have accumulated considerable data on the seasonal cycle of hydrography and of the chemistry of the estuarine network (see, for example, Qasim and Sen Gupta 1981). Little, however, is known about propagation of tides in the network. Hence, a study based on observations and mathematical modelling was initiated. In this article we describe the observations made as a part of the study, and infer prominent characteristics of tidal propagation.

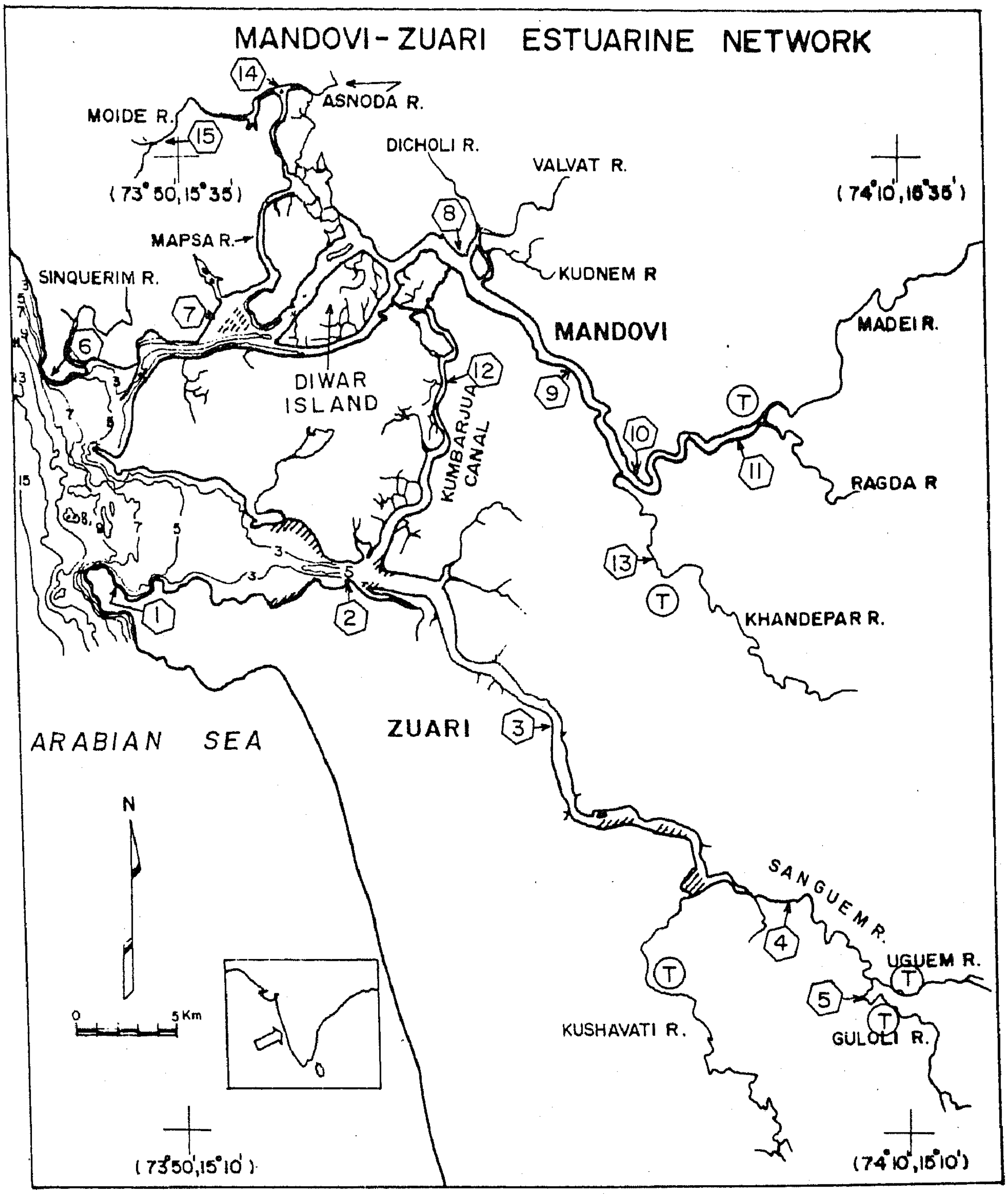


**Figure 1.** Map of the Mandovi-Zuari estuarine network based on publications from the Survey of India (1967), the Naval Hydrographic Office, India, and the Admiralty, U.K. The depth contours are with respect to mean sea level which is 1·3 m above Spring Low Water at Marmagao. To avoid clutter, the depth contours are shown only near the mouths of the main channels of the Mandovi and the Zuari. See figure 2 for variation of depth along the rest of the main channels. 'T' in a circle shows location up to which tidal influence is felt in the rivers Kushavati, Uguem, Guloli, Khandepar and Mandovi. The 15 locations where observations were made during April and August 1993 are shown with a number inside a hexagon. The correspondence between the numbers and the locations is as follows. **1**: Marmagao; **2**: Cortalim; **3**: Loutulim; **4**: Sanvordem; **5**: Sanguem; **6**: Aguada; **7**: Penha de Franca; **8**: Sarmanas; **9**: Volvoi; **10**: Sonarbaag; **11**: Ganjem; **12**: Banastarim; **13**: Khandepar; **14**: Sirsai; **15**: Mapsa.

Though tides dominate the advective field, another process, the effect of the influx of freshwater brought in by rivers and rivulets that join the network, also needs to be considered. The freshwater enters primarily at the upstream end of the channels. Many points along the channels also receive freshwater. The influx is high during the southwest monsoon (June – October), when most of the annual precipitation occurs over the catchment area, decreasing rapidly after the withdrawal of the monsoon. However, even during the dry season, at the upstream end of the channels the water is fresh.

Physical description of the Mandovi-Zuari is given in the next section. Tidal circulation in the network is forced by tides at the mouth. In § 3 we examine the tides at Marmagao, which is at the mouth of the Zuari. The data collected during the dry- and wet-season observation campaigns are described in § 4 and the characteristics of tidal propagation and of salinity variation are discussed in § 5. Our main conclusions are summarized in § 6.

## 2. A physical description of the Mandovi-Zuari estuarine network

The Mandovi is widest, approximately 4 km, at the Aguada Bay. The 4 km long stretch of the Bay is on average, marginally deeper than the rest of the estuarine channel, the average depth in the Bay being about 5 m. River Sinquerim joins the Bay. The 6 km long stretch upstream of the Bay is on an average, 750 m wide and 5 m deep. The Mapsa river joins the Mandovi at the upstream end of this stretch. Farther upstream, Diwar Island, approximately 11 km long, bifurcates the Mandovi into two channels. Before rejoining at the upstream end of the island, the two channels lead into an extensive network of narrow channels in a marshy area. The Kumbarjua Canal joins the Mandovi about 4 km upstream of the Diwar island. The 30 km stretch of the main channel of the Mandovi, from the eastern edge of the Diwar island to Ganjem, gets progressively narrower and shallower in the upstream direction (figure 2). Rivers Dicholi, Valvat, Kudnem and Khandepar join the Mandovi along this stretch. Khandepar is the largest of the four rivers and is fed by the river Dudhsagar (not shown) at its upstream end. The locations up to which tidal influence is felt on these rivers are noted in figure 1. During the dry season, in the main channel of the Mandovi, tidal influence is seen only till a little upstream of Ganjem. Farther upstream the channel bifurcates into the rivers Madei and Ragda. The Mapsa river, which joins the Mandovi at Penha de France, has at its upstream end the rivers Asnoda and Moide. The Mapsa river and its tributaries are joined by a large network of small rivulets which often flow through marshy areas.

The Zuari estuary is bigger than the Mandovi. The 10 km stretch upstream from the mouth of Zuari is approximately 5 km wide and 5 m deep: It is known as Marmagao Bay. At the upstream end of the Bay the channel narrows to a width less than one km. The 30 km long channel from Cortalim to Sanvordem narrows progressively. It is less than 50 m wide at Sanvordem. The Kushawati river (also known as Paroda) joins the Zuari 4 km downstream of Sanvordem. The 10 km long stretch of the main channel from Sanvordem to Sanguem is also known as the Sanguem River. At Sanguem two rivers, Uguem and Guloli, join to form the Sanguem river. During the dry season, the effect of tides is felt at Sanguem, and possibly as far as 4 km upstream in the Uguem river and 1 km in the Guloli. In the Kushavati, the tidal influence appears to be present

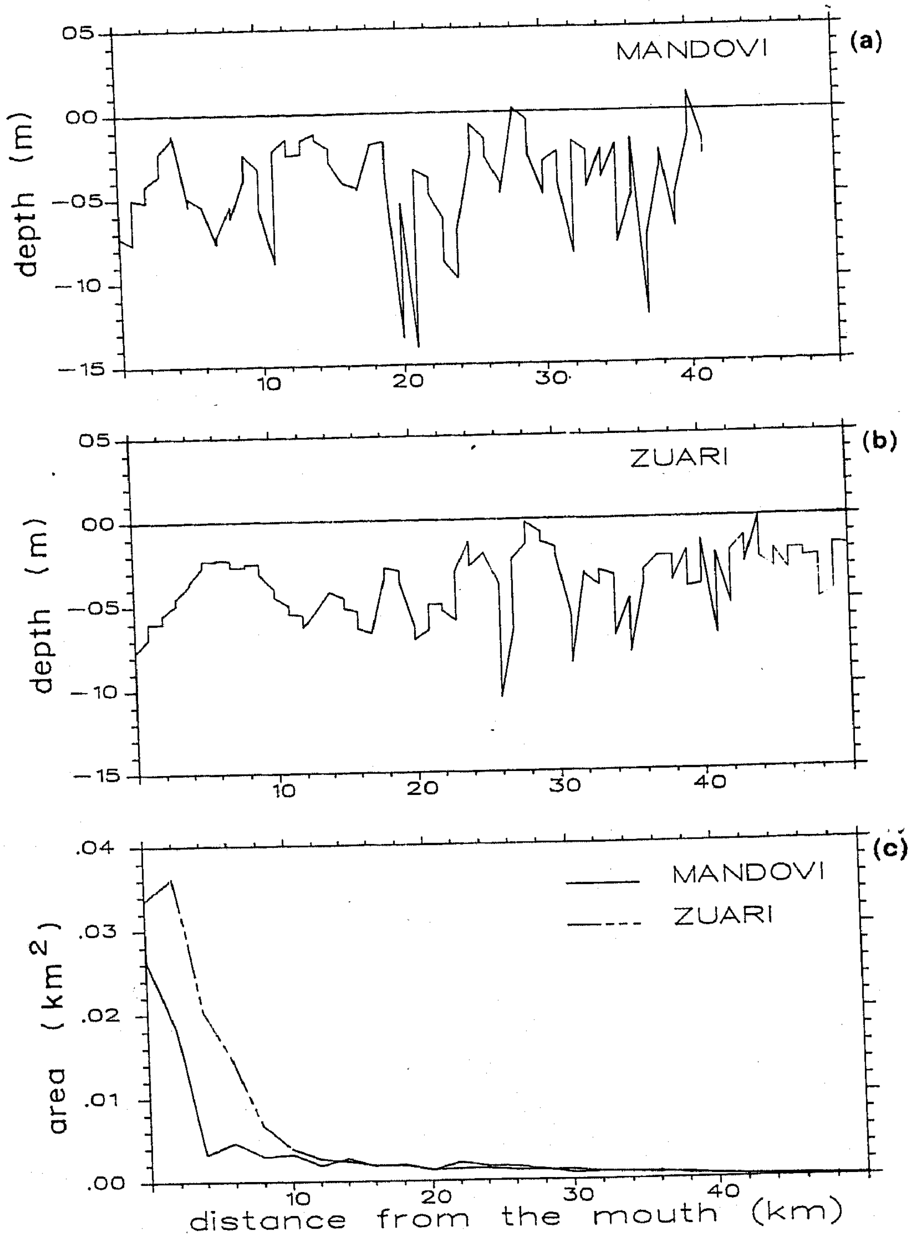


**Figure 2.** Depth (m) with respect to mean sea level along a line midway through the main channels of (**a**) Mandovi, and (**b**) Zuari. The horizontal scale gives distance (km) from the mouth of the two estuaries. The depth was computed by adding 1 m to the depths given in charts published by the Ministry of Shipping and Transport, Government of India. These charts are available only for those parts of the estuarine network used by iron-ore barges. Note that the mean sea level at Marmagao is 1·3 m above Spring Low Water. At the locations where depth is zero or positive, mudflats bifurcate the main channel and the flow is along the sides of the mudflats. (c) Cross-sectional area ($km^2$) with respect to mean sea level of the main channels of the Mandovi and Zuari. The horizontal axis gives distance (km) from the mouth of the two estuaries.

up to about 8 km upstream of the point where it joins the Zuari. During the wet season the flow at Sanguem is dominated by river runoff.

The bottom topography of the Mandovi-Zuari main channels varies considerably with location. This is brought out in figures 2a and 2b, which give the variation of the

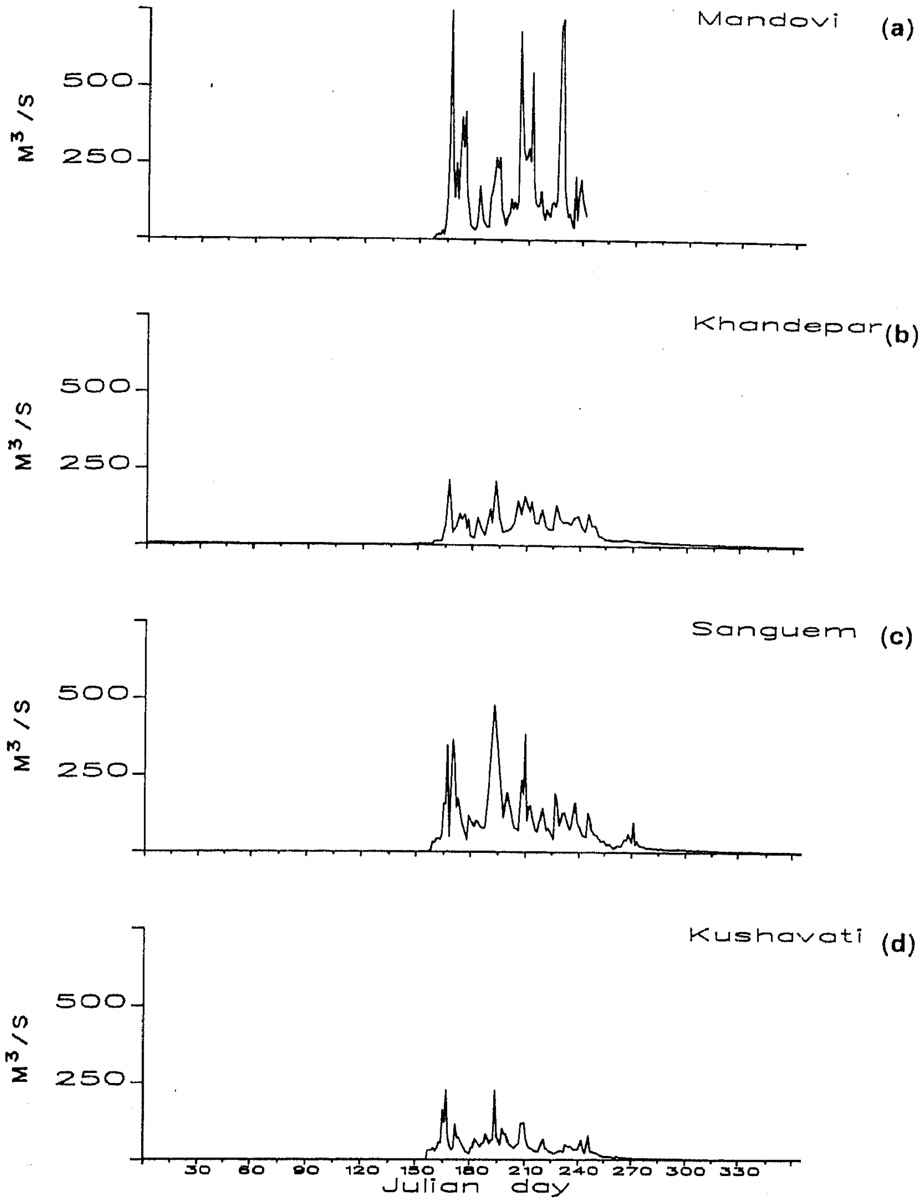


**Figure 3.** Discharge hodographs of (**a**) Mandovi River near Ganjem (see figure 1), (**b**) Khandepar River, (**c**) Sanguem River, (**d**) Kushavati River. The horizontal axis gives the day of the year 1978 from January 1st. The vertical axis gives the discharge in $m^3$/sec.

depth along a line in the middle of the main channels of Mandovi and Zuari rivers. The cross-sectional area of the channel drops rapidly in the upstream direction, primarily due to the decrease in channel width. Such channels have been described as 'strongly-convergent.' (Friedrichs and Aubrey 1994).

Most of the freshwater influx into the Mandovi-Zuari occurs during the south-west monsoon, when most of the rainfall over the catchment area of the network occurs. The nature of temporal variability of the freshwater discharge in the main channels of the two rivers can be appreciated from the estimates of discharge (hodographs) in the main rivers that bring freshwater to the two estuaries. These are given in figure 3.

## 3. Tides at Marmagao

A survey of India 'float-type' tide-gauge is maintained at Marmagao, an important port. We used hourly values of sea level recorded by this gauge during 5th June 1990 – 30th November 1993 to determine the tidal characteristics. The data record had 109 gaps, as a result of which data for about 59 days, approximately 17% of the total record, were lost. Harmonic analysis (Foreman 1977) of the record gave amplitudes and

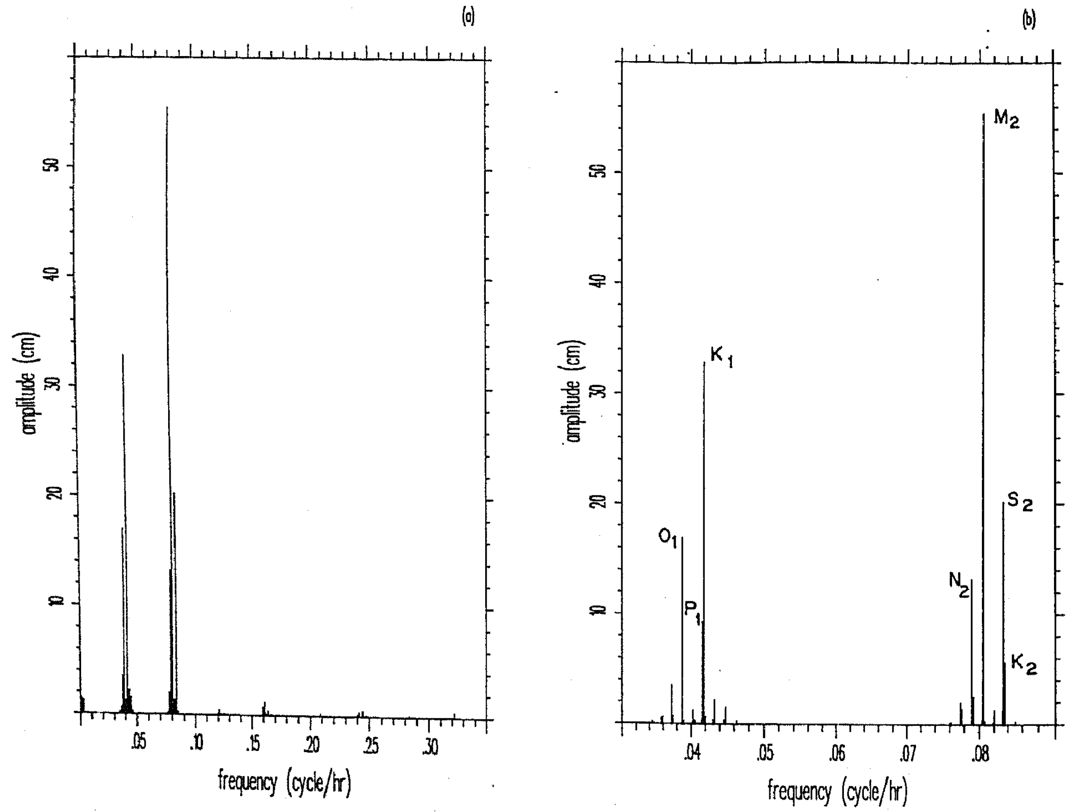


**Figure 4.** (a) Amplitude (cm) of the 69 most significant constituents at Marmagao. The horizontal axis gives frequency (cycle/hour). (b) Same as (a) but for only the diurnal and semi-diurnal constituents which dominate the tides at Marmagao. The enhanced resolution of the horizontal axis permits identification of the more prominent species.

**Table 1.** Tidal constituents at Marmagao with amplitudes greater than 5 cm.

| Symbol of the constituent | Description | Period (hr) | Amplitude (cm) |
|---|---|---|---|
| $S_a$ | Solar annual | 8766·55 | 8·55 |
| $O_1$ | Lunar diurnal | 25·82 | 16·17 |
| $P_1$ | Solar diurnal | 24·07 | 9·32 |
| $K_1$ | Combined diurnal | 23·93 | 31·98 |
| $N_2$ | Lunar semi-diurnal | 12·66 | 13·30 |
| $M_2$ | Lunar semi-diurnal | 12·42 | 55·65 |
| $S_2$ | Solar semi-diurnal | 12·00 | 20·23 |
| $K_2$ | Combined semi-diurnal | 11·97 | 5·41 |

phases of 69 tidal constituents with periods between 6 months (8766·547 hours) and 3·105 hours. Their amplitudes are shown in figure 4a. Diurnal and semi-diurnal constituents (figure 4b) clearly dominate the tide at Marmagao. Of the 69 constituents, the seven listed in table 1 had amplitudes in excess of 5 cms.

## 4. Observations and analysis

The 15 locations where tidal observations were made during campaigns conducted under this study are shown in figure 1. Of these, only the site at Marmagao Port had an automatic tide gauge. At the rest of the sites tidal observations were made visually using tide-poles, once every 15 minutes for 72 hours, the period being chosen primarily on the grounds of logistics. A sample of water was collected every hour for determining salinity using a Guideline salinometer (AUTOSAL 8400A). Water temperature was recorded, also every hour, using a bucket and a thermometer. Currents were measured at Banastarim in the Kumbarjua Canal using Aanderaa current meters. The dry (wet) season observations were carried out from 0000 hours on 7th April (19th August) 1993 to 0000 hours on 10th April (22nd August) 1993.

The modification of the tide as it propagates in the estuarine network is brought out in figure 5, for the dry season, and figure 6, for the wet season. Note that at the upstream

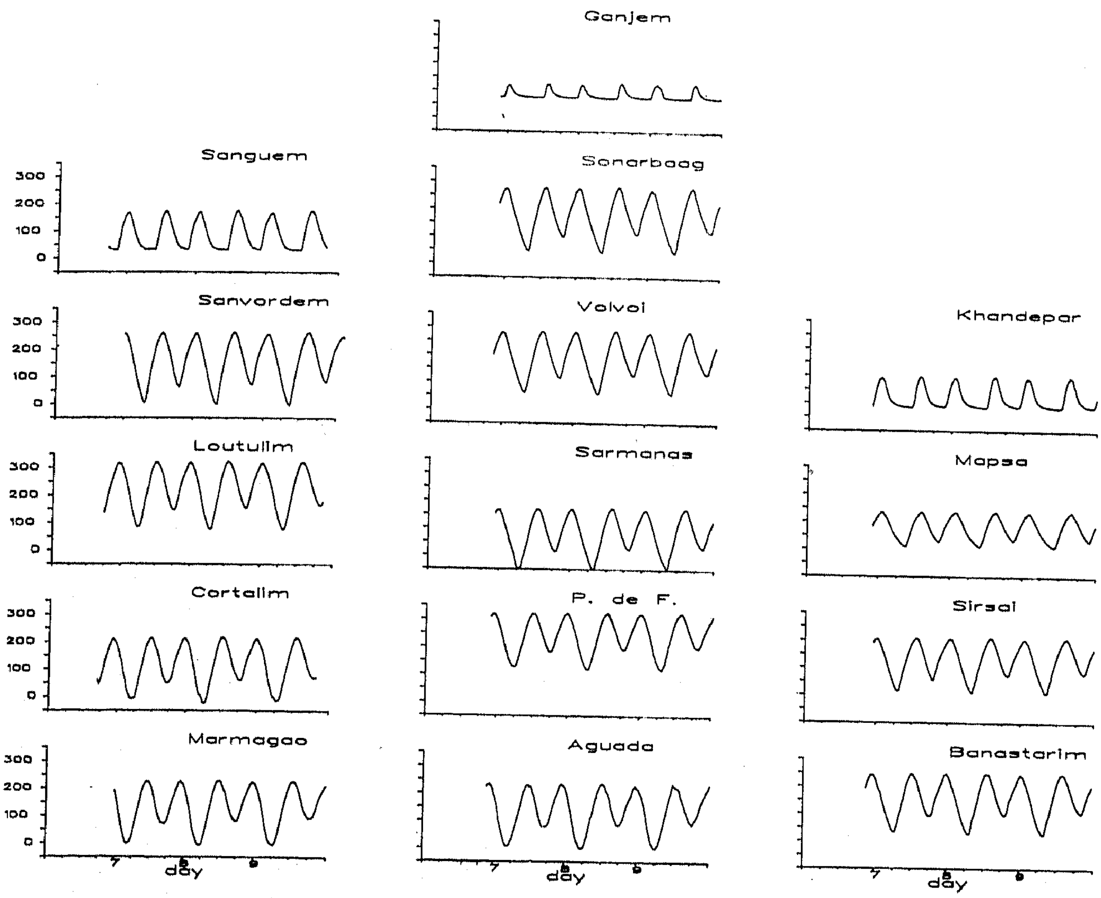


**Figure 5.** Sea level variation (cm) during 7th–9th April 1993 (dry season) at the 15 locations shown in figure 1. The horizontal axis gives the date.

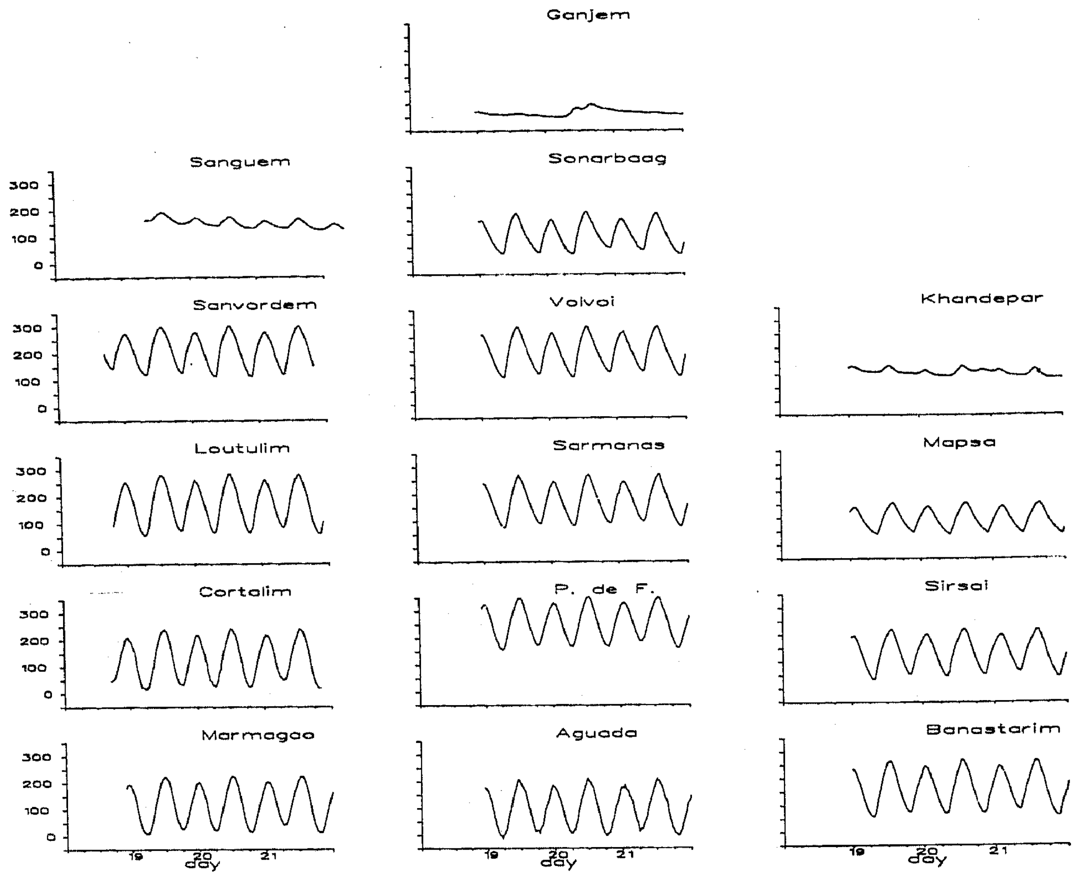


**Figure 6.** Same as in figure 5 but for 19th–21st August 1993 (wet season).

end of the channels, water level during the wet season was primarily changing due to the variation in runoff. Using these data, the principal question we address in this paper is the following: How do the major constituents (table 1) present at the mouth of the estuarine network change as they propagate into the network channels?

Strictly, to answer this question we should determine the amplitude and phase of each of these constituents. There are, however, two difficulties, both arising from the limited duration of observations. Because our data are only 72 hours long, the Rayleigh Criterion (Godin 1972) implies that we cannot resolve two constituents whose frequencies are separated by less than 0·0139 cycle/hour. Second, we cannot say anything about constituents whose periods are larger than 72 hours. Hence, of the seven constituents listed in table 1, the annual constituent, cannot be studied using our data. Of the remaining six, three are diurnal and three semi-diurnal.

Consider now the diurnal constituents. The frequencies of the dominant constituents (table 1) all lie within 0·0139 cycle/hour of one another. Hence, the Rayleigh criterion prevents us from distinguishing between the amplitudes of the three constituents. When we determine the amplitude of any one of the constituents, say $K_1$, using harmonic analysis, contributing to the energy of $K_1$ will be the energy from other diurnal constituents (including $O_1$ and $P_1$) that lie within 0·0139 cycle/hr of the frequency of $K_1$. Therefore, in our analysis, instead of referring to any single diurnal constituent, such as $K_1$, we refer to a 'diurnal band' which covers all constituents within the band. Similarly, we shall not be referring to a particular semi-diurnal constituent, but only to

**Table 2.** Characteristics of the bands used in the analysis.

| Name of the band | Range of frequencies of the band (cycle/hr) | Frequency used in least square analysis (cycle/hr) |
|---|---|---|
| Diurnal | 0·0279–0·0557 | 0·0418 ($K_1$) |
| Semi-diurnal | 0·0666–0·0944 | 0·0805 ($M_2$) |
| 8-hourly | 0·1069–0·1347 | 0·1208 ($M_3$) |
| 6-hourly | 0·1471–0·1749 | 0·1610 ($M_4$) |
| 5-hourly | 0·1883–0·2167 | 0·2028 ($2MK_5$) |
| 4-hourly | 0·2276–0·2554 | 0·2415 ($M_6$) |
| $3\frac{1}{2}$-hourly | 0·2694–0·2974 | 0·2833 ($3MK_7$) |
| 3-hourly | 0·3081–0·3359 | 0·3220 ($M_8$) |

the semi-diurnal band. The bands of tidal constituents that we shall be examining are defined in table 2. To answer the question posed earlier, viz., "how is the tide modified as it moves through the estuarine channels?", we shall examine how the amplitude and phase of the eight bands, defined in table 2, change with distance along the channels.

We carried out harmonic analysis (least-square) of the 72-hour record for the eight frequencies at each of the 15 (including Marmagao) observation sites. The amplitudes and phases of each frequency, now representing a band, then showed how the amplitude and phase of a particular band behaved as a function of distance along an estuarine channel. Table 3 gives the computed amplitudes and phases of the 4 most significant of the 8 bands.

## 5. Results

### 5.1 *The semi-diurnal band*

The amplitude of this band is the largest of all the constituents, and it was approximately the same during both the dry season and the wet season observations (table 3). This makes it convenient to compare the changes due to freshwater influx. During the dry season the amplitude of the semi-diurnal band in the Zuari remained unchanged – it in fact, increased marginally – for about 40 km from the mouth and then dropped sharply over the next 10 km (figure 7a). Similar behaviour was seen in the Mandovi (figure 7b).

During the wet season the distance from the mouth of the Zuari up to which amplitude remained unchanged decreased to about 30 kms (figure 7c). In the Mandovi too a similar change was observed from the dry to the wet season. This suggests that the principal change brought about by the influx of freshwater is to reduce the amplitude of the band at the upstream end of the channel.

The change in phase of the semi-diurnal band with distance along the length of the main channels of the Mandovi-Zuari is shown in figure 7(c and d). Note that at the upstream end of the channels, during the wet season, the water level was primarily controlled by runoff. The least-square fit for change in phase with distance from the mouth of a channel implied a propagation speed of 5·8 m/s (5·2 m/s) in the Zuari during the dry (wet) season. In the Mandovi phase the velocity was 5·2 m/s (7·2 m/s) during the dry (wet) season.

**Table 3.** Amplitude (cm) and phase (degree) of diurnal, semi-diurnal, 8-hourly, and 6-hourly tides at 15 locations during the dry season (April) and wet season (August). Amplitudes from the other bands listed in table 2 were much less than the amplitudes given here. Station locations are shown in figure 1. The first 4 stations (Marmagao – Sanguem) are on the main channel of the Zuari. The next 5 stations (Aguada – Ganjem) are on the main channel of the Mandovi. Sirsai and Mapsa are on the Mapsa River, and Khandepar is on the Khandepar River. Both Mapsa and Khandepar Rivers join the Mandovi. Banastarim is on the Kumbarjua Canal. The second column in the table gives the distance of a station from the mouth of the main channel on which the station is located. The distance of Banastarim is from the mouth of the Zuari whereas that of Sirsai, Mapsa and Khandepar is from the mouth of the Mandovi.

| | | Diurnal band | | Semi-diurnal band | | 8-hourly band | | 6-hourly band | |
|---|---|---|---|---|---|---|---|---|---|
| Station | Distance (km) | Amplitude Apr./Aug. | Phase Apr./Aug. | Amplitude Apr./Aug. | Phase Apr./Aug. | Amplitude Apr./Aug. | Phase Apr/Aug. | Amplitude Apr./Aug. | Phase Apr./Aug. |
| Marmagao | 1·9 | 42·8/13·4 | 297/340 | 91·9/93·6 | 152/143 | 0·7/1·1 | 145/105 | 3·1/2·7 | 62/55 |
| Cortalim | 14·1 | 40·7/14·4 | 302/350 | 92·6/96·5 | 162/151 | 2·5/1·7 | 285/128 | 1·8/3·3 | 131/74 |
| Loutulim | 23·8 | 39·1/14·2 | 315/1 | 94·9/95·6 | 184/167 | 4·9/0·6 | 287/123 | 6·7/6·6 | 214/201 |
| Sanvordem | 43·1 | 37·4/15·0 | 328/17 | 100·7/79·4 | 2·8/196 | 7·7/1·9 | 327/306 | 9·3/8·8 | 260/261 |
| Sanguem | 55·3 | 15·0/9·8 | 335/19 | 66·3/13·9 | 223/223 | 16·5/0·7 | 50/203 | 14·7/2·7 | 63/72 |
| Aguada | 00·0 | 42·1/13·0 | 237/340 | 90·4/91·9 | 151/141 | 1·2/0·8 | 188/244 | 3·5/1·1 | 63/59 |
| Penha de Franca | 9·1 | 35·5/13·2 | 311/357 | 78·4/81·4 | 174/161 | 2·4/1·0 | 276/185 | 2·4/2·1 | 161/160 |
| Sarmanas | 24·4 | 35·3/13·6 | 323/13 | 83·3/79·2 | 200/186 | 6·3/1·1 | 324/355 | 4·8/9·0 | 278/281 |
| Volvoi | 32·9 | 34·6/14·4 | 321/21 | 87·4/76·6 | 205/191 | 8·3/1·9 | 340/352 | 5·6/11·4 | 309/289 |
| Sonarbaag | 40·1 | 34·9/13·1 | 329/26 | 89·9/61·8 | 211/200 | 9·9/2·5 | 347/32 | 6·4/9·5 | 327/323 |
| Ganjem | 48·1 | 2·6/5·6 | 349/40 | 17·7/1·6 | 232/189 | 4·9/0·7 | 72/257 | 10·4/1·2 | 92/165 |
| Banastarim | 7·1 | 35·6/14·2 | 315/1 | 84·4/86·9 | 185/170 | 5·5/0·1 | 306/117 | 3·5/4·8 | 214/242 |
| Sirsai | 26·0 | 29·8/12·5 | 325/20 | 74·9/74·0 | 204/189 | 4·1/1·0 | 338/280 | 5·0/4·4 | 221/240 |
| Mapsa | 34·0 | 17·2/9·3 | 346/47 | 52·1/47·6 | 237/222 | 8·0/0·8 | 42/330 | 3·5/4·9 | 34/12 |
| Khandepar | 50·0 | 18·3/1·7 | 338/91 | 47·5/9·7 | 222/201 | 15·1/2·2 | 50/107 | 18·6/4·1 | 69/51 |

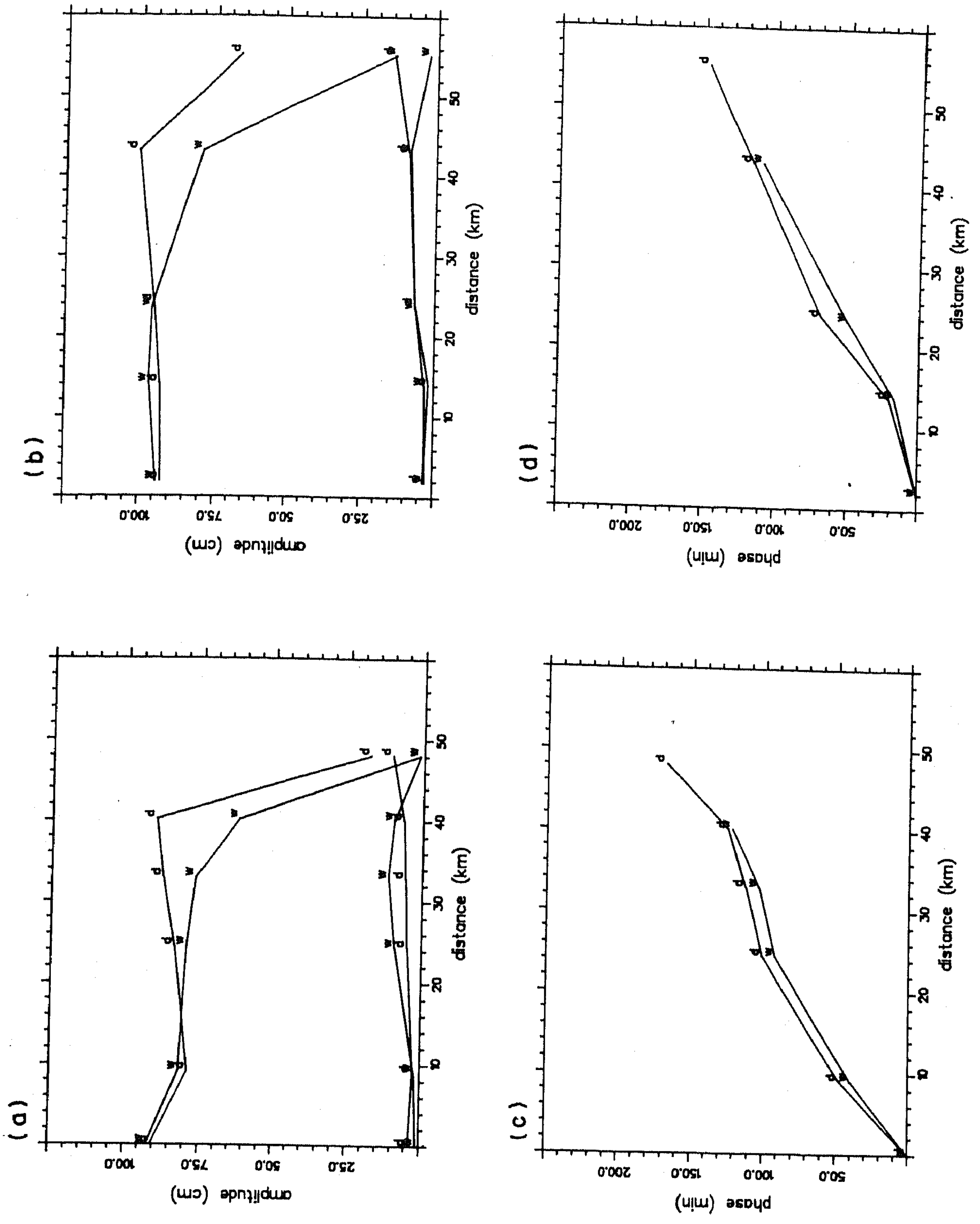


**Figure 7.** (**a**) Variation of amplitude (cm) with distance (km) along the main channel of the Mandovi during the dry season observations, 7th–9th April 1993 (marked 'd') and wet season observations, 19th–21st August 1993 (marked 'w'). The upper curves are for the semi-diurnal band and the lower curves are for the higher harmonic of the band, the quarter-diurnal ($M_4$). (**b**) Same as (a) but for Zuari. (**c**) Change of phase (minutes) of the semi-diurnal band in the main channel of the Mandovi with respect to the tide at Aguada. Variation during the dry season (wet season) observations is marked 'd' ('w'). The horizontal axis gives distance (km) from the mouth of the channel. The phase at the station at the upstream end during the wet season has not been shown because the flow was controlled by freshwater influx and there was no tidal influence. (**d**) Same as (c), except for Zuari, and the phase is measured with respect to that at Marmagao.

### 5.2 *The diurnal band*

The amplitude of the diurnal band at the mouths of the two channels during the wet season was about a third of the dry season value. However, the behaviour of this band was similar to that of the semi-diurnal band. The amplitude of the band remained unchanged up to about 40 km from the mouth and then dropped over the next 10 km. The speeds of propagation in the Zuari main channel was 5·63 m/s (5·34 m/s) during the dry (wet) season, and was 4·55 m/s (3·57 m/s) during the dry season (wet season) in the Mandovi.

### 5.3 *Higher harmonics*

Most prominent amongst the higher harmonics that get generated within the Mandovi-Zuari estuarine channels are the $M_3$ and $M_4$ constituents. The amplitude of $M_4$ increased with distance from mouth to head (figure 7, c and d). As seen from these figures, the amplitude of $M_4$ was very much smaller than that of $M_2$.

### 5.4 *Salinity variation*

Salinity in the Mandovi-Zuari varies seasonally in response to the runoff, which peaks during the southwest monsoon and decreases rapidly after its withdrawal (figure 3). However, even during the dry season, in April, the runoff reaching the upstream end of the estuarine channels is sufficient to restrict the salinity to undetectable levels. The variation of salinity in the main channels of the Mandovi and Zuari during the dry season is shown in figure 8. Note that at the upstream end of the channels salinity was negligible, indicating the strong influence of runoff. At this end, the channel cross-sectional area is small: even weak freshwater influx can influence salinity considerably.

Compared to the dry season, the salinity during the wet season was much lower. At the mouth of the Mandovi (Zuari) it fluctuated between 5–30 ppt (8–22 ppt). Note that during the dry season salinity at the mouth of the main channels remained steady at about 33 ppt. During the wet season the salinity upstream of about 20 km from the mouth was undetectable.

### 5.5 *Change in mean sea level*

During the observations bench-marks were established near the tide-pole. This permitted us to determine the change in mean sea level (during the 3 days of observations) from dry to wet season. The change in water level is shown in figure 9. The mean water level at the upstream end of the main channel in the Zuari (Mandovi) was 1 m (1·6 m) higher during the wet season.

At the mouth of the Mandovi the mean water level was marginally lower during the wet season. In the Zuari the mean water level was lower by about 10 cm. Such a lowering is expected from the dynamics of large-scale currents along the west coast of India. The southwest monsoon is the time of an equatorward current along this coast and upwelling occurs (Shetye *et al* 1990). This is expected to be accompanied by a lowering of sea level.

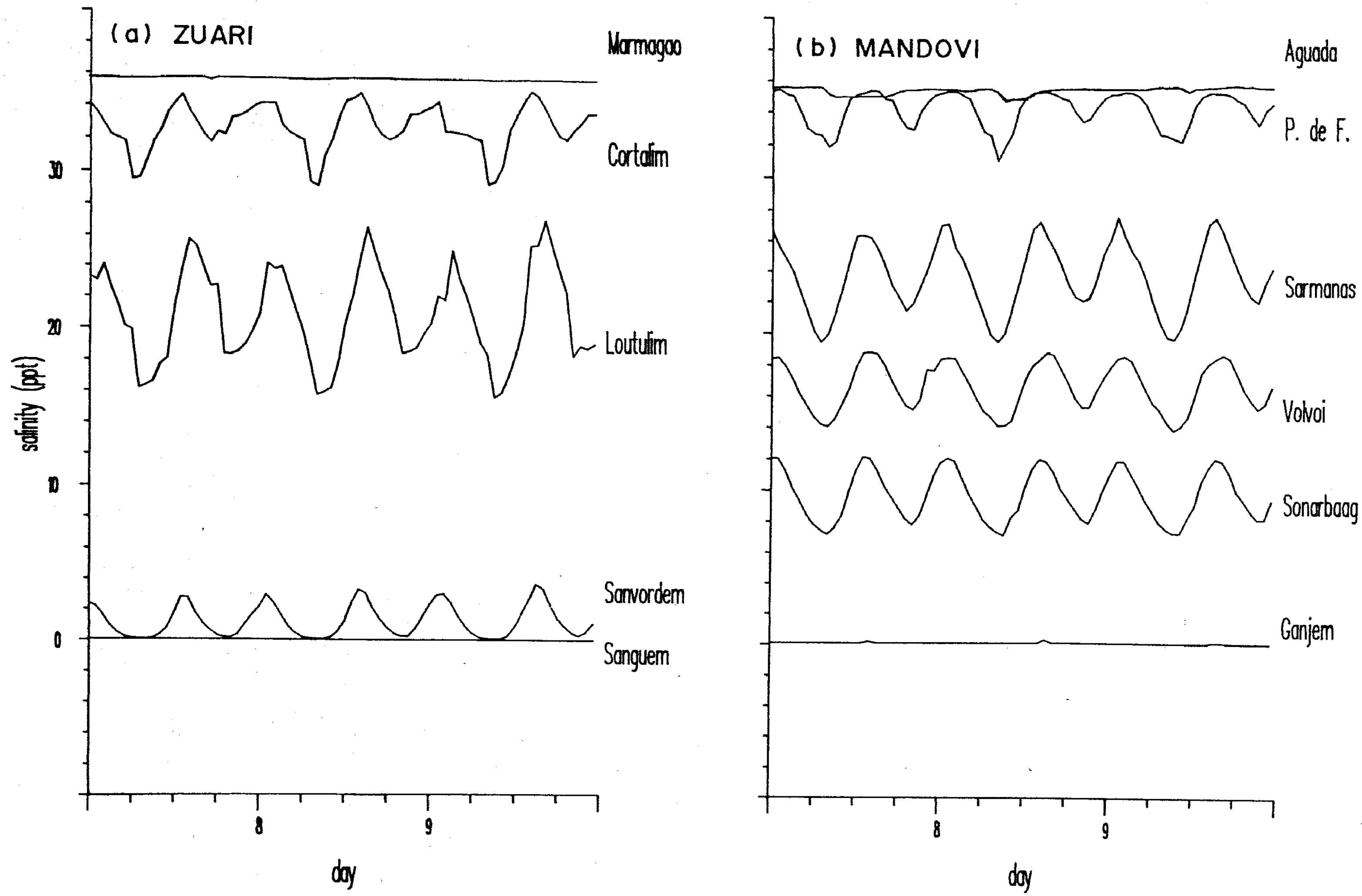


**Figure 8.** Variation in salinity (ppt) during 7th–9th April 1993, in the main channels of (**a**) Zuari, (**b**) Mandovi. Salinity at the upstream end of the channels, Ganjem in Mandovi and Sanguem in Zuari, was undetectable.

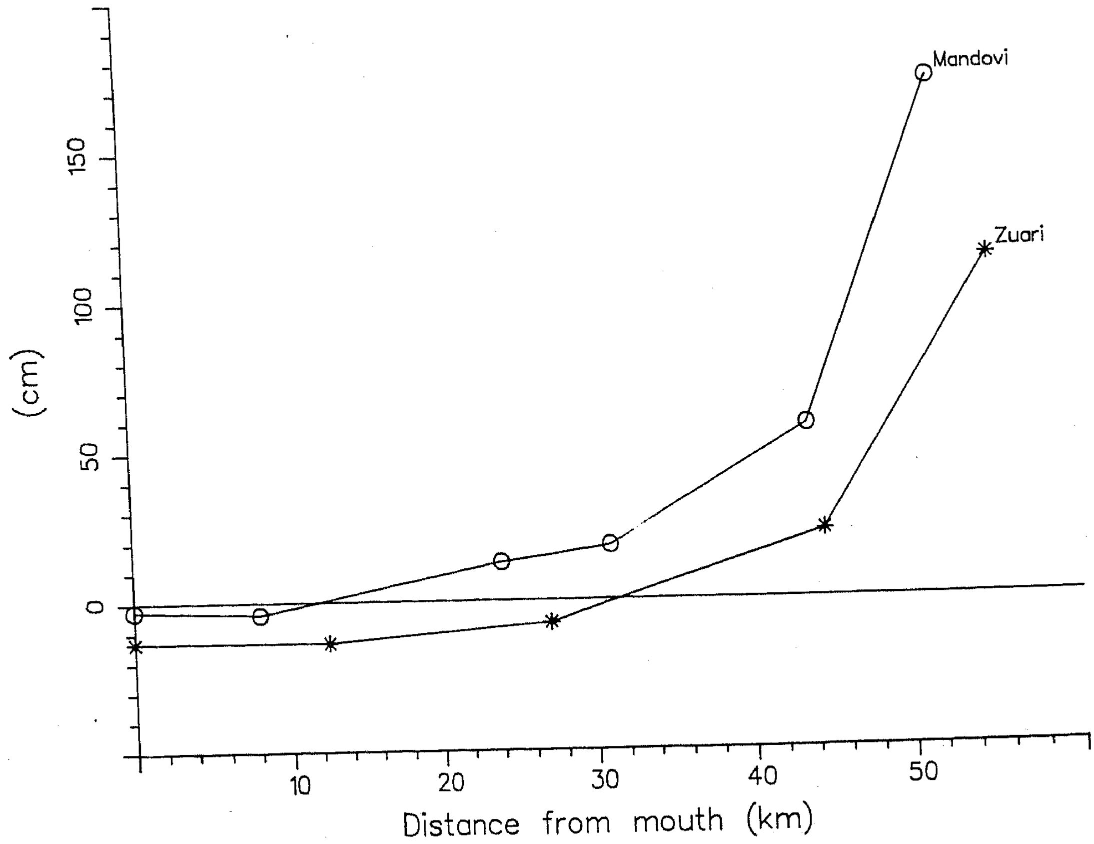


**Figure 9.** Difference (cm) in mean sea level between the wet season observations (19th–21st August 1993) and dry season observations (7th–9th April 1993) as a function of distance from the mouths of the main channels of the Mandovi and the Zuari.

## 6. Discussion

It is now well established that in shallow estuaries the momentum balance is primarily between the pressure gradient and friction. Friedrichs and Aubrey (1994) have shown that in such systems, if the estuarine channel converges (cross-sectional area decreases in the upstream direction) with distance from the mouth, then amplification due to convergence of the channel cancels decay due to friction, leaving the amplitude unchanged over large distances along the estuarine channels. This can explain why the amplitude remains unchanged over distances of the order of 40 km from the mouth in the Mandovi-Zuari channels. According to the Friedrichs and Aubrey theory the velocity of propagation in a channel of depth $h$, with cross-sectional area decreasing with $e$-folding distance $L_A$, the velocity of propagation is given by $gh/rL_A$, where $g$ is acceleration due to gravity and $r$ is a friction coefficient. Assuming $r = 10^{-3}\,s^{-1}$, $h = 5$ m and $L_A = 8$ km, we get a phase velocity of approximately 6 m/s, which is reasonably close to the estimates of phase velocity made in the last section. We therefore consider the Friedrichs and Aubrey theory to be a good theoretical framework to understand the behaviour of Mandovi-Zuari over a stretch of about 40 km from the mouth.

The above theory, however, cannot explain the rapid decay of amplitude at the upstream end of the channels. We believe that this decay is related to freshwater influx, which has not been considered in the theory. In the Mandovi-Zuari system the decay was seen over the stretches of the channels where salinity was negligible even during the dry season, implying that along these stretches the freshwater influx is sufficient to prevent upstream propagation of salt. It appears that the influx is able to prevent the tide too. This would explain why the decay was larger during the wet season (figure 7, a and b), when the influx is very much larger. Looked at another way, the freshwater flow sets up a pressure gradient in the downstream direction, overwhelming the gradient associated with the upstream propagation of tide, and the amplitude decays. The buildup of pressure gradient associated with freshwater influx can be seen in figure 9, which shows the difference in the mean sea levels between dry and wet seasons. The contribution of freshwater influx to tidal propagation in the Mandovi-Zuari network has been examined in a companion paper using a numerical model for the network (Unnikrishnan *et al* 1995, personal communication). Simulations with this model encourage us to suggest that it is the freshwater influx that is primarily responsible for the decay at the upstream end.

Hence, except for the region at the upstream end of the channels, where influence of freshwater is significant, a theoretical framework exists to understand the observations reported here. Though this is encouraging to efforts towards understanding the dynamics of the estuaries spread along the Indian coastline, of which the Mandovi-Zuari network is a typical example, more efforts are needed to sustain progress. We mention three possibilities. First, there is a need to repeat the observation campaigns reported here, but now with a period of observation of 30 rather than 3 days. This would help resolve amplitudes and phases of all diurnal and semi-diurnal constituents and hence help infer the behaviour of individual constituents rather than of the 'bands' as done here. Second, to understand the impact of freshwater influx, it is necessary to understand how mean water level changes along the estuarine channels. Third, an analytic framework similar to that proposed by Friedrichs and Aubrey, but now taking into account the impact of freshwater influx, is needed.

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