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Flushing characteristics of Amba river estuary, west coast of India

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Tide dominated Amba river estuary was studied to evaluate its flushing characteristics. Although, spring tidal range of 3.4 m was observed at 40 km inland, the seawater component here at high tide was < 1%. The wet weather flushing time of 22 tidal cycles for neap, 6 to 7 tidal cycles for spring and dry weather flushing time of 45 tidal cycles for neap, 6 to 7 tidal cycles for spring based on modified tidal prism method indicated that the load retained in the estuary after infinite number of tidal cycles was 17 times and 33 times for neap during wet and dry weather conditions and 2 times the load introduced per tidal cycle for spring during both the weather conditions. The flushing times calculated by the classical tidal prism method were shorter than those obtained by the modified tidal prism method.

Several estuaries in Maharashtra, central west coast of India, receive wastewaters from nearby industrial and domestic establishments. Amba river originates in the western ghats and follows a narrow and meandering course along its length of over 140 km before opening into the Bombay harbour. Although Amba river estuary receives substantial quantities of wastewater, nothing is known about the nature of pollutants entering the estuary. During April-May, Aug.-Sept. and Nov.-Dec. 1986, an extensive survey was undertaken in the estuarine region for evaluating its environmental status and the flushing characteristics are reported in this paper.

Materials and Methods

Amba river (Fig. 1) broadens into a wide estuary with the width exceeding 2600 m in the mouth region during spring tides. The estuary is shallow with the channel depth generally < 5 m during low tides. The lower reaches of the river often referred to as Dharamtar creek is navigable up to Dharamtar jetty for medium size crafts under all tidal conditions. In the intertidal region waves are generally low and breakers cause negligible littoral transport along the shore which is mostly fringed with rocks.

The estuary doesn't receive any pollutants through direct discharges, and is predominantly tide dominant during non monsoon months. Its water quality is expected to be largely influenced by the harbour water which receives an estimated 350 mld of domestic wastewater and over 180 mld of industrial effluents[1]. In addition, Patalganga river, which receives a variety of pollutants through industrial inputs joins the mouth region of Amba river, can also influence the water quality.

For the present study, spring and neap tide collections at 5 stations along the 40 km stretch in the estuary were selected (Fig. 1). A clean polyethylene

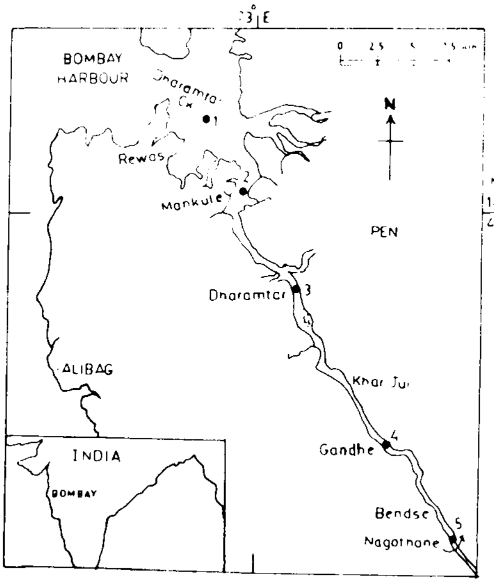

Fig. 1 Station locations

bucket was used for obtaining the surface samples while Niskin sampler was employed to collect bottom samples, 1m above the sediment level. Chlorinity of water samples was determined by argentometric titration. The river flow data were obtained from the gauging station near Nagothane. The field observations on currents were made at the surface, middle and 1 m above the sediment level using rotor induction current meter (NIO, Goa, accuracy for velocity ± 1 cm sec^{-1} and direction ± 2.68°). The water level changes were also simultaneously measured at these stations, using graduated staffs whose levels were connected to the local datum mark.

The estuarine volume under different tidal conditions was estimated from the bathymetry and tidal data. The tidal excursion was estimated by drawing a horizontal line between the low tide and high tide curves (Fig. 2) in the absence of displacement by freshwater[2].

The flushing time t in tidal periods is given by $t=(V+P)/P$ where V is the low tide volume of the estuary and P is the volume of the tidal prism[3]. The tidal prism and the low tide volume of the estuary was calculated using the bathymetric and tidal data. Flushing time was also calculated from the modified tidal prism method. In this, the tidal prism approach is modified by dividing the estuary into segments, the length of which is determined by the excursion of the water particle during the tide. The innermost segment is that above which the intertidal volume P_0 is supplied by the river flow R. The low tide volume of this innermost segment is V_0. The limit of the next segment is so placed that $V_1=V_0+P_0=V_0+R$. Thus, each segment at high tide contains the volume of water contained in the next seaward segment at the low tide. If the mixing is complete at high tide then the pattern of water removed on the ebb is the ratio between the local intertidal volume and high tide volume. Thus, an exchange ratio r_n for any segment n can be defined as $r_n=P_n/(P_n+V_n)$ and the flushing time T in tidal cycles will then be $T=1/r_n$.

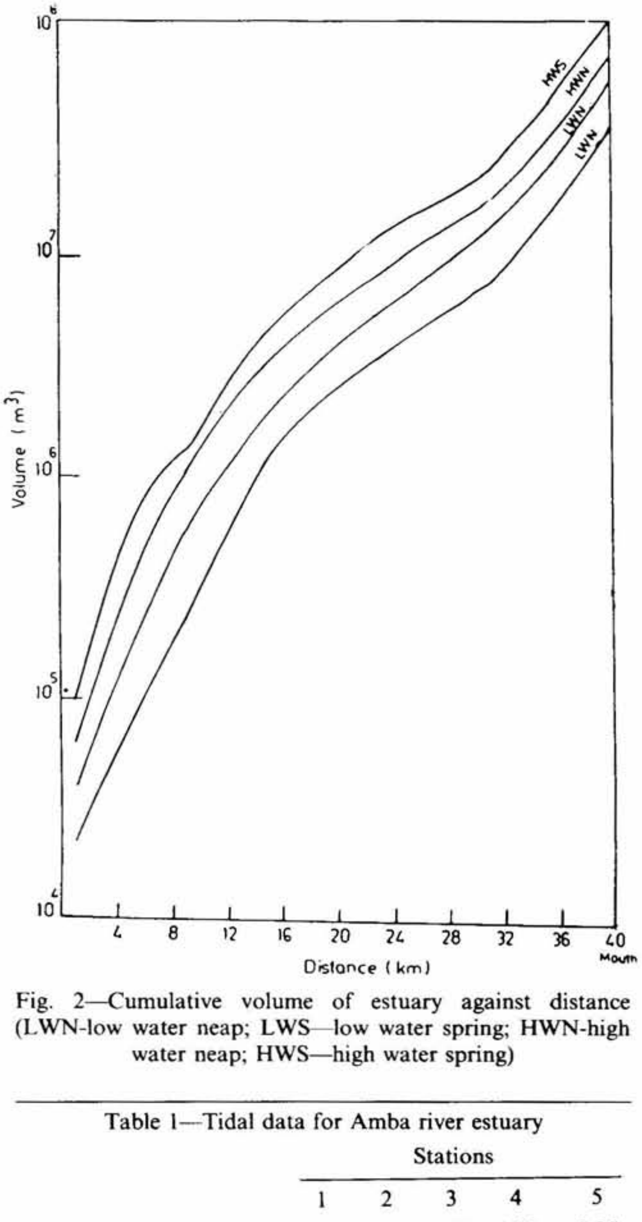

Fig. 2—Cumulative volume of estuary against distance (LWN-low water neap; LWS—low water spring; HWN-high water neap; HWS—high water spring)

Table 1—Tidal data for Amba river estuary

	Stations				
	1	2	3	4	5
Spring tidal range (m)	5.08	5.00	5.20	4.08	3.35
Neap tidal range (m)	1.04	1.16	1.15	1.62	1.90
Av. time difference (min) as compared to Apollo Bunder	−2 to −3	+2 to +3	+5	+45	+65 to +70

Results and Discussion

Tides and tidal excursion—The estuary experienced mixed semidiurnal tides with 2 high and 2 low waters occurring each tidal day with varying amplitudes. The spring range of 5.08 m at st 1 decreased to 3.35 m at st 5. The neap range however increased from 1.04 m to 1.90 m for the same pair of stations. About 12 cm increase in the tidal range at st 3 during spring tide as compared to that at st 1 may be due to the piling up of water due to the abrupt narrowing of the estuary channel upstream of st 3. The high tide at st. 1 preceeded Apollo Bunder by 2 to 3 min while the high tide at st 5 lagged by 65 to 70 min (Table 1). High tidal influx generated strong currents with the maximum speed exceeding 95 $cm.sec^{-1}$ during springs even at st 3. The nature of the current profile did not vary appreciably at the bottom and the speed was only marginally lower (Fig. 3).

The excursion length varied from 7 km at the mouth to 10 km at st 3 during spring low tide and 3 to 8 km during neap low tide. In effect, the direction of flow may be seaward throughout the tidal cycle near the

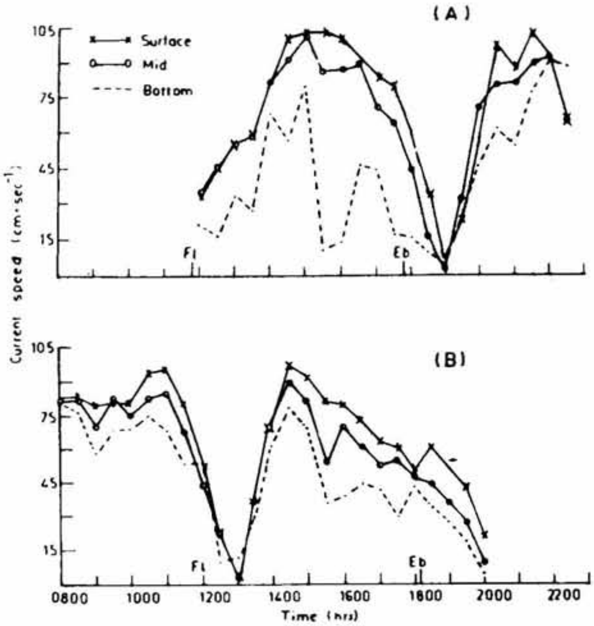

Fig. 3—Variation of current speed at (A) st 1 on 3 Oct. 1986 and (B) at st 3 on 4 Oct. 1986

Table 2—Flushing time of Amba river estuary (modified tidal prism method)

Estuary segment (km)	Low tide volume $\times 10^6$(m^3)	Tidal prism $\times 10^6$(m^3)	Exchange ratio	Flushing time (tide cycles)
Riverine freshwater flow per tidal cycle 4.3×10^6m^3*				
0-25.7	8.5	4.3	0.336	3.0
25.7-33.8	12.8	4.1	0.242	4.1
33.8-35.8	16.9	3.2	0.159	6.3
35.8-38.9	20.1	5.6	0.218	4.6
38.9-42.8	25.7	7.2	0.220	4.5
Revierine freshwater flow per tidal cycle 4.3×10^6m^3 +				
0-15.9	1.2	4.3	0.782	1.3
15.9-27.7	5.6	12.7	0.694	1.4
27.7-37.2	18.2	35.4	0.660	1.5
37.2-44.2	53.7	76.7	0.588	1.7
Riverine freshwater flow per tidal cycle 0.43×10^6m^3*				
0-8.9	0.53	0.43	0.448	2.2
8.9-13.6	0.96	0.67	0.411	2.4
13.6-18.0	1.6	0.98	0.380	2.6
18.0-21.8	2.6	1.1	0.297	3.4
21.8-26.3	3.7	1.4	0.274	3.6
26.3-29.5	5.1	1.6	0.239	4.2
29.5-33.7	6.7	2.1	0.239	4.2
33.7-35.5	8.9	2.5	0.219	4.6
35.5-37.2	11.4	3.2	0.219	4.6
37.2-39.4	14.6	4.1	0.219	4.6
39.4-41.3	18.7	5.2	0.217	4.5
41.3-44.9	23.9	6.7	0.219	4.6
Riverine freshwater flow per tidal cycle 0.43×10^6m^3 +				
0-49	0.12	0.43	0.782	1.3
4.9-13.1	0.55	2.3	0.807	1.2
13.1-22.0	2.8	7.0	0.714	1.4
22.0-34.3	9.8	20.4	0.675	1.5
34.3-41.8	30.2	57.2	0.654	1.5

* = Neap, + = Spring

head of the estuary at times of high flow. However, such an effect is expected to be only marginal in the lower estuary during the dry season in view of high seawater influx during flood tide and relatively small riverine flow. The major portion of the wastewater released up to st 3 in the estuary would therefore be flushed out to the sea during ebb tide.

The tidal prism for the Amba river estuary was 2.91×10^7m^3 and 8.50×10^6m^3 for spring and neap tides respectively on the basis of bathymetric and tidal data. With the average low tide volume of 1.28×10^7m^3 and 2.19×10^7m^3 during spring and neap respectively, the flushing time of the entire estuary was worked out to be 1.4 tidal cycles during springs and 3.6 tidal cycles during neaps. After an infinite number of tidal cycles under a continuous flow of pollutants the load retained in the estuary is given by $L = y/(1-y)$, where y is the fraction remaining after one tidal cycle[4]. L worked out to be only 0.4 and 1 during spring and neap respectively. Considering the average for spring and neap and assuming equal number of springs and neap occur in that infinite number of tidal cycle, the wastewater retained in the estuary will be just about 3000 m^3 which can be considered as negligible. However, as this method does not consider the freshwater input and assumes complete mixing which is rarely justified, it only sets a lower limit to the flushing time[4].

From the river flow data, it was evident that the average flow during July-August was of the order of 4.3×10^6m^3 per tidal cycle (avoiding abnormal peak discharges) and decreased considerably to about 0.43×10^6m^3 per tidal cycle during September (Table 2). Cumulative flushing time of the estuary was around 6 to 7 tidal cycles during spring tide, for both freshwater flow conditions, revealing the dominance of the tidal influence over the river discharge. However, during neaps when the seawater incursion greatly reduced, the cumulative flushing time of the estuary which was 22 tidal cycles for the flow of 4.3×10^6m^3 per tidal cycle increased considerably to 45 tidal cycles for the flow of 0.43×10^6m^3 per tidal cycle. The relation $L = y/(1-y)$ used in the classical method can also be applied in the modified tidal prism method[4]. Since

$r=P/(P+V)$, $Y=1-r$, and the equation then becomes $L=(1-r)/r=(1/r)-1$. The load retained in the estuary after an infinite number of tidal cycles will be 33 times the load introduced per tidal cycle during neaps and will be reduced to 2 times during springs at a river discharge of 0.43×10^6 m^3 per tidal cycles. For a flow of 4.3×10^6 m^3 per tidal cycles the corresponding values during neap and spring are 17 and 2 times respectively. All the above calculations are based on the assumption of minimum water discharge of 0.43×10^6 m^3 per tidal cycle, which may not be true after October. Nevertheless, it provides an insight into the problems likely to be encountered in the release of wastewater in the estuary.

Table 3—Observed salinity values at various locations in the Amba river estuary

Date	Observed salinity ($\times 10^{-3}$)			
	High Tide		Low Tide	
	Surface	Bottom	Surface	Bottom
		Station 1		
27 March 86	36.6	36.5	36.8	36.7
26 July 86	26.4	26.8	7.8	—
21 Sept. 86	35.0	35.4	30.6	31.4
24 Dec. 86	36.7	36.7	35.9	36.6
		Station 2		
31 March 86	36.9	36.9	37.3	37.4
23 July 86	8.7	17.9	0.1	0.2
23 Dec. 86	35.8	35.8	35.0	34.9
		Station 3		
6/7 April 86	37.7	37.6	37.8	37.7
21 July 86	0.2	0.2	0.06	0.07
19 Sept. 86	21.7	23.7	4.5	8.4
18 Dec. 86	34.1	24.3	30.9	31.2
		Station 4		
2 April 86	34.5	34.5	30.3	30.5
28/29 July 86	0.07	0.05	0.04	0.04
17 Sept. 86	1.1	1.3	0.2	0.1
24 Dec. 86	22.9	23.1	18.6	19.0
		Station 5		
4 April 86	26.9	27.4	26.1	-
28 July 86	0.05	0.05	0.05	0.04
15 Sept. 86	0.05	0.11	0.04	0.05
22 Dec. 86	14.9	15.1	13.9	—

Salinity incursion—The distance of the estuary up to which seawater may penetrate is an indication of the distance over which polluting matter discharged into the saline reaches may exert an influence. The premonsoon salinity of $36\text{-}37 \times 10^{-3}$ in st 1 (Table 3) remained more or less the same along the estuary up to st 3 followed by gradual descrease to $30\text{-}34 \times 10^{-3}$ at st 4 (Table 3). Although there was no freshwater release through the Bandhara, the decrease in salinity downstream suggested some seepage through the Bandhara. The observed salinities (Table 3) revealed a freshwater content of about 20% at st 5 and 5% at st 4. The freshwater volume retained in this segment therefore worked out to be roughly 17×10^5m^3 at neap flood tide. Considering the flushing time of the segment as about 3 tidal cycles then the average freshwater input to the estuary could be roughly 0.5×10^5m^3 per tidal cycle which is about an order of magnitude less than the flow of 4.3×10^5m^3 per tidal cycle occurring during September-October.

During September when the river discharge decreased considerably, weak penetration of seawater was noticed at st 4 with high tide salinity of 1.2×10^{-3} (Table 3). St 3 and regions downstream experienced considerable seawater influence, though, the salinity was widely variable over tidal cycles, as expected. Some stratification throughout the tidal cycle was also noticed at st 3. The influence of freshwater seepage on salinity was also observed at st 3 during December though to a small extent. The freshwater component of Nagothane-Gandhe segment was high as 50% during this period.

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