

Residence time of pollutants discharged in the Gulf of Kachchh, northwestern Arabian Sea

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Abstract

A 2D Hydrodynamic- Particle Analysis model was applied to the Gulf of Kachchh (GoK) to estimate the residence time of pollutants. The tidal currents in the Gulf have a strong E-W component, which prevents the material in the north being transported towards south. In the regions situated very close to the open boundary, where the GoK waters exchange freely with the northern Arabian Sea, dilution takes place rapidly with the incoming waters and hence, the residence time is on the order of 1 day. Influence of eddies and a dynamic barrier across the Sikka-Mundra section on the residence time is apparent. Eastern GoK shows a relatively large residence time, on the order of 2-4 days, warranting caution while releasing industrial wastes in the northeastern Gulf. The region around location-5 behaves like a bay; the dissolved matter gets trapped in this bay and the residence time increases by 3-4 days.

Keywords: Gulf of Kachchh, hydrodynamic and particle tracking, numerical modelling, coastal circulation, residence time, pollutant transport.

1. Introduction

The residence time of a passive tracer in a partially mixed estuary is a strong function of the time of release (spring vs neap tide), the location of release and the initial vertical placement (Warner et al, 2010). Generally during neap tides, residence time is maximum near the bottom of the estuary at the mid-salt intrusion length. During spring tides, the residence time is primarily a function of along-channel location and does not exhibit a strong vertical variability. In general, the residence time is an increasing function of the distance to the mouth of the estuary (Blaise et al., 2010). Brauwere et al. (2011) computed the residence times and exposure times for 13 boxes in the Scheldt Estuary located in Belgium and the Netherlands using a high resolution tracer transport model, Second - generation Louvain-la-Neuve Ice - Ocean Model (SLIM). SLIM is a finite element model that solves the shallow water and the tracer transport equations. The Scheldt Estuary has two open boundaries through which water can leave; one upstream (connection with the tidal river) and one downstream (mouth). The residence time decreased towards both the open boundaries of the domain i.e. the mouth and the upstream end of the Scheldt Estuary. It was observed that the residence time is clearly time dependent and there is a strong dependence on the upstream discharge; this was reflected by the long term (seasonal and interannual) variations in residence time.

Brooks et al. (1999) addressed the questions of dispersion and flushing of Cobscook Bay, a macrotidal estuary situated near the entrance to the Bay of Fundy, where the mean semi-diurnal tidal range is 5.7m, using a three-dimensional numerical model and simulated the circulation driven by the semi-diurnal tide and runoff from principal rivers. Abdelrhman (2002) presented model estimates of how the hurricane barrier in New Bedford Harbour, an embayment of Buzzards Bay, Massachusetts, has affected circulation patterns, residence times and distributions of a tracer over a range of tidal forcing. Rasmussen and Josefson et al. (2002) calculated the water exchange and residence time for 31 small Danish estuaries to assess the spatial variability of estuarine processes and biogeochemical properties. Barber (2003) detailed a tidal prism model for predicting the water quality response of well - mixed tidal embayments. Wang et al (2004) calculated the residence time of the Danshuei River estuary through a series of numerical experiments using a laterally integrated two-dimensional hydrodynamic model (HEM-2). Choi et al. (2004) described a general method to systematically determine the flushing time of a stratified water body via a numerical tracer experiment.

Abdelrhman (2005) has offered an additional characteristic time, the local residence time, to deal with spatial heterogeneities within an embayment and applied it to 42 embayments in southern New England, USA. Yuan et al. (2007) have outlined a numerical modelling study to predict the average release of a conservative tracer in a macrotidal estuary, namely, the Mersey Estuary, UK. Oliveira et al. (2006) and Dias et al. (2009) used a three-dimensional barotropic and baroclinic numerical

model in conjunction with a two-dimensional particle tracking model, VELApart, to compute residence times for passive tracers in a lagoon in Portugal. Liu et al. (2010) used a three-dimensional high resolution hydrodynamic model with a Lagrangian particle tracking approach to estimate transport times in the Danshuei river estuarine system of northern Taiwan.

Easy availability of sea water for cooling and desalination purpose, possibility of disposal of effluents in the coastal environment and cost effective transportation of raw materials and finished products via the sea route lead to the development of cluster of industries along the Gulf of Kachchh (GoK) coast. Refineries, fertilizer, chemical and cement industries, power plants, minor and major ports and salt works are the major industries which make use of the Gulf (Vethamony et al., 2005). Eco-sensitive areas like Marine Sanctuaries and a Marine National Park are located in the southern shore of the Gulf.

The residence time is an important parameter that measures the effectiveness of tidal flushing in removing a pollutant from the system. A well mixed estuary will have a short residence time, and the pollutants will be prevented from exerting their adverse effects within the estuary. A short residence time is beneficial to pollutant removal (Liu et al., 2008). To address questions of sustainability it is necessary to understand the extent to which the tidal circulation is able to flush pollutants from the bays (Brooks et al., 1999). The month long residence time was ascribed to be the cause of eutrophication and hypoxia/anoxia in the Cheseapeake Bay for most of the anthropogenic nutrients discharged into the system exert their effects within it (Cereo and Cole, 1993). The reported increase of primary production rates in the Hudson River as the flow decreased was also attributed to the increased residence time (Howarth et al., 2000).

2. Study area

The study area considered for residence time estimation is the Gulf of Kachchh (GoK), which is a highly energetic, macrotidal water body located in the northeastern part of the Arabian Sea, between 22° 15' N - 23 ° N and 69° - 70° 15' E. It has a length of ~ 180 km and the width decreases from ~ 70 km at the mouth to about 1-2 km off Navalakhi near the head; the mean depth being ~ 30m. Across the western open boundary, the Gulf waters interact with the northern Arabian Sea and in the eastern part, it opens into the shallow creek system with a depth of ~ 3m called the little Rann of Kachchh. The Gulf is relatively shallow with maximum water depth varying from 60m at the mouth to 20m at the head (Vethamony et al., 2005). The Gulf of Kachchh is known for its high tidal range and currents; the tidal elevation reaches a maximum of about 6.6m at Kandla and 7.2m at Navalakhi (Babu et al., 2005). The bathymetry and geomorphological features of the Gulf of Kachchh are shown in Fig. 1.

3. Methodology

3.1. Model set up

A vertically integrated, 2D hydrodynamic model namely, MIKE 21 HD developed by the Danish Hydraulic Institute (DHI), Denmark, has been applied to simulate water level variation and currents. The computational domain of the model extends from Okha to near Navalakhi between Long 68° 37' E to 70° 21'E and Lat 22 °14'N to 23° N. The model domain is divided into a 500m * 500m grid in x and y directions.

Bathymetry of the study area was prepared by extracting depth data from MIKE CMAP and Naval Hydrographic Office (NHO) charts. Surface elevations at the coastal tidal stations Dwaraka and Godia along the western boundary were predicted using four major constituents M2, S2, K1 and O1, given in the master tide file of MIKE 21. Eastern boundaries at Navalakhi and Kandla were kept closed. Model runs were carried out using the horizontal eddy viscosity = $0.5\text{m}^2/\text{s}$. The bottom roughness in the Gulf of Kachchh varied according to bed sediment grain sizes. The bed consists of various sizes of clay, silt, sand and rock soils. The bed roughness depends on the sediment/ particle size, defined as d_{50} . The bed resistance increases for small values of Manning Number (M) and subsequently the velocity decreases. MIKE 21 model uses the reciprocal of the Manning Number and based on past experience, Manning's roughness parameter = $32\text{m}^{1/3}/\text{s}$ was used. Considering the irregular bathymetry, a time step interval of 6s was selected which yielded a Courant Number of 0.336343. Initial surface elevations at the model grid points were interpolated from the predicted tides.

The vertically integrated momentum equations were simplified by assuming that the GoK waters were vertically homogeneous and there was no stratification or vertical density gradient. The HD module was run from 1/4/2002 to 2/6/2002 with a wind speed = 4.5m/s and wind direction = 290° (premonsoon season) (Babu et al, 2005). Though the simulations were carried out for 2 months, the results and comparison are presented for a period of one month only.

3.2. Estimation of residence time

In general terms, the residence time of an estuary is defined as the average time a dissolved or suspended matter resides in the estuary before it is carried out into the open sea (Wang et al., 2004). However, during the experimental model runs it was observed that there is a dynamic barrier across Sikka - Mundra section which prevents the material released in the eastern Gulf from coming out through the mouth. The existence of the central, well mixed zone which acts as a dynamic barrier and helps in maintaining horizontal salinity gradients in the eastern Gulf is reported earlier by Vethamony et al. (2005). Therefore, in this paper, the residence time is considered as the

time required for the mean concentration of a constituent in the estuary to drop to 1/e of its initial value (Abdelrhman, 2002). The residence time of an estuary can be defined by analogy to a steady state chemical reactor that is stirred continuously (Abdelrhman, 2002). The equation for conservation of mass is derived by assuming that dye is added at a constant rate, R, and mixed instantaneously, and that mass leaves the system at a rate, km, (where k is a constant), that is proportional to the mass, m, inside the system. After an increment of time dt, the mass will be m + Rdt - km dt, and the net change in mass will be dm = (R - km) dt, which when integrated gives:

$$m = m_0 e^{-kt} + \frac{R}{k} (1 - e^{-kt})$$

After the end of injection, R will be zero and the net change of mass (e.g. due to tidal flushing) will be:

$$m = m_0 e^{-kt}$$

Dividing the above equation by V, the volume of the system, we get equation for concentration as follows:

$$c = c_0 e^{-kt}$$

The residence time is defined as the time when the mass declines to 1/e of its initial value m_0 , i.e.

$$t = \frac{1}{k} = \tau$$

This theory assumes steady state flow. It also assumes complete and instantaneous mixing and that mass leaving the system is linearly proportional to the average mass inside the system. The freshwater discharge into the Gulf is negligible (Vethamony et al., 2005) and hence its impact on the velocity field, dilution and stratification would also be negligible.

For the estimation of residence time, Particle analysis (PA) module of MIKE 21 was used. Eight locations were selected to study pollutant dispersion as shown in Fig. 5(a). The hydrodynamic model (HD) runs were taken for two months each, for three seasons namely, pre-monsoon (March - May), southwest monsoon (June - September) and northeast monsoon (November - February). The output of the HD model serves as the input for the PA model.

In the PA model, dissolved matter is released at each of these locations at the rate of 100 kg/s at every time step of 60 s. The hydrodynamics of the region distribute the dissolved matter, and the concentration of the dissolved matter reduces over time. At each location, the maximum

concentration values were noted, and the time required for the maximum concentration to decline to $1/e$ (~ 0.37) was considered as the residence time.

4. Results and discussion

4.1. Model validation

A comparison between predicted and modelled water levels and modelled and measured currents (u-v components) has been carried out for the locations Loc2, Loc5 and Loc7 situated in the western, central and northern Gulf, respectively, and only that of Loc2 is presented in Fig. 2. The model simulated current components agreed very well with the measured current components. Similarly, the predicted tides compared very well with the model simulated values.

Figs. 3 and 4 show the current pattern in the Gulf of Kachchh during a typical neap tide on 06 April 2002 and spring tide on 13 April 2002, respectively. During both spring and neap tides, the flood and ebb currents exhibit intensification in the central Gulf. Though the flow is, in general, parallel to the coastal orientation the currents show tidal eddies around the islands and shoals. These eddies will have implications to the residence times of pollutants discharged in the upstream of GoK.

For understanding the flow in the Gulf during the southwest monsoon, simulation was carried out from 1 July to 1 Sept 2002 with a constant wind speed of 6.5 m/s and wind direction 245° . We observed that at Loc5, flood currents were stronger than the ebb currents due to strong westerly winds. The results of simulation are given in Table 2. Further, simulation was also carried out from 1 November 2002 to 2 January 2003 (representing NE monsoon) with a constant wind speed of 3.5 m/s and wind direction 335° . During this season, the ebb currents were stronger than the flood currents at Loc 2 (western Gulf), Loc5 (central Gulf) and Loc7 (eastern Gulf) as the wind direction reversed during this season.

4.2 Pollutant transport during different seasons

Pollutant transport has been studied for all the 8 locations and 3 seasons (Fig. 5). In the PA model domain, dissolved matter was released at each of the 8 locations at the rate of 100 kg/s at every time step of 60 s. Due to strong currents present in the Gulf, the dissolved matter dispersed and, therefore its concentration reduced with time. At each location, the maximum concentration values were noted, and the time required for the maximum concentration to reduce to $1/e$ (~ 0.37) was thereby estimated. Tables 3,, 4 and 5 show the residence time (in days) calculated at all the 8 locations (Fig. 5a) for April - May 2002, July- August 2002 and November - December 2002, respectively.

Locations 1 and 2 are situated very close to the open boundary, where the Gulf water is exchanged with the northern Arabian Sea. Dilution takes place rapidly with the incoming water and hence, the residence time at these 2 locations was very short, on the order of 1 hour, for all the three seasons. We have presented the figures of only one season (pre-monsoon: April - May 2002) and one location (Loc 3). It is seen that the material released at Location 3, initially oscillated between Long 69°30" and Long 70° 00" and at the end of simulation, the material has accumulated in the northern head of the Gulf (Fig. 5). The maximum concentration was observed to be 0.2483 kg/m³. Similar exercise was carried out for all the 8 locations during the three seasons and the results have been appended in Table 3 a, b and c.

The depth is ~ 15m near the head region. The circulation shows a net transport towards Kandla (along the northern rim of the Gulf) with a tendency to form a clockwise circulation. The tidal currents in the Gulf have a strong E-W component, which prevents the material from the north from being transported southwards. Some influence on the residence time is apparent from the central eddies and dynamic barrier across the Sikka- Mundra section. Locations 4 and 8 situated in the eastern Gulf region show a large residence time, of the order of 2-4 days, compared to the Locations 1, 2 and 3 and the particles released into the eastern Gulf region actually do not come out of the system (Tables 3-5). Therefore, extreme care must be taken when the industrial wastes are released in the north-eastern Gulf. The region around location 5 behaves like a bay; due to shoals and eddy formation, the dissolved matter gets trapped in the bay, and hence the residence time is higher at location 5, on the order of 3-4 days, though it is situated not far from the coast or the mouth of the Gulf (Tables 3-5).

The residence times within the Gulf of Kachchh were site-specific; the sensitivity of the particle trajectories to their initial locations indicated a complex, non-linear nature of the tidal regime. Such flow character is described as Lagrangian Chaos by Zimmerman et al., (1986). The residence time varies spatially due to bathymetry and related hydrodynamical features.

5. Conclusions

The residence time of the pollutants released at 8 locations in the Gulf of Kachchh has been calculated for three seasons, namely pre-monsoon, southwest monsoon and northeast monsoon. Generally the residence time is relatively short for the Gulf of Kachchh, and therefore, the Gulf waters are relatively unpolluted. The residence time increases as we move from the mouth to the head region of the Gulf. As different sections of the Gulf behave differently with respect to residence time, the studies can be extended to identify locations where coastal based industries could be installed.

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Figure Captions

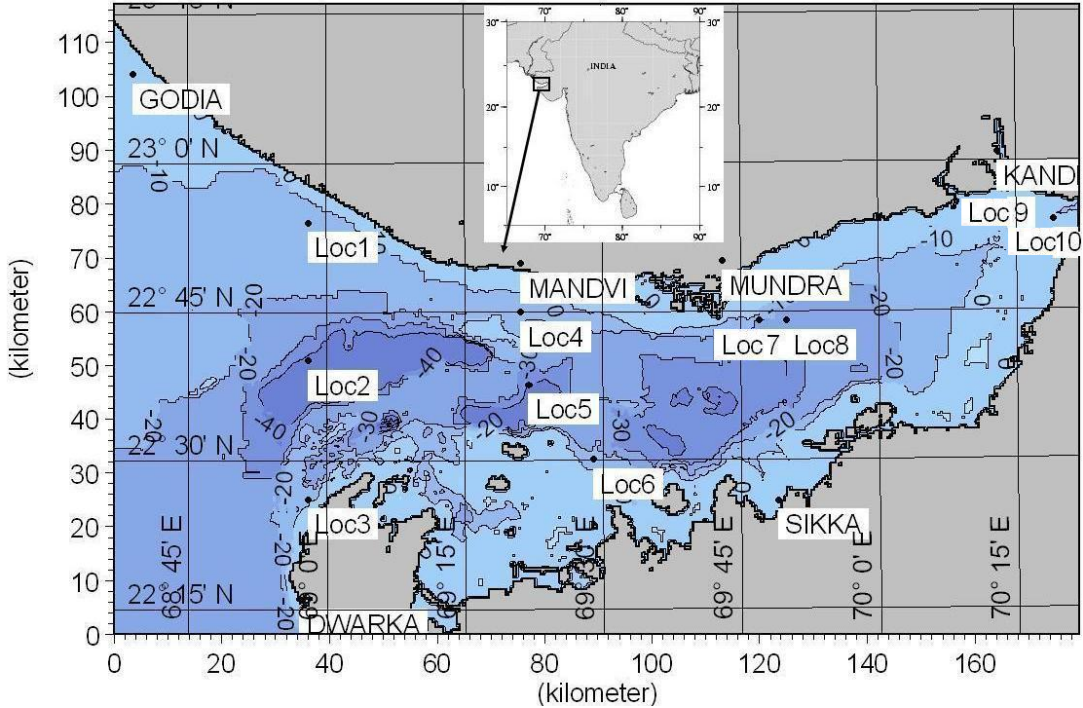


Fig. 1. Bathymetry and geomorphological features of the Gulf of Kachchh along with current meter mooring locations (depth values are in meters).

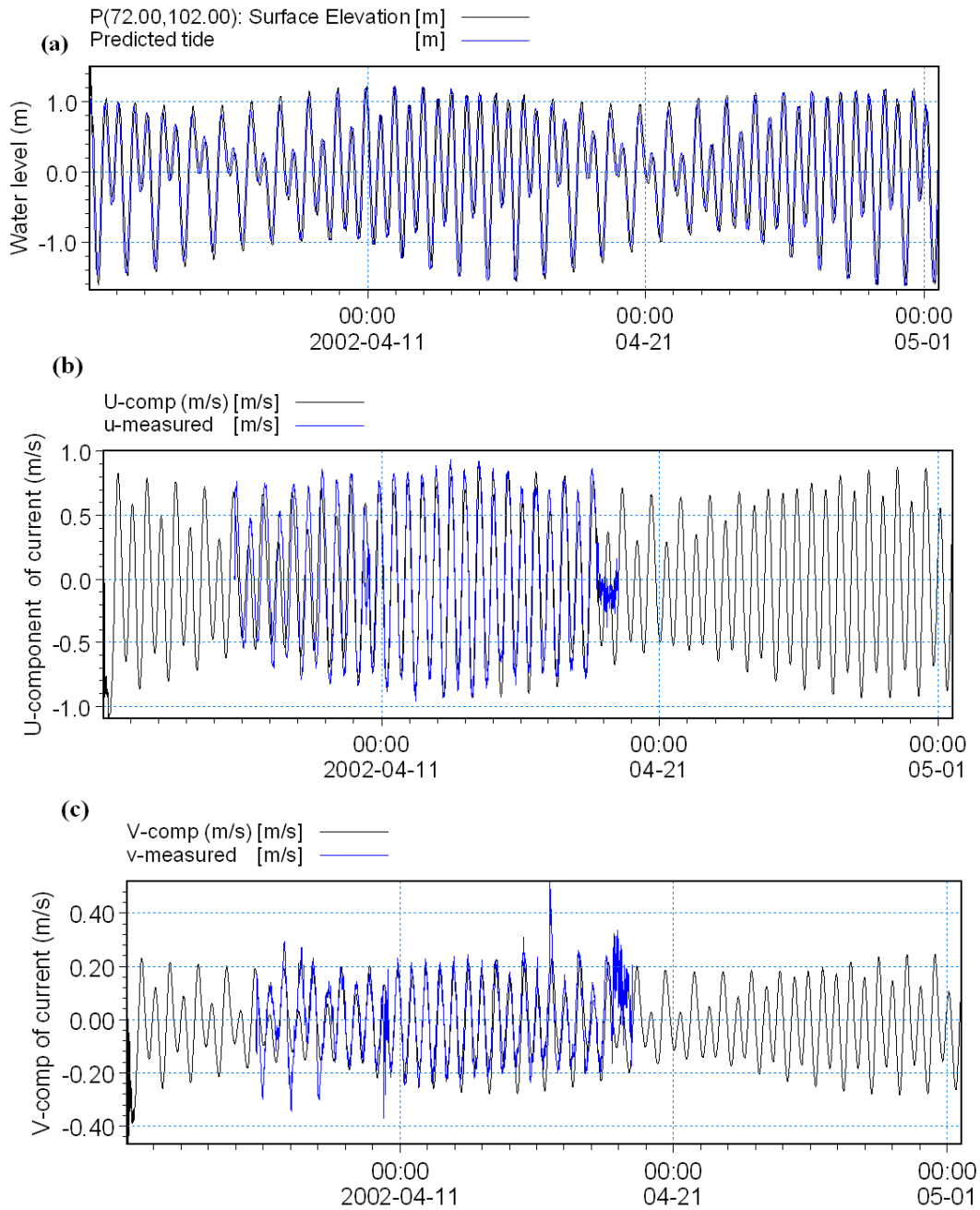


Fig. 2. Comparison between (a) water levels, (b) u- component of currents and (c) v- component of currents at location 2 during April 2002

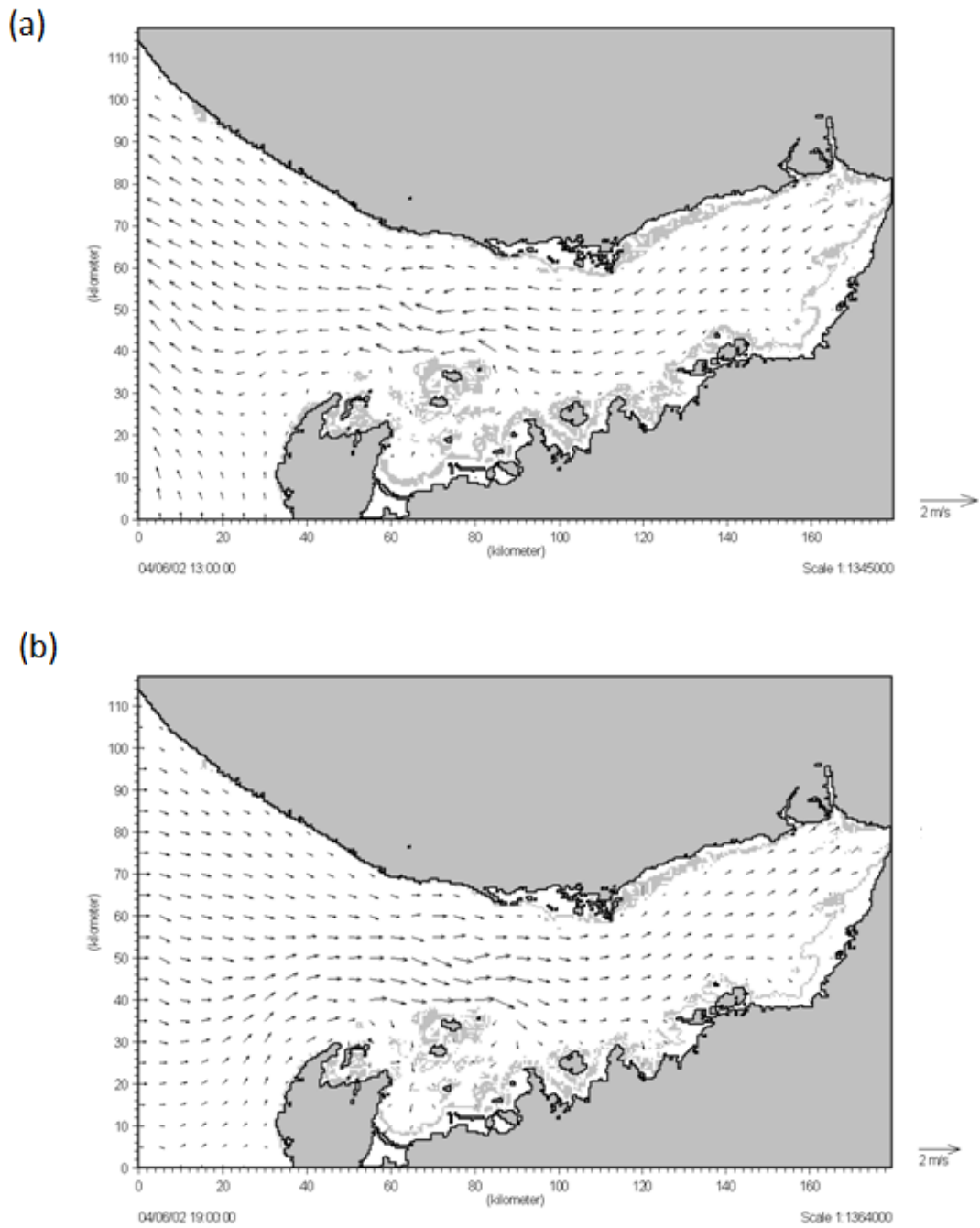


Fig. 3. Current pattern in the Gulf of Kachchh during a typical neap tide on 06.04.2002: (a) ebb currents and (b) flood currents.

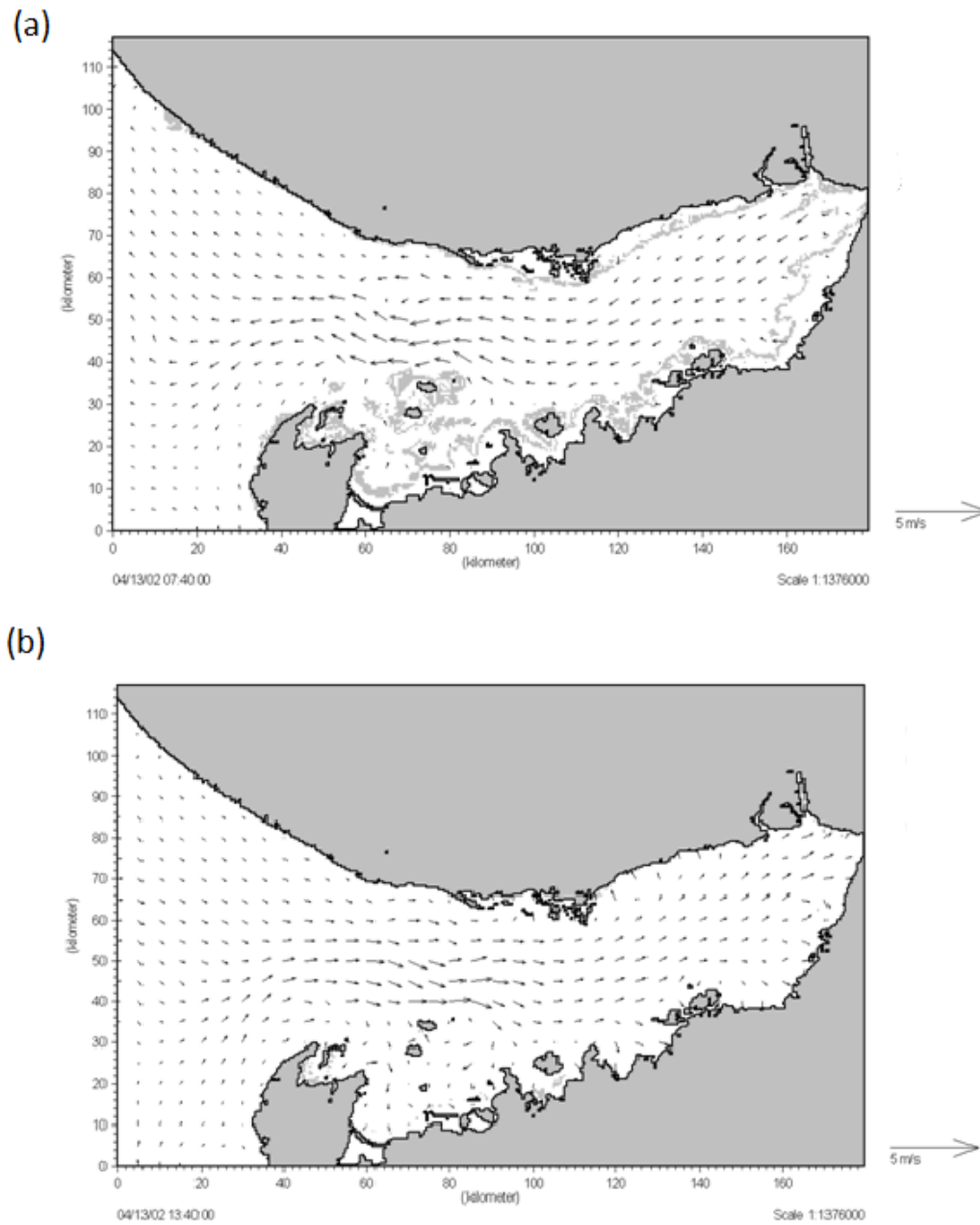


Fig. 4. Current pattern in the Gulf of Kachchh during a typical spring tide on 13.04.2002: (a) ebb currents and (b) flood currents.

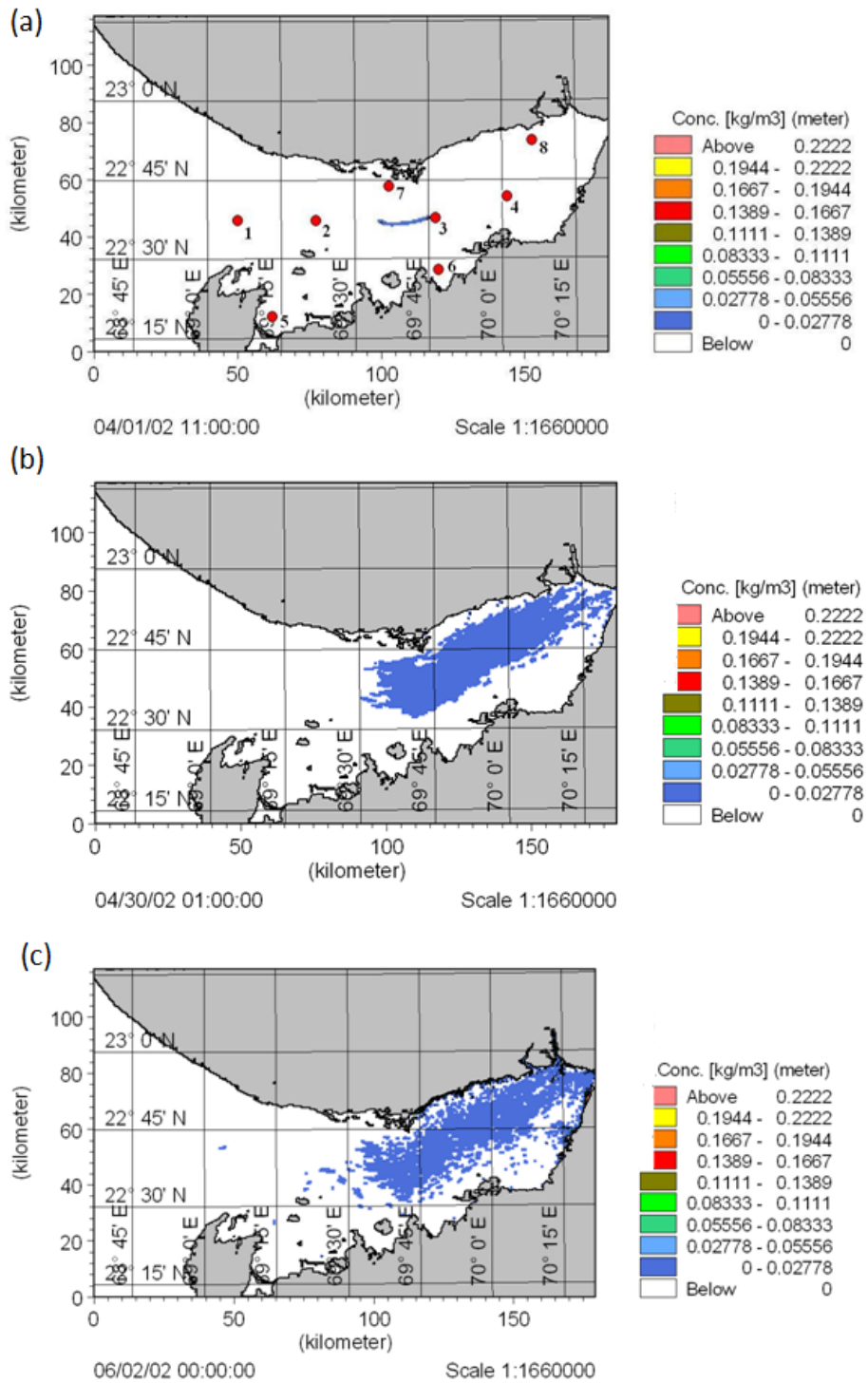


Fig. 5. Dispersion of particles released at location 3: (a) soon after the release (b) one month after the release and c) 2 months after the release during April-May 2002.

Locations selected for the estimation of residence time are marked in Fig. 5(a).

Tables

Table 1 Comparison of currents during April 2002

| Location | U - component (m/s) | | | | V - component (m/s) | | | |
|----------|---------------------|------|-------|------|---------------------|-------|-------|-------|
| | Measured | | Model | | Measured | | Model | |
| | West | East | West | East | South | North | South | North |
| Loc 2 | 0.96 | 0.93 | 1.09 | 0.91 | 0.36 | 0.51 | 0.47 | 0.29 |
| Loc 5 | 1.36 | 1.34 | 1.34 | 1.32 | 0.32 | 0.06 | 0.22 | 0.07 |
| Loc 7 | 0.69 | 0.81 | 0.71 | 0.71 | 0.51 | 0.51 | 0.42 | 0.37 |

Table 2 Seasonal variability of u and v- components of currents at Loc2, Loc5 and Loc7

| Location Period | Loc2 | | | | Loc5 | | | | Loc7 | | | |
|-----------------------|--------------------------|------|----------------------|-------|--------------------------|------|----------------------|-------|--------------------------|------|----------------------|-------|
| | u- component (m/s) | | v-component (m/s) | | u- component (m/s) | | v-component (m/s) | | u- component (m/s) | | v-component (m/s) | |
| | West | East | South | North | West | East | South | North | West | East | South | North |
| Pre- monsoon | 1.09 | 0.91 | 0.47 | 0.26 | 1.34 | 1.32 | 0.22 | 0.07 | 0.71 | 0.71 | 0.42 | 0.37 |
| Southwest monsoon | 1.15 | 0.90 | 0.61 | 0.22 | 1.29 | 1.39 | 0.25 | 0.08 | 0.79 | 0.70 | 0.49 | 0.38 |
| North east monsoon | 1.45 | 1.07 | 0.28 | 0.12 | 1.68 | 1.41 | 0.35 | 0.08 | 0.89 | 0.71 | 0.57 | 0.37 |

N.B: u represents east - west component and v north - south component of currents

Table 3(a) Residence time estimated at different zones in the GoK during April- May 2002

| Location | April- May 2002 (wind speed = 4.5 m/s; wind direction = 290°) | | |
|----------|---|---|-----------------------|
| | Maximum concentration (kg/m ³) | 1/e of concentration (kg/m ³) | Residence Time (days) |
| Loc 1 | 0.164 | 0.061 | 0.97 |
| Loc 2 | 0.141 | 0.052 | 0.98 |
| Loc 3 | 0.248 | 0.092 | 1.62 |
| Loc 4 | 0.354 | 0.131 | 3.40 |
| Loc 5 | 1.603 | 0.590 | 3.10 |
| Loc 6 | 1.000 | 0.370 | 2.33 |
| Loc 7 | 7.280 | 2.690 | 0.63 |
| Loc 8 | 0.750 | 0.280 | 2.72 |

Table 3(b) Residence time estimated at different zones in the GoK during July-August 2002

| July- August 2002 (wind speed = 6.5m/s; wind direction = 245°) | | | |
|--|--|---|-----------------------|
| Location | Maximum concentration (kg/m ³) | 1/e of concentration (kg/m ³) | Residence Time (days) |
| Loc 1 | 0.191 | 0.070 | 0.88 |
| Loc 2 | 0.135 | 0.050 | 1.27 |
| Loc 3 | 0.276 | 0.102 | 1.15 |
| Loc 4 | 0.313 | 0.116 | 1.83 |
| Loc 5 | 1.208 | 0.446 | 2.67 |
| Loc 6 | 0.959 | 0.354 | 1.77 |
| Loc 7 | 6.506 | 2.407 | 1.80 |
| Loc 8 | 0.817 | 0.302 | 2.18 |

Table 3(c) Residence time estimated at different zones in the GoK during November - December 2002

| November - December 2002 (wind speed = 3.5 m/s; wind direction = 335°) | | | |
|--|--|---|-----------------------|
| Location | Maximum concentration (kg/m ³) | 1/e of concentration (kg/m ³) | Residence Time (days) |
| Loc 1 | 0.124 | 0.046 | 1.23 |
| Loc 2 | 0.104 | 0.038 | 0.90 |
| Loc 3 | 0.219 | 0.081 | 1.68 |
| Loc 4 | 0.279 | 0.103 | 1.70 |
| Loc 5 | 2.754 | 1.019 | 4.03 |
| Loc 6 | 0.774 | 0.286 | 2.00 |
| Loc 7 | 4.725 | 1.748 | 2.58 |
| Loc 8 | 0.647 | 0.239 | 2.70 |