

A numerical investigation on the tide-induced residence time and its association with the suspended sediment concentration in Gulf of Khambhat, northern Arabian Sea

Aditi Mitra^{1,2}, V. Sanil Kumar^{1*}

¹Ocean Engineering, CSIR-National Institute of Oceanography (Council of Scientific & Industrial Research), Dona Paula 403 004 Goa India

²Research Scholar, Bharathidasan University, Tiruchirappalli 620023 Tamil Nadu, India

*corresponding author email:sanil@nio.org

Abstract

A 2D-numerical model is used to estimate suspended sediment (SS) transport and residence time (RT) of the Gulf of Khambhat (Gulf). Tidal current, as well as bottom topography, play a key role in sediment entrapment inside the Gulf and hinders the SS exchange between Gulf and Arabian Sea. The northern and central regions of the Gulf experiences high RT throughout the year. RT of more than a month were recorded in the northern region of the Gulf where SS concentration was also high (>500mg/l). A barrier formed during non-monsoonal months cause distinct RT and SS in the Gulf compared to Arabian Sea. During monsoon, a partial withdrawal of the barrier could be seen leading to lower RT inside the Gulf, in the southern region. Whereas, the SS plume resided in the northern region even during the monsoon. Present study infers that particle entrapment occurs inside Gulf for a prolonged period.

Keywords: Gulf of Khambhat, residence time, suspended sediment transport, tidal hydrodynamics

1. Introduction

Sediment transport studies in the marine environment have been widely used in various coastal engineering applications. In coastal regions, discharge of sediment particles mainly occurs from the estuarine run-off, beach or mudflat erosion, channel dredging, and dumping, and those could be accumulated, transported, or dispersed to offshore waters. Sediment predominantly gets transported from erosion-prone areas (mainly upstream) to depositional areas such as lowland regions e.g., floodplains and estuaries. The accumulation of sediment is particularly important to those places where dredging is required to maintain the navigation. Changes in the sediment supply might alter the turbidity of the estuary, and eventually the photosynthesis and primary production (Cloern, 1987), as well as the supply and distribution of the sediment related contaminants (Domagalski and Kiuvi, 1993; Flegal et al., 1996; Schoellhamer et al., 2003). A small change in the flow might affect the annual sediment discharge of a particular region (Wright and Schoellhamer, 2004). The sediment concentrations in the coastal area have extensive spatio-temporal variability, which is not apprehended by the observations and hence indirect techniques such as remote sensing or numerical model studies are used. Studies on the suspended sediment (SS) transport in the marine environment are essential not only for the coastal engineering or navigational problems but also for ecological assessments (Ramakrishnan and Rajawat, 2012). Hydrodynamic action plays a major role in the sediment transport mechanism since it provides the force needed for movement of sediments. Tides, waves, river discharges, wind stress, sea-level changes, and currents alter the transport and distribution of SS (Muralidharan et al., 2015); climate change also has the potential to affect the sediment yield (Wright and Schoellhamer, 2004). Tides, in particular, play an important role in the SS movement. The distinct variability in the bathymetry and geometry of a coastal region leads to irregularity in current velocities and eventually controls the disparity in the SS distributions in that region. Thus, maximum erodability could be seen at places with strong hydrodynamic action. On the other hand, accretion problems generally occur at places where the sediment transporting capacity of the hydraulic system is reduced due to the reduction in wave and current velocities (Jha et al., 2017).

Mixing and residence times of freshwater are salient proxies to understand the ecological state of an estuary since they are essential for developing ways to reduce the adverse impact on an aquatic system due to natural and anthropogenic interventions. Residence time (RT) is a predictable parameter that is often used to describe the time scale of physical transport as well as biogeochemical processes. RT is the average time taken by the particles to escape the estuary and can be calculated for any type of material, which mainly depends on the starting location of the material and the hydrodynamic characteristics of the water body. Concepts such as the residence time, flushing rates,

and the age of water have been recommended to quantify the retention of water in estuarine and coastal habitats (Deleersnijder et al., 2011; Monsen et al., 2002; Oliviera and Baptista, 1997; Wolanski, 2007). RT is a good indicator of the potential of a system to advect SS, which is particularly pertinent to large water bodies like Gulf of Khambhat (GoK) due to the presence of discharge of treated effluent from several industries along the coast as well as from the riverine discharges. It is often advantageous to model a semi-enclosed coastal embayment (GoK) as a separate system connected to the outer sea (Arabian Sea) in terms of the RT. The hydrographic residence time is a fundamental proxy to determine the extent of biogeochemical activity (e.g., Morris, 1990; Shaw et al., 1998), and it could be a tool to decide about the long-term sustainable coastal zone management. The assimilative capacities of coastal seas for SS transport and effluent discharges are predominantly determined by the rates at which the SS or effluents are first dispersed and then removed from the coastal region into the open sea (Alosairi et al., 2011). Engineering and industrial activities in the GoK can affect its aquatic environment if carried out without examining the circulation of water and RT. In tidally dominated shelf seas, seasonal circulation may significantly modify water retention times.

SS usually enters the coastal area from land-derived sources mostly from river run-off and redistributed in open seas, shorelines, and beaches, which might affect marine organisms (like fishes) through ingestion, leading to a threat to human health (Politikos et al., 2019). Thus, understanding the sources, dispersions, and fate of sediment in the oceans using numerical simulations is a valuable research goal. GoK presents an ideal condition to examine the tidal effect on the SS transport due to its macro-tidal regime and high SS concentration. Knowledge of the hydrography of GoK is vital, not only to understand the SS transport process but also in view of its socio-economic consequences. Even though the SS transport and hydrodynamics of GoK are investigated in the past, there are a few questions that are still unanswered. i) What are the primary pathways of SS inside the Gulf? ii) How do physical processes and topography control the SS transport?

Thus, the goal of the present study is to apply a 2D-numerical model in GoK to understand the seasonal variability as well as the variability during different tidal phases (ebb/flood and spring/neap) in SS. GoK being a shallow water system, the significant vertical gradient of SS is not expected and hence a depth-averaged model is used in the study. Estimation of the assimilative capacity of the Gulf and surrounding region in terms of the residence time and its impact on the suspended sediment transport process is another aspect covered in the present study.

2. Study Area

Gulf of Khambhat (GoK) is a major turbid water body along the west coast of India between the Saurashtra peninsula and the mainland of Gujarat and connects two of the industrially important states of India i.e., Maharashtra and Gujarat (Fig. 1). The Gulf is a funnel-shaped indentation and a large number of industries are present at both the banks of the Gulf. For a prolonged period, the Gulf has been used as a disposal area of the treated effluents from these industries. Mudflats of GoK constitute an important ecosystem of the west coast of India. Four major rivers i.e., Narmada, Tapi, Mahi, and Sabarmati drain out a large amount of sediment in the form of suspended load into the Gulf. In the past, the SS transport in the Gulf has been studied by numerical approach (Sinha et al., 2010; Dandayudapani and Murali, 2013; Jha et al., 2017), by remote sensing (Kunte, 2008; Misra et al., 2014; Gupta, 2014) and also by both of modelling and remote sensing (Ranganath et al., 2019). All of these studies mainly focus on the northern part of the Gulf, while information on SS from the southern GoK and surrounding areas are missing, which is pivotal for understanding the overall SS transport process and its seasonal variability.

3. Materials and Methods

3.1 Hydrodynamic Model

Shallow water equations of continuity and momentum balance (Stoker, 1957) have been used to determine the SS transport and RT of the GoK. The 2D model developed by Advanced Computing Research Institute (ACRI, 1994), used in the study is the same used by Mitra et al. (2020a) to obtain the Lagrangian circulation of the Gulf. The model had also been used in other locations in the east coast (Babu et al., 1998) and the west coast of India (Naidu and Sarma, 2006; Naidu et al., 2016). The model is barotropic and neglects horizontal diffusion terms in the momentum equations.

(a) Continuity and mass balance

$$\frac{\partial \eta}{\partial t} + \frac{\partial(HU)}{\partial x} + \frac{\partial(HV)}{\partial y} = Hm_v \quad (1)$$

Where, t =time coordinate, $\eta=H - h$, H =total instantaneous water depth, x, y = set of horizontal, mutually orthogonal Cartesian coordinates, U and V =horizontal velocity components in x and y direction respectively, m_v =vertically integrated average rate of input/output mass of fluid per unit volume divided by the fluid density, h =the depth of water measured positively downwards from the reference datum plane.

(b) Momentum balance equations

For a shallow water body, the vertically integrated momentum balance equations are given by;

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = -g \frac{\partial \eta}{\partial x} - \frac{1}{\rho} \frac{\partial P_a}{\partial x} + \Omega V + \frac{C_w W^2}{H} \cos \theta - \frac{C_f (U^2 + V^2)^{\frac{1}{2}}}{H} U + S_u \quad (2)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} = -g \frac{\partial \eta}{\partial y} - \frac{1}{\rho} \frac{\partial P_a}{\partial y} - \Omega U + \frac{C_w W^2}{H} \sin \theta - \frac{C_f (U^2 + V^2)^{\frac{1}{2}}}{H} V + S_v \quad (3)$$

Where, η =tide elevation, g =acceleration due to gravity, ρ =fluid mass density, Ω =Coriolis parameter, P_a = fluid pressure, W =wind speed, C_w =wind stress coefficient, C_f =bottom friction coefficient, θ =wind angle measured from the positive direction of x to the positive direction of y -axis, S_u and S_v = average rate of momentum generated/dissipated per unit volume derived by mass density of water in x and y directions.

Due to the smaller magnitude than all other terms, horizontal diffusion terms in the momentum balance equation have been neglected. Equations (1 to 3) are solved in Alternating Direction Implicit (ADI) scheme and the input data were smoothed using the spline function to obtain the tides at finer intervals. The equations were solved with the initial and boundary conditions on a staggered grid system (Leendertse, 1970). The model simulations were done by applying boundary tide at the eastern, southern, and western boundary of the model domain and the northern boundary was kept closed. The tides at the intersection of two straight open boundaries, i.e., the southwest and northwest corners of the model domain with a grid resolution of 500 m were obtained from Oregon State University Global Tidal Model (Egbert and Erofeeva, 2002), and the tide at the other two corners; Diu and Mumbai (Apollo Bundar) in this case, were derived from the Indian Tide Table. The model domain was tilted by an angle of 45° in an anti-clockwise direction for ease of giving model input. The results are represented using the geographical coordinates of the area. The model extends up to the inter-tidal area and a positive value in the bathymetry figure (Fig. 1) denotes the land area.

The bottom friction (C_f) was based on the Chezy coefficient using the formula, $C_f = (1/32) \times [\log_{10} (14.8 H)/K]^2$, with K as roughness length. Varying C_f magnitudes were applied in different regions of the model domain to calibrate and validate the model since it is the function of depth (Sathish and Balaji, 2015). The stability of the numerical scheme depends on $\Delta t < \Delta x / \sqrt{2gH_{\max}}$.

where Δt is the time step in s, Δx is grid size in m, H_{\max} is the maximum depth in the model domain and g is the acceleration due to gravity. Δt is found to be 11 s in the present work as H_{\max} is 100 m and Δx is 500 m. Since the model was initially at rest ($t=0$, $u=v=0$), it took more than 15 hours to get stabilized; hence, the first one day output from each model simulations have been discarded. Reanalysis data of u and v components of wind speed at 10 m height having one-hour interval with a resolution of $0.25^\circ \times 0.25^\circ$ for the entire study area, obtained from NCEP / NCAR (Kalnay et al., 1996), were used as model inputs. The river discharge data of major rivers (Narmada, Tapi, Mahi, and Sabarmati) was obtained from the Central Water Commission, New Delhi. Standard seawater density has been used in the entire model domain and GoK was assumed to be a one-layer system.

RT was analyzed using the Lagrangian particle tracking method by releasing particles at a fixed time. The path of these particles with time was determined in a 2-D model, using a 4th order Runge-Kutta (RK) scheme for particle advection. The trajectories of the particles were calculated by time-integrating the horizontal velocity field (Mitra et al., 2020a; Naidu et al., 2016). The velocity at an arbitrary point was calculated by using four-point linear interpolation.

$$\bar{x}(t + \Delta t) = \bar{x}(t) + U\Delta t \quad (4)$$

where \bar{x} is the particle's position, Δt = time step. Here the diffusion term was neglected.

3.2 SS Observation

SS concentration data collected from various parts of the Gulf and river mouths are used for the numerical simulation of this study. SS concentration (mg/l) was determined by filtering the sample through a Millipore membrane filter (pore size, 0.45 μm) and after drying at 70 $^\circ\text{C}$ for 6-8 h (APHA, 2005).

3.3 SS Transport Model

2D Sediment transport module of the model (ACRi, 1994) is applied to simulate the SS transport process of the Gulf. The equation to simulate the depth-averaged SS concentration is as follows:

$$\frac{\partial(hP)}{\partial t} + \frac{\partial(hUP)}{\partial x} + \frac{\partial(hVP)}{\partial y} = \frac{\partial}{\partial x} \left(hK_1 \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left(hK_2 \frac{\partial P}{\partial y} \right) + E_r - D_p \quad (5)$$

where, P = average SS concentration; h = total water depth; U & V = zonal and meridional depth-averaged velocity components; K_1 and K_2 = diffusion coefficients; E_r and D_p = erosion and deposition rates respectively.

The change in bed sediment thickness is estimated as follows:

$$\frac{\partial Z}{\partial t} = - \frac{(E_r - D_p)}{(1 - p_r) \rho_s} \quad (6)$$

where p_r is the porosity and ρ_s is the density of the sediment deposit. Based on the sediment texture analysis in this region (Anonymous, 2017), it was observed that the sediment is dominated by sand (more than 90%). Hence, in this study, magnitudes of 0.25 and 1600 kg/m³ are used as porosity and density of the suspended sediment. The approximations from Elliott and Clarke (1998) have been followed in this study. The SS transport model permits the SS to exit the model grid by settling or lateral advection; however, no re-suspension mechanism is included in the model. In this study, months from June to October were considered as the monsoon. All other months were assumed to be non-monsoon.

4. Results

4.1 SS Concentration

Observed SS concentrations at several places of the Gulf revealed that the maximum concentration of sediment is experienced at the northern GoK near the Narmada mouth on the east coast and Bhavnagar on the west (Table 1). More often, during monsoonal months, the concentration exceeds 1000 mg/l, which reduces to 400 mg/l during the non-monsoon season. River Tapi drains into GoK with SS load with average concentrations of 800 and 320 mg/l during monsoon and non-monsoon respectively in the southern region. The other two important rivers that drain into GoK (Mahi and Sabarmati) show comparatively less SS concentration. Among all the locations in GoK, the maximum concentration of sediment was recorded in Bhavnagar with an average maximum of 1380 mg/l during monsoonal months. The SS concentration is found to be high inside the Gulf, which has a downward decreasing trend. Apart from rivers, the contribution of SS from other sediment sources was not considered in the present work.

4.2 SS Transport

The study examines SS transport based on releasing certain concentrations of SS at the major river mouths in different seasons since these rivers were assumed to be the primary sources of SS for the Gulf and surroundings. The release points were limited to coastal sites considering the land-derived sediments as the only source of SS in GoK. The average SS spill of each season was taken into consideration. The model results revealed that after one month of simulation, the maximum SS concentration resides near Dahej inside the Gulf. During flood condition, the concentration varied between 100 and 650 mg/l, while during ebb, the concentration was 50-750 mg/l for monsoonal months. SS concentration is found to be maximum during the neap ebb condition and is found to be

lesser during spring flood condition. The model simulations also denote that the sediment plume is mostly Narmada-centric and resides at the northern GoK irrespective of the seasonal and tidal conditions (Fig. 2). All other areas from the model domain show nearly uniformity in the sediment concentration. During the non-monsoon season, the SS concentrations reduced drastically. The concentration during ebb condition varied between 4 and 32 mg/l and it is 2 to 28 mg/l during the flood. The sediment plume was found to be located in the northern Gulf (Narmada mouth in the east to Bhavnagar in the west) during the dry season (Fig. 3). Even though the adjacent sea showed more or less uniformity in SS concentration, an additional plume of a smaller extent was noticed at the eastern coast (north of Mumbai), which completely dwindled in the non-monsoonal months. The area covered by the SS plume was found to be maximum (minimum) during flood (ebb) condition of spring (neap) tide with lowest (highest) concentration. The central region of the Gulf shows the greatest response towards seasonal and tidal variability. The study indicates that the SS discharge by the Narmada River is locally entrapped and the contributions from other major rivers into the total SS concentration of GoK were found to be trivial and the Gulf has a tendency for retention of SS. The southward extension of the plume was found to be quite smaller than the north. During the monsoonal months, the plume travelled about 35 km south from the Narmada mouth which got decreased to 12 km during the non-monsoon season. On the other hand, the northward advection was quite larger for both seasons.

4.3 Residence Time

The simulated results obtained the RT characteristics of GoK, which would eventually indicate the assimilative capacity of GoK. RT of GoK is the time when a particle exits the Gulf and RT of the surrounding sea was considered to be the time taken by a particle to reach the model boundary. Monthly maximum RT was considered as 31 days, which indicates retention of water parcel in a particular region for over a month. The total time has been categorized into three sub-intervals i.e., March-April-May (MAM) as pre-monsoon, June-July-August-September-October (JJASO) as southwest monsoon, and November-December-January-February (NDJF) as the northeast monsoon. Even though October is the transition month between the southwest and northeast monsoon with the wind reversal during this month, several monsoonal characteristics were retained in this period. Hence, the present study considers October as one of the monsoonal months. Monthly averaged RT were calculated for each month of the entire year (Fig.4). Maximum RT was obtained during pre-monsoon and lower RTs were obtained from the southern parts of the model domain, which is not reflected inside GoK and high RT were recorded in the entire Gulf. During monsoon season, even though RT of the southern region of the model domain had an increase,

comparatively lower values were observed inside GoK. Minimum RT was found during the monsoonal months. During the pre-monsoon season, the northern region of Gulf was found to be isolated from the rest of the model domain. A barrier was developed between the Gulf and the Arabian Sea, which caused distinct RT characteristics between these two water bodies. This barrier gets slumped during the northeast monsoon season and completely dwindles in the southwest monsoon months.

Monthly-averaged RT of GoK also manifested similar results (Fig5), which illustrates the occurrence of the highest RT during the month of May, which sharply declines during June and remains low for the monsoonal months. Even though the average RT of the Gulf decreases during the monsoonal months, the northern and central regions of the Gulf experiences high RT throughout the year. Parts of the northern region clearly do not exchange water parcels with the Arabian Sea, even though they have tendencies to travel downward. Figure6 indicates the RT regime of the Gulf, where the northern region was found to have maximum RT followed by the central, southern, and extreme southern regions of GoK. Even though the southern region was found to be have minimum RT of the Gulf during the pre-monsoon season, the exchange of water parcel was found to be restricted even from this region.

4.4 Connectivity between regions

The Lagrangian particle track results surmised that mostly every part of GoK is interconnected with each other except for some areas from the extreme north (Fig. 1). Particles from the Mahi estuary traversed towards Narmada mouth and even further downward. The particle trails revealed that even though the sub-regions of the Gulf are well-connected, there is hardly any connection between GoK and the Arabian Sea. Very few regions from the southern GoK exchanged water with that of the sea.

5. Discussion

The study explored the SS drift as well as the RT characteristics of GoK with the help of coupled models of hydrodynamics, sedimenttransport, andparticle tracking. Since measured SS concentrations were unavailable for the entire Gulf, a model evaluation was a necessity. Model results showed that SS concentrations are high at the river mouths and eventually get dispersed at other parts of the Gulf. Maximum SS concentration is found at Bhavnagar, where tidal height and current speed are found to be maximum.Maximum SS concentration isobserved during the neap ebb condition. This is due to the low current speed at that time, which aids high SS concentrations in a particular region,whereascomparatively lower SS concentration was recorded during spring flood

conditions. The extension of the SS plume was found to be lower for neap tide than that of the spring. Since the tidal forcing is maximum during spring tide, it is the tidal advection that is greatest due to the sufficiently large current speed. On the contrary, during the neap tide, the tidal forcing gets reduced and hence it becomes hard for the plume for a spatial escalation (Schoellhammer, 1996). Thus, the area covered by the plume during spring tide is much higher than that of the neap. Tide causes the water and the SS to waddle between the Gulf and the sea; on the other hand, the wind and river run-offs were the peripheral parameters for the temporal modulation of the SS concentration (Schoellhammer et al., 2007). The shallower sea in this area tends to accumulate SS and related contaminants, which could intrude to the food chain through lower trophic organisms such as planktons and eventually get propagated towards large fishes (Schoellhammer et al., 2007; Stewart et al., 2004). A previous study by Mitra et al., (2020a) illustrated that the influence of Narmada river discharge is quite a localized factor and does not influence the entire Gulf dynamics. The simulated SS dynamics also reinforces their result where maximum SS concentration is mainly Narmada-centric or restricted in the northern Gulf. Even though the SS plume could extend in the northern and central GoK, it barely has a considerable advection towards the southern region of the Gulf compared to the northward extension. During the last couple of decades, this area became more urbanized. Construction of ports, dams, industrial activities, and other anthropogenic interventions resulted to relatively higher SS. Since SS concentration is a less costly, and more easily measured surrogate for several trace metals and contaminants, its distribution could be manipulated as an ecological indicator of that area (Schoellhammer et al., 2007). Thus the zones with high SS concentration (Narmada mouth and surroundings) are of environmental concerns. Since several trace metals and organic substances are associated with sediment, their fate and future are strongly regulated by that of the sediment. Accordingly, SS moving into, within, and out of the aquatic system could provide the pathways of these elements (Bergamaschi et al., 2001; Le Roux et al., 2001). The high concentration of sediment in Narmada and its surroundings indicate the possibility of contamination of sediment and the overlying water column. There is a decreasing trend in the total fish catch in Narmada estuary, which could be attributed to the anthropogenic activities in this region (Bhakta et al., 2019). In addition to the other industries, a ship-breaking yard is located at Alang, on the southwestern GoK (45 km south of Bhavnagar). It was set up in 1983 on a small scale and has become the largest hub within the last few decades. Earlier studies on pollution showed significantly higher levels of heavy metals and several toxic materials like polychlorinated biphenyl (PCB), polyaromatic hydrocarbon (PAH), organotoxins like tributyltin (TBT), polyvinyl chloride (PVC). These are the wastes from ship dismantling which could be mobilized within the Gulf either as a suspension or agglomerated in sediment (Reddy et al., 2005; Basha et al., 2007; Demaria, 2010;

Ahmed et al., 2013; Jobaid et al., 2014; Frey, 2015). The Lagrangian trails resulted into the alongshore movement of particles on the southern coast of GoK. Due to the circulatory water movement in the central region, the sediment gets entrapped, leading to a more turbid aquatic condition. Lagrangian tracks inferred that particles from the few regions of northern GoK had traveled far from their sources. Thus, some discrete areas of the northern Gulf showed a self-restoration technique. Since the SS contribution from Mahi and Sabarmati rivers is comparatively less, this pattern is not well-reflected in the overall SS transport of GoK. The SS plume further manifests that there is hardly any water parcel exchange between the Gulf and the Arabian Sea during the non-monsoon season since the adjacent sea shows a predominant uniformity in SS concentration. The previous study by Mitra et al. (2020b) showed that the flood current is stronger than ebb, thus the possibility of an inward advection of offshore waters is perceptible, but it would not be convenient in the case of return travel. This could be cause long-term effects on the health of the Gulf, especially the central and northern region.

The water quality information from the coastal waters of Dahej (Anonymous, 2011) is utilized as a case study in the present work (Table 2). Metal concentrations had an increase in this area except for cobalt, which was found to be invariant. The concentration of heavy metal like mercury had doubled up within a decade. Manganese concentration also had a perceptible increase which is indicative of the anthropogenic sources such as sewage sludge, emission from alloy, steel and iron production, combustion of fossil fuel, etc. (WHO, 2004). Available information from the NIO database (Anonymous, 2011) has revealed that water quality parameters e.g. SS and the petroleum hydrocarbon (PHC) have experienced increase. SS concentration in this region was 1574 mg/l in 1996, which has increased to 2852 mg/l in 2006. SS plays a key role in the advection of heavy metals and eventually in the hydrological cycle of marine ecosystems (Singh et al., 2005; Wu et al., 2014; Panseriya et al., 2020). PHC concentration during 1996 had a three-fold increase during the present scenario. Thus, the decadal alterations in the water quality parameters are in agreement with the model results, which have inferred the entrapment of water particles including SS within the Gulf.

The residence time was found to be a great accomplice of the SS characteristics of GoK. It has provided a method to quantify the spatial heterogeneity in the distribution of particles and how long they have spent in GoK before exiting. In the present study, RT of the entire water parcel was estimated which was found to be strongly associated with the overall SS dynamics of GoK. There is no justification for assuming the RT of SS and the water parcel to be equal, but the dynamicity (RT) of water should impact the settlement/suspension of SS (Brodie et al., 2012). Lower RT during

monsoonal months was recorded inside GoK, which is quite evident as the Gulf circulation had a pronounced impact on the RT, especially at regions with varying river discharges (Alosairi and Pokavanich, 2017). Even though the average RT of the surrounding sea had a slight increase during monsoon, an overall uniformity was observed in the entire model domain, whereas a clear distinction between the magnitude of RT of the Gulf and the adjacent sea was obtained during pre-monsoonal months. This is due to the partial withdrawal of the hindrance of water-mass exchange between GoK and the Arabian Sea. Maximum RT was present at the northern GoK, followed by central and south (Fig.6). Since RT of different regions could be availed as a factor of the assimilative capacity of that region, a zonation with potential risk was assessed. The Gulf is a home for 37 landing facilities in GoK including six minorports of India, which are mainly utilized as ferry and cargo operations. They facilities play crucial role in inter-state transportation (Table 3). Among these, three ports are situated at the central and northern Gulf where a very high magnitude of RT persisted throughout the year. On the other hand, even though the average RT of the southern region is comparatively lower, the Lagrangian track results elucidated that there are possibilities of water mass advection from south to north during flood tide. Thus, the discharge from industries/ports from the southern region could have an easy ingress towards the central and northern GoK during flood tide events and sooner or later would be accumulated due to the comparatively weaker ebb current. The study by Patgaonkar et al. (2012) had come across similar results where they found high RT in the northeastern region of the Gulf of Kachchh, west coast of India. They have suggested that extreme care should be taken to release industrial waste in the Gulf of Kachchh. The sediment plume and the Lagrangian connectivity of the Gulf established that even though Narmada is the major contributor to the SS load of GoK, its contribution towards the overall dynamics of the Gulf and surroundings was found to be less since the SS discharge by Narmada is concentrated in the central and northern Gulf. This result resembles the RT characteristics where the high magnitude is recorded in the Narmada region. The variability of the RT is predominantly dependent on the topography and hydrodynamics of the Gulf. The model simulation was continued for a period of one year; however, to identify the long-term trends of SS transport, the multi-annual integration time is certainly essential, which might be the future research goal. SS concentration within the Gulf brought out by the strong tidal currents in regions like Bhavnagar are not considered in the study. Also, since the flocculation and re-suspension of SS are not considered in this study, the sediment mobility might be underestimated at a few places, but the overall assessment would still be valid. In spite of the model limitations, these datasets could provide valuable information on the SS transport and RT of GoK.

6. Conclusion

The suspended sediment transport and residence time of the Gulf of Khambhat have been determined for different seasons. High residence time is recorded from almost every part of the Gulf, which makes the Gulf more turbid. The major contributor to the suspended load is river Narmada which is more than 1000 mg/l during monsoonal months, where high residence time is also observed. The Gulf retains suspended sediment inside for over a month in the central and northern regions, which could be a warning on the health of GoK. The decadal variability of the water quality parameters revealed an increasing trend, which is in agreement with the simulation results of entrapment of particles inside the Gulf.

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Table 1: Observed suspended sediment concentration of GoK

Locations	SS Concentration (mg/l)	
	Monsoon	Non-monsoon
Narmada Mouth	1200	400
Sabarmati Mouth	400	3.87
Mahi Mouth	400	2.7
Tapi Mouth	800	320
Bhavnagar	1380	554
Dahej	397	40
Vapi	-	518
Luhara	907	760

Table 2: Comparison of the status of water quality parameters with that of the earlier datasets from the coastal water of Dahej, Gujarat (Anonymous, 2011)

Water Quality Parameters	1996	2006
Mn ($\mu\text{g/g}$)	805	1347
Co ($\mu\text{g/g}$)	28	31
Cu ($\mu\text{g/g}$)	30	59
Zn ($\mu\text{g/g}$)	96	119
Hg ($\mu\text{g/g}$)	0.06	0.12
SS (mg/l)	1574	2852
Cr ($\mu\text{g/g}$)	68	103
PHC ($\mu\text{g/l}$)	12	89

Table 3. List of landing facilities in GoK

Total no. of landing facilities	Region			No. of minor ports	Region		
	North	Central	South		North	Central	South
37	6	9	22	6	1 (Dholera)	2 (Bhavnagar, Dahej)	3 (Pipavav, Jafrabad, Surat)

Figure Captions

Figure 1. Bathymetry of the study area with major locations around the Gulf. Rivers are denoted as italics. Connectivity between different areas of the Gulf is marked by colored lines

Figure 2. Suspended sediment plumes during monsoon in various phases of tide; a) spring flood, b) spring ebb, c) neap flood and d) neap ebb

Figure 3. Suspended sediment plumes during non-monsoon in various phases of tide; a) spring flood, b) spring ebb, c) neap flood and d) neap ebb

Figure 4. Monthly averaged residence time of the model domain for different months

Figure 5. Average residence time of the Gulf for different months

Figure 6. Regime of residence time and anthropogenic activities of the Gulf

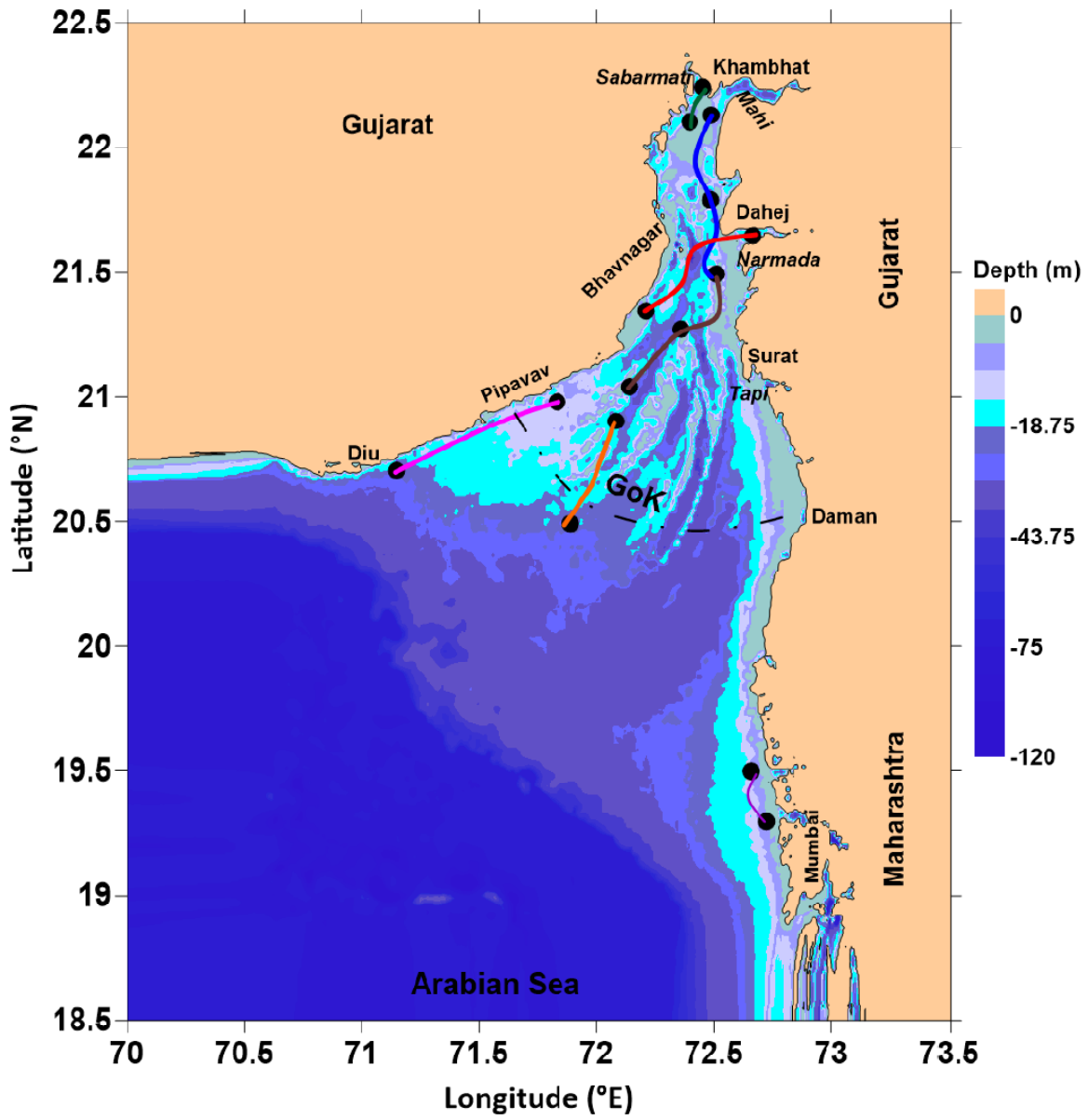


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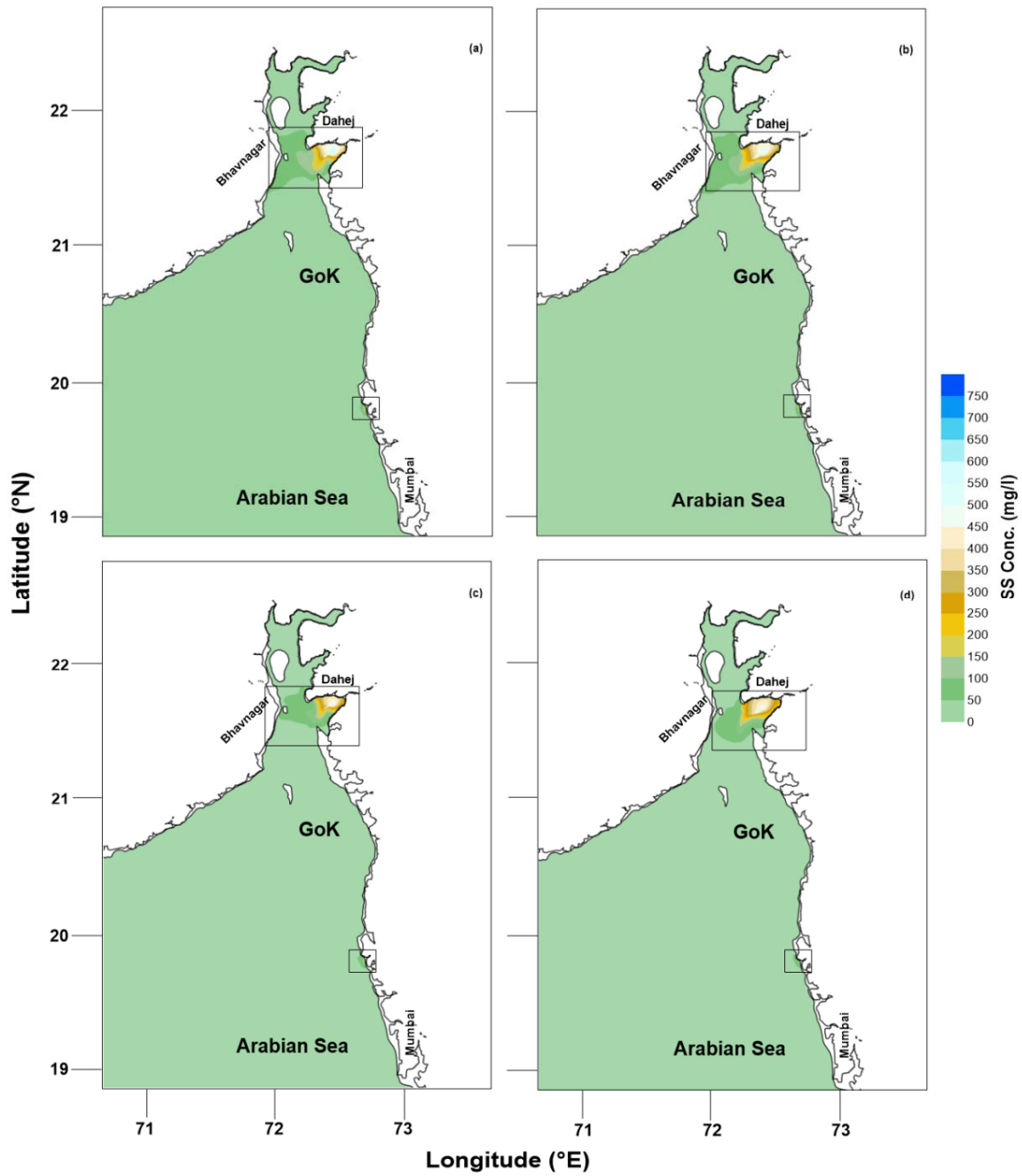


Figure 2. Suspended sediment plumes during monsoon in various phases of tide; a) spring flood, b) spring ebb, c) neap flood and d) neap ebb

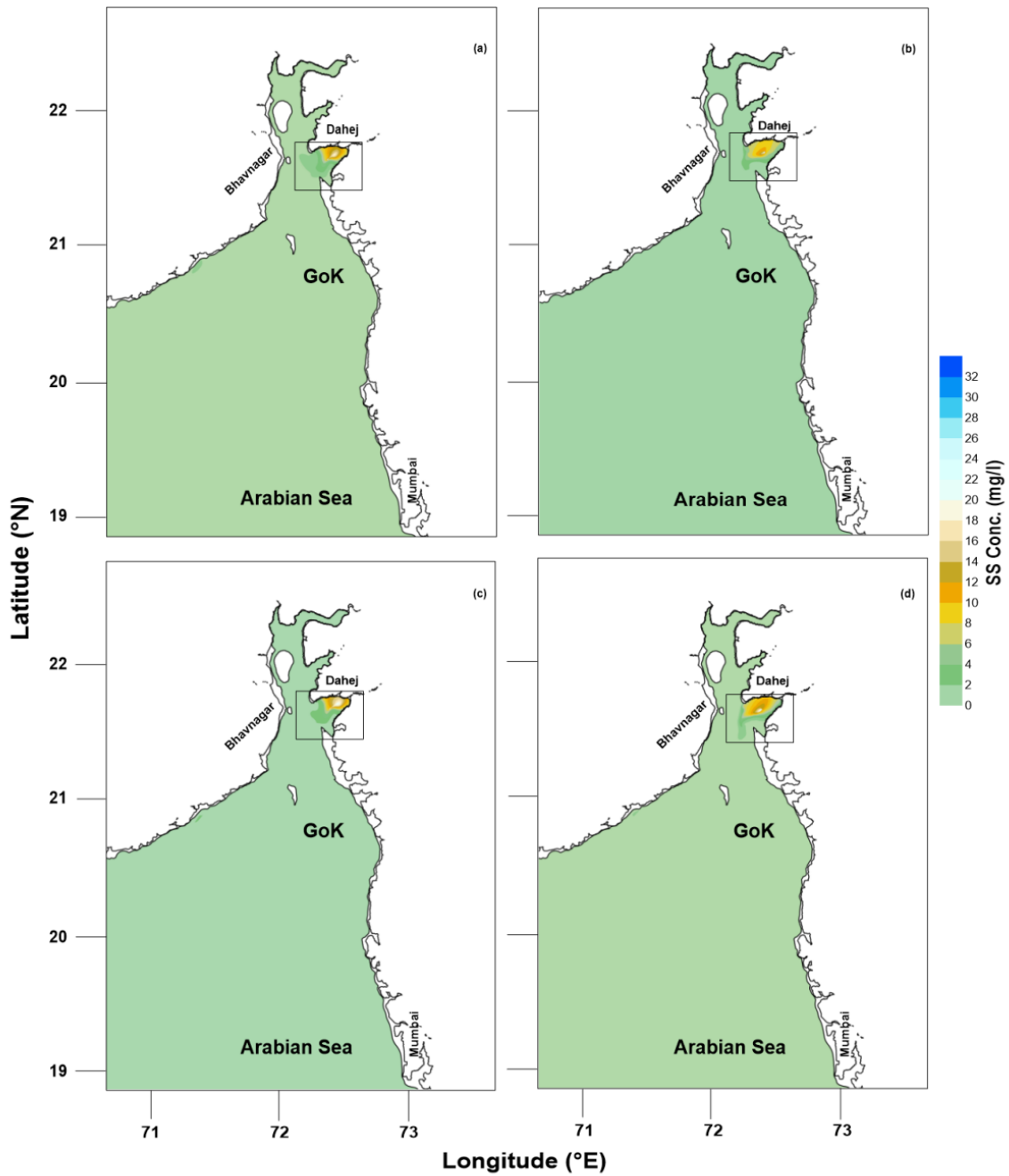


Figure 3. Suspended sediment plumes during non-monsoon in various phases of tide; a) spring flood, b) spring ebb, c) neap flood and d) neap ebb

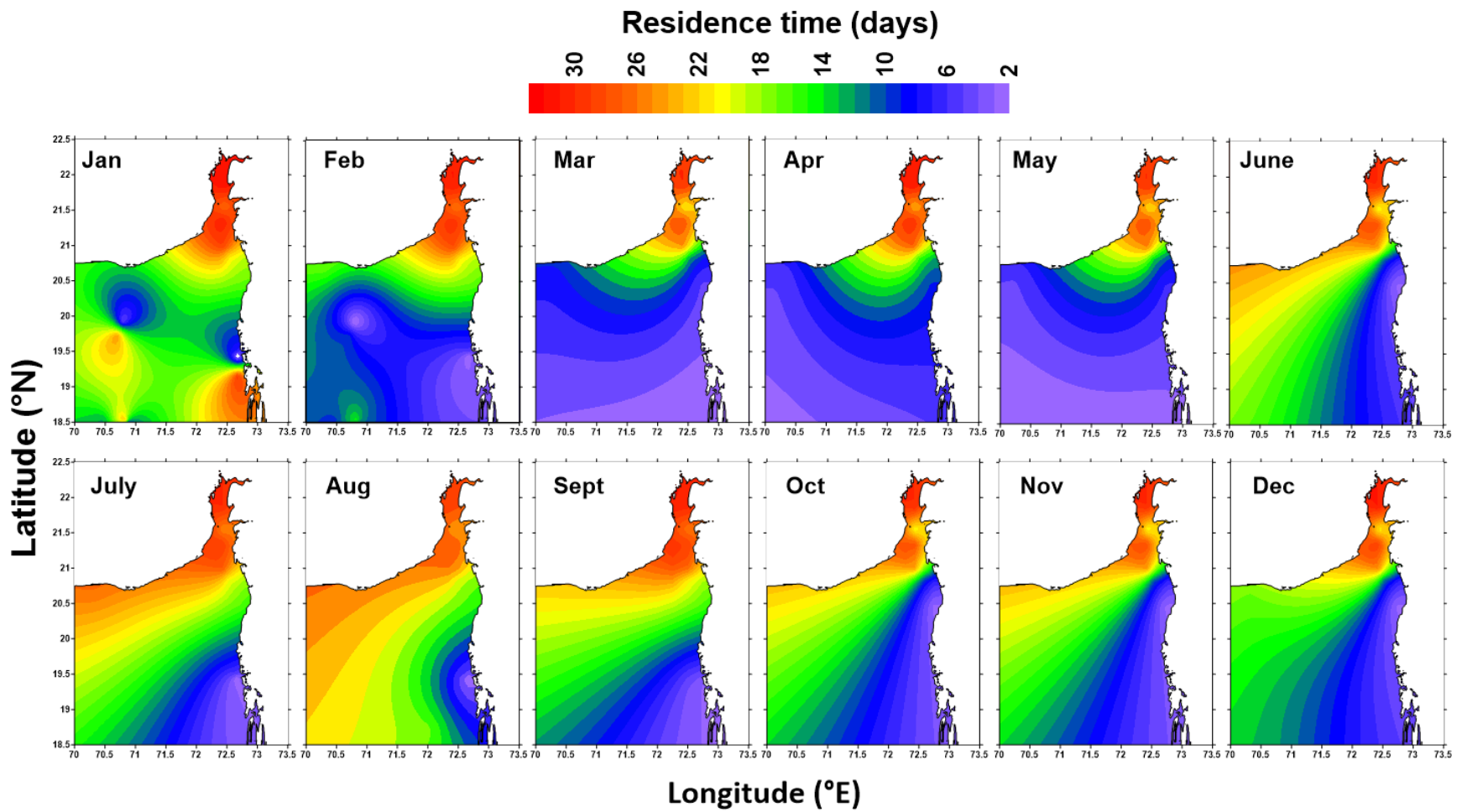


Figure 4. Monthly averaged residence time of the model domain for different months

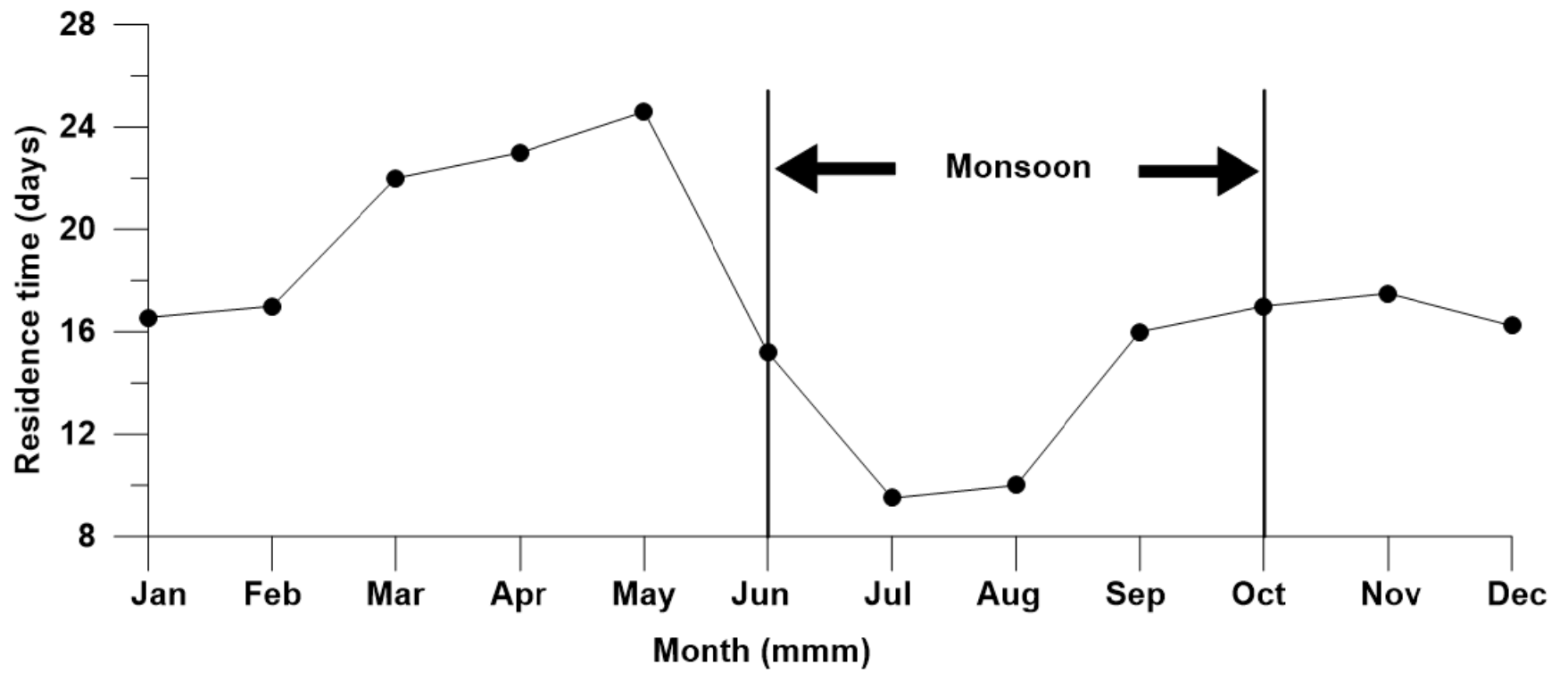


Figure 5. Average residence time of the Gulf for different months

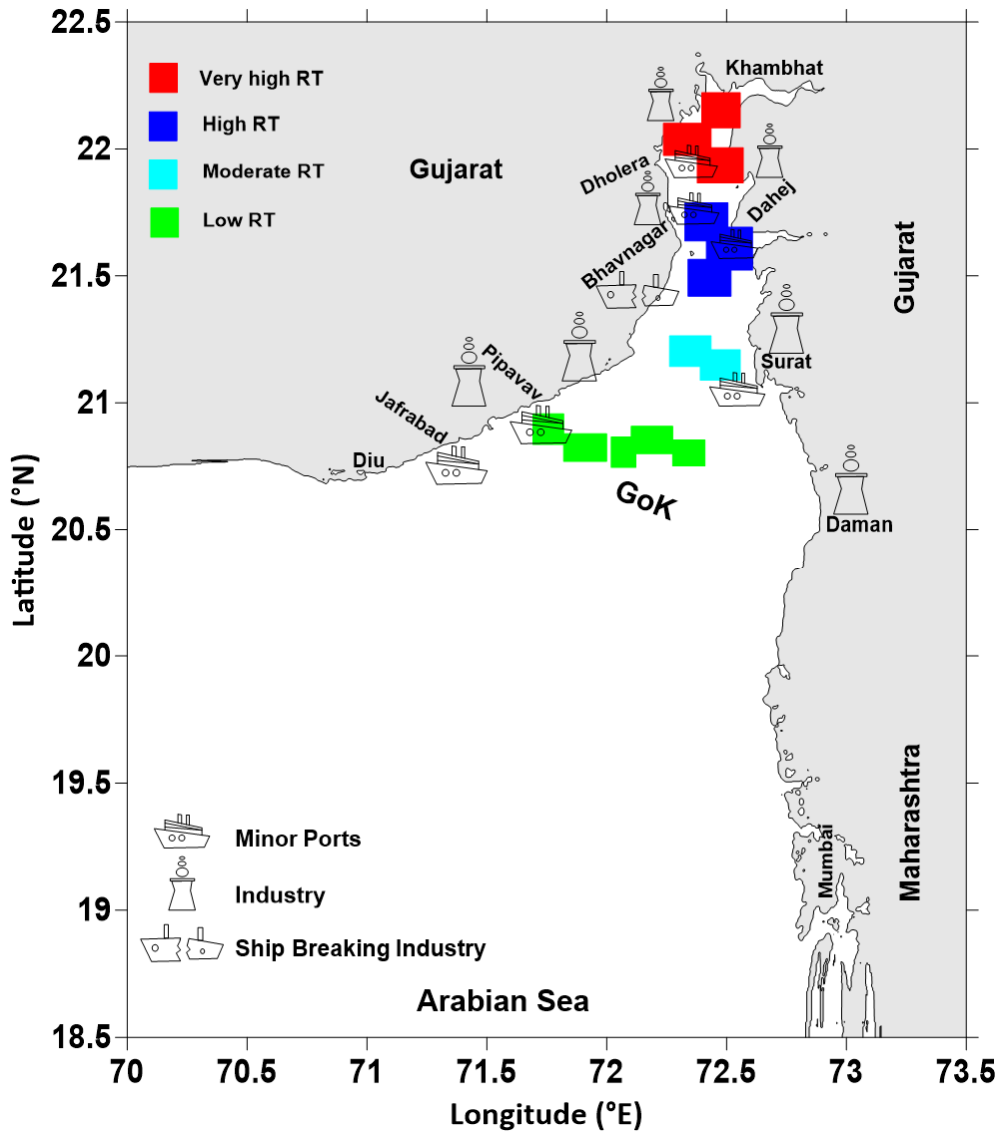


Figure 6. Regime of residence time and anthropogenic activities of the Gulf