Assessment of surface water quality during different tides and an anthropogenic impact on coastal water at Gulf of Kachchh, West Coast of India

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Abstract
The port-based activity is often associated with industrial growth in the hinterland and similar phenomenon reported from the Gulf of Kachchh, India. Industrialization exerts pressure on coastal water through the release of waste water or effluents which influence the entire marine ecosystem. The present paper tries to evaluate the variation in the water quality during the high tide and low tide in relation to the anthropogenic or natural influence in Gulf of Kachchh. The tidal variation is important as it reflects the influence of the land-based activity on the coastal waters. To prove this logic, a series of stations were taken along the coastal water and statistical analysis, viz., Pearson correlation, Box plot, hierarchical cluster analysis (HCA), and factor analysis (PCA/FA) were conducted. Pearson correlation and Box plot represent visual impact of parameter variations in respected tides. The chemometric analysis, i.e., HCA and PCA/FA, clearly indicates an anthropogenic impact on coastal water. The results of HCA revealed that major anthropogenic and domestic impacts were found at various stations during the low tide. The HCA points out that an anthropogenic and the tidal activity in the Gulf of Kachchh influence the physical water quality parameters like pH, salinity, dissolved solid, oxygen, turbidity, sulfate, and nutrients in the coastal ecosystem. The PCA/FA further ascertains the finding of HCA analysis that the state of the art of the water quality of coastal ecosystem has direct relevance with the land-based activities and sewage outfall points. Tide-based control on the water quality parameters was evident that the high tide nutrients like phosphates and nitrogen were high, while during the low tide, temperature, salinity, total solids, and sulfate showed higher concentrations. The findings of the paper will be useful for developing effective management strategies for policy makers or stakeholders operating in the coastal area.

Keywords Assessment · Anthropogenic pollution · Chemometric methods · Coastal water · Gulf of Kachchh · Tidal variation

Introduction

Water is the most essential element for the sustainability of life on earth and the establishment of human civilization near to water sources is a witness (Noori et al. 2010; Jonah et al. 2015; Sachaniya et al. 2020). In our Earth, ocean is the largest reservoir of water harnessing 97% of the total water body (Gosai et al. 2018a, b). The tides in the ocean are governed with the wind flow and the lunar movements that ultimately control the largest reservoir and coastal ecosystem. Therefore, marine ecosystem is the largest ecosystem on the earth and covers great potential of various habitats such as mangrove, coral reefs, sandy beaches, mudflats, and others. If we saw socioeconomic development of humans and coastline, that was majorly dependent on various habitats or their end products (Sachaniya et al. 2021; Gosai et al. 2022). Therefore, more attention has been given to water research and an impact of anthropogenic activity on coastal waters and dependent biota (Pejman et al. 2009; Velsamy et al. 2013; Panseriya et al. 2019; Sachaniya et al. 2019). Furthermore, excessive nutrient load led to eutrophication and impact on mangrove forest, coral reef, marine animals, microbes, seaweed, and other coastal biotic communities.
(Fallah et al. 2016; Gosai et al. 2018b). Additionally, natural aspects that cover tidal flow, sediment transport with tidal current, rain flow, and seasonal changes are also able to change microhabitat of coastal environment (Panseriya et al. 2021). The shift in the abiotic components influences the biotic component (productivity and fishing yield etc.) and finally at the ecological food web on larger scale (Praveena and Aris 2013; Sankpal et al. 2015).

In coastal environment, tide is a primary source of energy and regulates various coastal processes (Bokuniewicz and Gordon 1980). Tides also regulate biogeochemistry at spatial scale such as circulation cycle, tidal flooding, discharge, re-suspension, exchange flow, and many more (Geyer et al. 2000; Bianchi et al. 2013). Additionally, tidal regime plays a pivotal role in control of phytoplankton biomass and nutrient input into estuaries. Various sources such as agriculture, urban, rural, wastewater, and industrial discharge enter into coastal environment which are responsible for phytoplankton growth promoting nutrients. An event such as eutrophication, harmful algal blooms, and water quality deterioration occurs mostly due to over enrichment of nutrients in coastal areas (Rabalais et al. 2001). A variation in biochemical characteristics of coastal ecosystem complicates further developmental events. Hence, understanding the biogeochemical characteristic and physical processes which control chemistry and biology of coastal ecosystem is crucial for the evaluation of complex environmental issues such as biodiversity, climate change, pollution, and deforestation.

Various authors have summarized abiotic components, i.e., nutrients and other water quality parameters such as dissolved solids, oxygen demand, turbidity, and salinity which could impact on coastal water quality and dependent habitat (Tien et al. 2017; Rybak and Gąbka 2018; Semprucci et al. 2019; Lalegerie et al. 2020). Similar trends have been evaluated by its spatial behavior of abiotic components in coastal water for Gulf of Kachchh (Kunte et al. 2003; Vethamony et al. 2007; Saravanakumar et al. 2008; Bhadja and Kundu 2012; Devi et al. 2014; Gosai et al. 2018a, b; Panseriya et al. 2020, 2021; Maurya and Kumari 2021). Bhadja and Kundu 2012; Devi et al. 2014; Gosai et al. 2018a, b; Panseriya et al. 2021 revealed that various industrial activities, mining activities, geographic location, seasonal change, strong agricultural, and domestic activities are major factors contributing towards vulnerability of water pollution in the Gulf. These factors influenced abiotic parameters which control overall marine ecosystem during high and low tide. At the international level, similar studies have been reported from other parts such as east coast of Terengganu, Malaysia (Juahir et al. 2018), Queensland, Australia (Mill et al. 2006), and Sundarban mangroves, Bangladesh (Shil et al. 2014). In India, various researchers have concluded that the major factors influenced differently during low and high tide at Port Blair Bay, South Andaman (Sahu et al. 2013), Mahanadi Estuary, East Coast of India (Das et al. 1997; Acharyya et al. 2021), Gangetic Delta Region, West Bengal (Mitra et al. 2011), Mulki estuary, Southwest coast of India (Vijayakumar et al. 2000), and Bay of Bengal, India (Sourav et al. 2015). In contrast, there is no evidence of similar studies reported in west coast of India especially in gulf of Kachchh (GOK), where there is presence of rich mangrove, biodiversity and coral ecosystem.

Therefore, there is a limited knowledge on variability of tidal cycle over physical, chemical and biological variables in the Gulf of Kachchh. On this backdrop, the present study was carried out to understand the variability of different abiotic parameters in response to tidal cycle and land-based anthropogenic pressure. The main objectives of the study were (i) assessment of physico-chemical parameters to investigate tidal variation in surface water quality along GOK; (ii) extraction of key environmental indicators by hierarchical cluster analysis (HCA) and principle component analysis/factor analysis (PCA/FA) influencing water quality at GOK; and (iii) comprehensive investigation based on HCA and PCA/FA to represent susceptibility of marine biodiversity along GOK. To the best of authors’ knowledge, the present study taking into account the assessment, extraction of key environmental indicators, and water quality at various sites of GOK would be helpful to policy makers and stakeholders to design strategies for effective environmental management of coastal regions.

Materials and methods

Study area, sampling strategy, and sample collection

Study area

The study area lies in the southern coast of Gulf of Kachchh, Gujarat along the west coast of India in the Arabian Sea. The area comprises of industrial cluster that includes oil refineries and fertilizer plants, mining area, and major and minor jetties or ports covering an area of ~150 km² from 22° 28’ N 69° 04’ E to 22° 56’ N 70° 04’ E illustrated in Fig. 1. The geomorphology of gulf system has complex setup of shoals, channels, inlets, creeks, and islands, and no major river flows into it (Kunte et al. 2003). The tidal current in Gulf of Kachchh is measured at Navlakh, shows maximum tidal height of 7.2 m and tidal current measured during spring season is 1.5–2.0 m/s (Babu et al. 2005). This unique predominant tidal-driven characteristic demarcated GOK as highly energetic gulf and topographic shoaling generates high tidal flux. The coastline is dotted with industries cluster such as fertilizer, oil refinery, cement plant and thermal power plants, interspersed with ports, jetties and presence of precious Marine National Park (MNP). The effluents are released into the coastal area and previous studies indicated
impact on MNP and National Sanctuary (Kunte et al. 2003; Babu et al. 2005; Vethamony and Babu 2010). The Gulf coastline has presence of natural and anthropogenic activity overlooking and influencing each other finally impacting the ecosystem at larger scale. The health of the ecosystem with the overriding climate change prospects shifts from degenerate state to degrade state with little time for recovery (Bogan et al. 2015). Hence, it becomes enviable to conserve and maintain the precious natural resources.

**Sampling strategy and sample collection**

A total of seven monitoring stations were considered for evaluating the coastal water quality. The sampling points included S1-Okha port, S2-Pindara, S3-Salaya, S4-Dhani Beyt, S5-Narara, S6-Sikka, and S7-Rozi Beyt as shown in Table 1 and sampling was conducted between summer-premonsoon, 2016. The sampling strategy was designed to cover a wide range of study area so as to have representation of entire GOK stretching about 150 km. The study examines precisely the influence of various industries during different tidal interval on coastal water located along the GOK. The samples were collected in triplicates at each station from the intertidal zone. Three samples were collected during the high and low tide from each station. A distance of 500 m was maintained between each sampling point to obtain the best representation of contamination and water quality. Each sample from the corresponding station comprised 3 pooled samples, collected at a distance of 250 m each. Therefore, comprehensively total 9 samples were collected from each sampling station during each tide. Samples were kept in an ice container till transported to laboratory and then stored at −20 °C for further analysis.

**Sample analysis**

Water quality parameters comprised 12 variables, i.e., temperature (Temp), pH, electrical conductivity (EC), salinity, total suspended solids (TSS), total solids (TS), turbidity (Turb), dissolved oxygen (DO), 5-day biochemical oxygen demand (BOD), total nitrogen (TN), total phosphate (TP), and sulfate. Temperature, EC, salinity, and pH were
measured on the field using handy instruments like thermometer, conductivity meter, refractometer, and pH meter, respectively. Turbidity were estimated with the help of nephelometric method, whereas TSS and TS were estimated by Gravimetric method (APHA 1995). DO and BOD were estimated by Winkler’s method whereas, nutrient parameters such as TN, TP, and sulfate using spectrophotometer (Grasshoff et al. 2009; COMAPS 2012). The methods used for sampling and analysis were the standard methods as given in APHA (1995), Grasshoff et al. (2009), and COMAPS (2012).

Statistical analysis

Statistical analysis for primary water quality parameters such as mean value data transformation, Pearson’s correlation analysis, hierarchical cluster analysis (HCA), and principle component analysis/factor analysis (PCA/FA) was done using software SPSSv20.

Pearson’s correlation coefficient

Correlation coefficient ($r$) was used for statistical relationship between two variables to check significance of the models. It was considered to be more significant when the probability of significance ($p$) was less than 0.05 ($p < 0.05$). Generally, correlation coefficient was followed by Ward’s method which gave one and two tailed $p$ values (Satheeshkumar and Khan 2012; Panseriya et al. 2022).

Data treatment

Chemometric (multivariate statistical) methods require normal distribution of variables. The normality of the distribution of each variable was checked by analyzing kurtosis and skewness statistical tests before and after (log transformed data of original dataset) multivariable statistical analysis. The kurtosis and skewness statistical tests indicate that log transformed data were more suitable for normal distribution of dataset. In case of hierarchical cluster analysis and principle component analysis/factor analysis, all log-transformed variables were also z-scale standardized (the mean and variance were set to 0 and 1, respectively) to minimize the effects of different units and variance of variables for rendering the data dimensionless (Huang et al. 2011).

Hierarchical cluster analysis (HCA)

The sampling stations were located within ~ 150 km stretch and therefore HCA was used for qualitative identification of water quality contamination. The mean concentrations of each parameter were used for the similarities of the water quality along the various sampling stations in HCA analysis. The analysis was carried out using squared Euclidian distance by Ward’s method (Panseriya et al. 2020; 2021).

Principal component analysis/factor analysis (PCA/FA)

Generally, PCA/FA is used to extract variables from large datasets to investigate effect of key variables. PCA analysis explains variance in observed data using a compact structure of orthogonal variables known as principal components (PC) (Pekey et al. 2004). Before conducting PCA, the Kaiser–Meyer–Olkin (KMO) test was performed to examine the validation for the PCA. Once Kaiser’s VARIMAX rotation is performed, factor loadings remain orthogonal and are no longer directed toward maximum explained variance, and the scores are not orthogonal (Pere`-Trepat et al. 2006). Using PCA along with FA, the unobservable, latent pollution sources could be identified (Helena et al. 2000).

Result and discussion

The results of physico-chemical characteristics of water quality parameters are summarized for high and low tide in Table 2 and the description for different parameters is elaborated.


| Parameters       | S1   | S2   | S3   | S4   | S5   | S6   | S7   | S1   | S2   | S3   | S4   | S5   | S6   | S7   |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| **Salinity (ppt)** | 36.00| 45.00| 43.00| 52.00| 44.00| 38.00| 39.00| 37.00| 40.00| 44.00| 51.00| 38.00| 37.00| 39.00|
| ± 0.00           | ± 0.30| ± 0.10| ± 2.00| ± 1.00| ± 2.00| ± 1.00| ± 2.00| ± 1.00| ± 1.00| ± 2.00| ± 2.00| ± 1.00| ± 1.00| ± 2.00|
| **Temp (°C)**    | 33.60| 33.20| 34.10| 32.90| 33.60| 32.70| 33.50| 32.10| 33.00| 33.70| 33.80| 34.00| 32.70| 33.00|
| ± 0.10           | ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10|
| **pH**           | 8.24| 8.18| 8.06| 8.79| 8.70| 8.20| 8.22| 8.40| 8.20| 7.90| 8.20| 8.30| 8.30| 8.20|
| ± 0.20           | ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10| ± 0.10|
| **EC (mS/cm)**   | 4.06| 2.43| 5.69| 4.87| 5.28| 4.06| 6.09| 6.09| 3.65| 4.47| 4.47| 6.91| 6.09| 6.09|
| ± 0.02           | ± 0.08| ± 0.10| ± 0.20| ± 0.15| ± 0.20| ± 0.20| ± 0.05| ± 0.10| ± 0.20| ± 0.20| ± 0.20| ± 0.20| ± 0.20| ± 0.20|
| **DO (mgO₂/L)**  | 2.45| 1.63| 2.47| 2.46| 3.27| 1.65| 3.28| 2.47| 2.05| 1.65| 2.06| 4.49| 3.28| 3.28|
| ± 0.20           | ± 0.10| ± 0.20| ± 0.20| ± 0.20| ± 0.10| ± 0.20| ± 0.10| ± 0.20| ± 0.10| ± 0.20| ± 0.00| ± 0.30| ± 0.20| ± 0.10|
| **BOD (mg O₂/L)**| 0.19| 1.54| 0.21| 0.10| 0.16| 0.13| 0.19| 0.19| 0.35| 0.65| 0.17| 0.21| 0.17| 0.18|
| ± 0.01           | ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01|
| **TP (mg/L)**    | 23.60| 34.90| 32.60| 37.30| 32.80| 29.60| 30.90| 27.40| 30.10| 32.10| 36.0| 29.60| 30.10| 29.60|
| ± 1.00           | ± 2.00| ± 2.00| ± 2.00| ± 1.50| ± 2.00| ± 1.50| ± 2.00| ± 1.50| ± 1.50| ± 2.00| ± 1.50| ± 1.50| ± 2.00| ± 2.00|
| **Sulphate(mg/L)**| 0.38| 0.78| 0.49| 0.51| 0.58| 0.40| 0.48| 0.39| 0.63| 0.60| 0.45| 0.43| 0.43| 0.41|
| ± 0.01           | ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01| ± 0.01|
| **TN (mg/L)**    | 2.24| 5.03| 2.67| 2.68| 2.55| 6.98| 6.89| 2.18| 3.04| 2.79| 2.58| 1.88| 2.98| 3.53|
| ± 0.01           | ± 0.10| ± 0.05| ± 0.09| ± 0.09| ± 0.09| ± 0.01| ± 0.02| ± 0.03| ± 0.01| ± 0.02| ± 0.01| ± 0.01| ± 0.01| ± 0.02|
| **TSS (g/L)**    | 52.30| 68.60| 62.50| 75.80| 64.30| 81.50| 61.40| 50.70| 57.10| 59.40| 72.70| 55.10| 53.70| 55.80|
| ± 2.00           | ± 3.00| ± 1.00| ± 2.00| ± 1.00| ± 3.50| ± 2.00| ± 1.50| ± 2.50| ± 2.70| ± 1.20| ± 1.40| ± 1.80| ± 1.40| ± 1.80|
| **TS (g/L)**     | 7.00| 21.00| 4.00| 3.00| 4.00| 6.00| 12.00| 8.00| 32.00| 12.00| 5.00| 4.00| 4.00| 7.00|
| ± 0.00           | ± 2.00| ± 0.00| ± 0.00| ± 0.00| ± 1.00| ± 1.00| ± 2.00| ± 0.00| ± 0.00| ± 0.00| ± 0.00| ± 0.00| ± 0.00| ± 0.00|

Table 2 Mean value of physico-chemical characteristic of high tide (HT) and low tide (LT) at Gulf of Kachchh.
Assessment of physical, chemical, and biological variation of coastal water

Surface water temperature in all the stations fluctuated between 32.1 °C and 34.1 °C during both of the tides. The temperature difference between high tide and low tide was marginal and ranged from 32.7 °C (S6) to 34.1 °C (S3) during high tide, while it was between 32.1 °C (S1) and 34.1 °C (S5) during low tide. Only the S1 site showed the fluctuations in the surface water temperature to the tune of 1.06 °C between both the tides attributed to site geographic location viz., in the mouth of the Gulf (Shetye 1999; Kumar et al. 2015). The absence of fluctuation in the tidal temperature is because of sampling close to the open sea coastline at Arabian sea.

The pH of the water governs the chemical state of the water. In the present study, the pH of the coastal water was recorded in a range of 8.0 to 8.7 during the high tide while, 7.9 to 8.4 during the low tide. The observed pH results were similar to the previous studies in the GOK (Devi et al. 2014; EIA & EMP 2015). The electric conductivity (EC) of water is dependent on the presence of total dissolved solids. The present study, EC values ranged from 6.3 mS/cm (S2) to 9.5 mS/cm (S7) during the high tide, whereas 6.5 mS/cm (S4) to 9.9 mS/cm (S7) during the low tide. The influence of tides on conductivity was highly observed at S6 and S7, during both tides the conductivity was recorded maximum (> 9 mS/cm) throughout the study area. These two stations are located at inner gulf where the arid climatic conditions and high temperature regime are prevalent that influence the water quality.

On the temporal scale, water salinity showed negligible variations at each station during high and low tide. While, on the spatial scale water salinity values ranged from 36.0 ppt (S1) to 52.0 ppt (S4) during high tide and 37.0 ppt (S1) to 51.0 ppt (S4) during low tide. The high evapo-transpiration rate along with an absence of inflow of freshwater into the marine system has accounted for higher salinity in the Gulf. Other authors have reported similar results from the GOK (Saravanakumar et al., 2008; Devi et al., 2014; EIA & EMP 2015). The presence of high salinity at S4 indicates the release of brine from the salt pans located in the coastal region of the sampling site.

There was no significant difference in the DO values between the high tide and low tide in major stations except S1 and S6. These both stations S1 and S6 have the highest oxygen fluctuations ~ 2.03 mgO₂/L due to high tidal flux (Kunte et al. 2003). The study area S1 lies in the open sea and is under the higher influence of high tide which brings in oxygenated rich water from the sea. On the other hand, S6 lies at inner gulf where the biggest industrial cluster is established and various towns developed for the workers. The major source in the S6 was these industrial effluents and domestic input near shoreline has resulted in low DO during the low tide. Similar results also investigated by various researchers and conclude that the lower DO conditions in the coastal areas were mainly due to the anthropogenic influence or industrial activities (Vijayakumar et al. 2000; Bhadja and Kundu 2012; Devi et al. 2014). The BOD values were 1.63 mgO₂/L (S2) to 3.28 mgO₂/L (S7) during the high tide whereas, 1.65 mgO₂/L (S3) to 4.49 mgO₂/L (S5) during low tide indicated the highly dilution effect in the Gulf.

The TSS results revealed that all the stations had higher suspended solids during high tide (2.24–6.98 g/L) as compared to low tide (1.88–3.53 g/L). The sampling was conducted during the onset of monsoon due to the highly active currents. Among that, there is heavy churning of the sea bottom bringing the sediments into the water suspension. The long-shore currents are active bringing in Indus sediments into the GOK and finally exiting from the mouth of the Gulf at Okha (Nair et al. 1992). The observation revealed that the presence of high TSS at S6 and S7 (6.89–6.98 g/L) as compared to other stations (2.42–2.68 g/L) supports the earlier fact that sediment travels from east to west in the southern coastline of the GOK (Shetye 1999; Vethamony and Babu 2010).

Turbidity in study sites was recorded from 3 NTU (S3) to 21 NTU (S2) during high tide and from 4 NTU (S5&S6) to 32 NTU (S2) during low tide. Similar results were previously reported by various studies (Shetye 1999; Rasheed and Balchand 2001; Sinha et al. 2010; Masood et al. 2015). Spatial distribution showed that S2 and S3 have higher turbidity during low tide attributed to geographic location and bay-like conditions. The presence of low turbidity at S5 located in the central part of the Gulf that incidentally represents Marine National Park (MNP) justifies the occurrence of corals and various marine biota at the site (Panseriya et al. 2021).

The data of nutrient at spatial scale indicated variation in the total phosphate concentration throughout the study area attributed to distribution of industries along the GOK. The total phosphates levels were higher during the high tide (0.10 to 1.54 mg/L) as compared to the low tide (0.17 to 0.65 mg/L). Earlier Saravanakumar et al. 2008 and Srilatha et al. 2013 obtained similar results in the GOK. The result of ANOVA from high and low tide indicated that significant level is less than 0.05. Total nitrogen in the present study ranged from 0.38 to 0.63 mg/L during both tides. A similar result was also reported previously at many locations from GOK (ICZM 2013), indicative of no major input in nitrogen load. Sulfate values varied from 23.66 to 37.35 mg/L during both tides. A comparison of sulfate values among different stations showed higher concentration at S6. The presence of heavy transportation of coal and cement industry nearby accounted for the presence of higher sulfate at S6. Therefore, total sulfate and chloride ratio of the present study were
Fig. 2 Tidal variations-box plot for selected parameters for two tides (LT: low tide, HT: High tide) (DO: dissolved oxygen (mgO₂/L), BOD: biological oxygen demand (mgO₂/L), EC: conductivity (mS/cm), salinity (ppt), Temp: temperature (°C), turbidity (NTU), TSS: total suspended solid (g/L), TS: total solid (g/L), TN: total nitrogen (mg/L), TP: total phosphorus (mg/L), sulfate (mg/L)). In each box plot, the central point represents the median, the box gives the interval between the 25% and 75% percentiles, and the whisker indicates the range; moreover, circles and asterisks are also called the outliers and far outliers.
higher than the standard seawater sulfate:chlorine ratio of 1.18. The sulfate:chloride of high tide and low tide were 1.34 and 1.36, respectively. Moreover, the results indicate higher sulfate concentration could be attributed due to land-based activities especially anthropogenic sources at the coastline during summer and pre-monsoon seasons (Stromberg and Cumpston 2014).

The box plot or whisker plot is summarized and interpreted in tabular data and provides a visual impact of the location and shape of a primary distribution. The box plot results of physico-chemical parameter are illustrated in Fig. 2, which explain long whiskers at the top of the box (e.g., pH and EC box plot) and indicate primary distribution has been scattered towards high concentration. The pH, TSS, and TS in the box plot showed a visual difference between the low tide and high tide values (Fig. 2). The circles and asterisk were prominent for turbidity and sulfates indicative of a difference in the values between the stations. Turbidity represents a quantum of suspended solids present in the water as explained in the previous section, whereas the TS differed between two tides attributed to current movements. A similar observation was confirmed from the box plot method. There are coal transportation jetties close to S1 and S7, which accounted for high sulfate levels in the water column. The box plot justifies this observation and relates the influence of anthropogenic activity on the water quality during the low and high tides.

The Pearson's correlation coefficient

The correlation analysis indicates nutrients were significantly correlated during low tide as compared to high tide (Table 3). This could be due to the discharges of anthropogenic activities from industries or domestic waste bringing in high nutrients.

| Tides          | Parameters | Salinity | DO | BOD | Temp | TP | Sulfates | TN | TSS | TS | Turb |
|----------------|------------|----------|----|-----|------|----|----------|----|-----|----|------|
| High Tide (HT) | Sulfates   | .910**   | .017 | -.748 | -.507 | -.148 | .333 | 1   |
|                | TN         | .516     | -.480 | -.197 | -.004 | .866 | .638 | 1   |
|                | TSS        | .538     | -.215 | -.489 | -.750 | .016 | .605 | .110 | 1   |
|                | TS         | .420     | -.219 | -.507 | -.800 | .062 | .555 | .102 | .977** | 1   |
|                | Turb       | -.103    | -.609 | -.356 | -.113 | .912** | .087 | .687 | -.201 | -.083 | 1   |
|                | Salinity   | 1        |      |      |      |      |      |      |      |      |      |
|                | DO         | -.602    | 1   |      |      |      |      |      |      |      |      |
|                | BOD        | -.558    | .859* | 1   |      |      |      |      |      |      |      |
|                | Temp       | .582     | -.148 | .125 | 1   |      |      |      |      |      |      |
|                | TP         | .000     | -.743 | -.468 | -.053 | 1   |      |      |      |      |      |
| Low Tide (LT)  | Sulfates   | .953**   | -.527 | -.410 | .656 | -.067 | 1   |      |      |      |      |
|                | TN         | .257     | -.824* | -.605 | .272 | .842* | .230 | 1   |      |      |      |
|                | TSS        | .974**   | -.513 | -.394 | .637 | -.044 | .966* | .163 | 1   |      |      |
|                | TS         | .976**   | -.540 | -.416 | .620 | -.022 | .973** | .183 | .997** | 1   |      |
|                | Turb       | -.032    | -.733 | -.488 | -.132 | .996** | -.112 | .813* | -.083 | -.059 | 1   |

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed)
the GOK samples. The results from Table 3 indicated high physico-chemical parameter load during low tide by industrial or anthropogenic pressure. This indicates that there was low flushing of waste out of the Gulf and the presence of waste by industrial clusters will result in high nutrient concentration in the Gulf in coming years disrupting the coastal and marine ecosystem process. In the longer run, the mangroves and corals are likely to be affected by the release of industrial and domestic sewage or anthropogenic impact.

Assessment of water quality for different tide by Hierarchical cluster analysis (HCA)

The result obtained by HCA based on physico-chemical parameters classified similar groups of dendrogram into two statistically significant clusters. The HCA of the current study express tidal characteristics of coastal water quality, viz., nutrients, pH, temperature, conductivity, turbidity, TSS, DO, and BOD. The clusters obtained for both the tides were highly distinct from each other, largely due to differences in the contaminant load prevalent during the respective tide (Fig. 3).

During high tide, HCA results indicate the distribution of all the stations in two clusters, cluster I and cluster II. Cluster I have similar water quality and contains S4, S6 and S2 study zone. However, the sources of pollution differ in all these stations. The S4 receives concentrated brine discharged from salt pans, while industrial clusters and effluent discharge points represent S6. The S2 is a geographical bay, where the tidal current played a significant role. The cluster I results indicated that salinity sulfate, TSS, and turbidity were key parameters that influenced the water quality. The Cluster II results were the water quality of S3, S5, S7, and S1. The S3 receives water from the open sea and enters into estuarine of the study area which increase salinity, and DO. The S5 zone recognized as MNP which sustains corals, marine creatures, and mangroves forest. The reported higher concentration of DO is important for the aquatic life such as bacteria, fish, invertebrates, and plants. The BOD possibly received from the effluent discharge points located close by to the S5. The S7 has well-developed industrialization, fishing, transportation of coal and cement, etc. along with outlets of industrial effluents which influenced the water quality. The S1 is located at the mouth of the gulf which opens in the Arabian Sea; therefore, dilution effect is very high as described in previous studies by Shetye 1999; Bhadja and Kundu 2012.

During low tide, the HCA result generated two clusters, i.e., cluster I and cluster II. Cluster I includes S2 and S4 with similar water qualities. In which S2 is a bay condition wherein the water column contained a mixture of nutrients and litter detritus that increased the phosphate, nitrogen, and turbidity of coastal water. The field observation suggests S4 had salt pans which influenced the DO, salinity, and sulfate. Cluster II includes stations S5, S6, S7, S1, and S3. The water quality parameters such as salinity and EC observed variation in the stations S5, S6, and S7. Stations S5 and S6 were located in the inner gulf in the study area. The results indicated that domestic waste influenced S5 coastal water quality, whereas S6 is an industrial zone but most of the industrial effluents were disposed into the deep-sea through pipelines while discharges of domestic waste were near the coastline. In contrast, S7 has both contaminants from the domestic waste of Jamnagar city and industrial waste from the surrounding land area. In other stations, S1 was located at the mouth of the open sea and S3 received waste from domestic discharges, fishing activity, transport and boat construction activities. The key impacted parameters were EC, salinity, and DO during the low tide.

**Fig. 3** Dendrogram based on Ward’s clustering method showing spatial clustering between the studied sites (high tide and low tide)
The overall analysis indicates industrial pressure was on the coastal area of the Gulf of Kachchh. The present study points out that during the high tide, the effluents that are discharged into the sea return back with the water column towards the coastline. Further, land-based domestic and industrial activity contributes to deteriorating water quality during low tide.

**Assessment of water quality for different tide by Principle component analysis/factor analysis (PCA/FA)**

The results of factor analysis were separately applied to the water quality data set of high and low tide. Factor analysis includes eigenvalues, factor loading, variable loading, and total and cumulative variance and represented in Table 4. The results of the eigenvalue and scree plot were used for significant factors, whereas the factor loadings were sorted as strong, moderate, and weak according to the absolute loading values of >0.75, 0.75–0.5, and 0.5–0.3 respectively (Liu et al. 2003; Panseriya et al. 2021). Chemometric or factor loadings were illustrated in Fig. 4.

A chemometric analysis produced four significant factors with > 1 eigenvalue that explained the total variance (93.75%) of the high tide dataset. The factor 1 (PC1) indicates 29.10% of total variance which includes strong positive loading (> 0.8) of total nitrogen, total phosphate, and turbidity. Hence, PC1 comprises of a common source of nutrients due to natural tidal activity and also included with outfall of industrial waste from the deep sea. The second (PC2) explains 24.79% of total variance which includes strong positive loading (> 0.75) of salinity, pH,
and sulfate. PC2 suggests the combined effect of natural and anthropogenic activities. The PC3 explains 21.60% of total variance with strong positive loading (0.69) of DO and BOD and moderate negative loading (>0.75) of total solids. The PC3 indicates the natural scenario of the Gulf of Kachchh and is indicative of the biological activities during the summer season. During summer high evaporation rate and low inflow of water from the existing streams have ultimately affected TS and TSS. The last PC4 explains 18.26% of total variance with strong positive loading (>0.8) of EC and TSS.

Similarly, factor analysis of the low tide data set produced three significant factors that explained 80.22% of the total variance of the data set. In FA, PC1 explains 28.87% of total variance which includes strong positive loading (>0.75) of salinity, temperature, sulfate, and TS with moderate negative loading (0.56) of pH. The PC1 indicates the loadings were due to the receding water effect on the substratum, which re-suspends the bottom sediments and degrades mangrove stands. The high level of suspended solids in low tide is purely due to re-suspension of bottom and coastal eroded sediment by tidal effect. Moreover, positive loading of salinity is mainly due to brine water from salt industries near Okha, Pindara, Dhani, Sikka and Rozy (Fig. 2). The PC2 explains that 27.44% of total variance with strong and moderate positive loading (0.66) of phosphate, nitrogen and turbidity, as well moderate negative loading (0.69) of DO. The positive loading of nutrients and negative loading of DO clearly show the main source of contaminant load from land-based activities, sewage disposal, or other anthropogenic activities. The third PC3 explains that 23.91% of total variance include strong and moderate positive loading (0.64) of DO, BOD and EC. This component explained impact of anthropogenic activity on biological system of the coastal waters. The PC1 and PC2 explained industrial/domestic waste water and organic pollutants discharged near the coastal zone. The presence of high organic matter enhances the microbial activities which affects the BOD. These hydrolysis processes required for degradation of acidic material cause a decrease in pH value (Singh et al. 2005).

Several studies have been undertaken to evaluate various components that influence coastal water quality during high tide and low tide using hierarchical cluster analysis and factor analysis (Das et al. 1997, Mill et al. 2006, Mitra et al. 2011, Sahu et al. 2013, Shil et al. 2014, Sourav et al. 2015, Juahir et al. 2018, Vijayakumar et al. 2000 and Acharyya et al. 2021).

Conclusions

The present work is a study for Gulf of Kachchh to identify tidal and spatial pattern of physico-chemical parameters using correlation analysis, box plot method, hierarchical cluster analysis, and factor analysis. Tidal influence, industrial impact along with domestic waste on the water quality was assessed in this study. The results revealed that the coastal waters are highly affected with the land-based industrial development and release of effluents during the low tide. The geographical location in the Gulf of Kachchh played a major role in presence of pollution load and influenced with the tidal activity. The Pearson correlation and box plot revealed that the concentration of parameters in a reasonable boundary. The hierarchical cluster analysis grouped the sites as natural and anthropogenic input which showed similarities between sites during the tides. The major impacted parameters were oxygen, BOD, salinity, turbidity, total nitrogen, and phosphate by industrial impact or tidal variation. The results concluded that higher anthropogenic impact is observed at S4 and S2 during both tide, whereas at S6 the anthropogenic impact increase during high tide compared to low tide. Factor analysis identified natural and anthropogenic variables that impact the coastal waters such as land run-off, organic and sewage outfall. The factor analysis concluded that the major source of nutrients and other major parameters were from land run off, industrial outfall into the sea and port based activity. The factor analysis justified that physico-chemical parameters like salinity, pH, sulfate, DO, and BOD were impacted during the high tide. Whereas, during the low tide highly impacted parameters were observed as salinity, temperature, total solids, and sulfate followed by phosphate, nitrogen and turbidity were impacted. Overall, the study area showed enhanced contamination load during low tide attributed to land-based anthropogenic influence, which could be detrimental to marine biodiversity in long run. Thus, this study can be used as a foot print to develop policies and strategies for remediation of Gulf of Kachchh, west coast of India.

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Data availability The authors can confirm that all relevant data are included in the article. The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.
Declarations

Ethics approval Not applicable.

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