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RESEARCH

Evaluation of Surface Water from the Western Coast Bhavnagar, Gulf of Khambhat, Gujarat, India

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Abstract

The current study focuses on seasonal variations in coastal water along the Bhavnagar coast, Gulf of Khambhat, Gujarat, India, during three consecutive seasons (pre–monsoon, monsoon, and post–monsoon). The coastal water samples were collected from seven different locations (Ghogha, Kuda, Mithivirdi, Sosiya, Alang, Sartanpar, and Gopnath). In the designated research region, coastal water samples were collected and evaluated for water physico–chemical characteristics and heavy metals. As a result, sea surface temperature, pH, conductivity, total dissolved solids (TDS), total suspended solids (TSS), total hardness (TH), calcium hardness (Ca^{+2}), chloride (Cl^{-}), salinity, dissolved oxygen (DO), 5th –day biochemical oxygen demand (BOD), chemical oxygen demand (COD) and distribution of dissolved heavy metals (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn) were investigated at Bhavnagar coast, Gulf of Khambhat. The multivariate statistical analysis indicates that temperature, DO, BOD, COD, Cr, Co, Mn, and Fe, the natural and anthropogenic condition affects the water parameter and dissolved heavy metal. The outcome revealed a dilution effect in physico–chemical parameters and dissolved heavy metal during the monsoon season. The results indicate that anthropogenic disturbances and the growth of a range of activities with increasing point and non–point rainfall poured directly into coastal regions affect coastal water. As a result, the current study's findings may be useful to government authorities trying to safeguard the long–term sustainability of the Gulf of Khambhat.

Keywords Anthropogenic activity · Coastal water pollution · Gulf of Khambhat · Heavy metal · Hydrochemistry

Introduction

The interfaces between the land and the water are called coastal regions, and they are home to significant ecosystems and infrastructure. Around 40% of mankind lives within 100 km of coastal areas (Xiong et al. 2023). Coastal regions (including estuaries and deltas) are extremely complex settings with different hydrodynamic and bio-geomorphological contexts, as well as significant socioeconomic and ecological issues. These systems are among the most impacted by human influence as a result of urbanization and port operations, as well as industrial and tourism activities. Climate change has a direct influence on sea level, storm surge frequency and severity, and the recurrence of coastal river floods (Laignel et al. 2023). India has a coastline that stretches for over 8000 km, with nine coastal states, 60 districts, and two main island groupings where fishing provides a living for many Indian populations (Senapati and Gupta 2014). India, being a developing country, is rapidly industrializing and expanding economically. As a result, the country is dealing with climate change and pollution of the marine environment, posing health risks to marine biota and humans. Out of the nine coastal states in India, Gujarat possesses the longest coastline (about one-fifth of the country's total length), with 49 ports and businesses that support peoples livelihoods including the automotive, energy, chemical, and pharmaceutical sectors (MM&FICCI 2019; Rabari et al. 2022).

Coastal water contains more marine species than open ocean water. Water characteristic in coastal areas is an important component of marine life and its surroundings (Gray 1997; Zenati et al. 2023). Humans have a substantial detrimental

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influence on coastal and estuarine ecosystems across the world due to pollution and habitat loss. More than 80% of the sources of marine pollution are industrial, agricultural, and urban activities (Priya et al. 2023). Among the contaminants most typically found in these places are nutrients, plastic debris, metals, and persistent organic pollutants which come from both point and nonpoint sources. The ecological effects of coastal pollution include habitat and biodiversity loss, as well as changes in environmental functions and processes, which result in increased sensitivity to disturbances and a decline in ecosystem services. Aside from all of these consequences, pollution in coastal areas creates public health issues as well as significant economic losses (Bessa et al. 2018; Kanchana et al. 2023; Qian et al. 2015; Sathish et al. 2023).

Sustainable Development Goals (SDG) 14 (Life below water) is one of the UN's worldwide SDGs aimed at reducing marine pollution and its possible harmful consequences, as well as conserving marine and coastal regions and ecosystems, and is significantly interconnected with and linked to other SDGs (Xiong et al. 2023). Coastal water evaluation and monitoring is a critical and high-priority component of environmental policy (Patel et al. 2022). However, in recent years, much focus has been dedicated to studying the impact of anthropogenic activity on physico–chemical characteristics and dissolved heavy metals of the coastal waters around India to determine marine water properties and productivity (Athira et al. 2022; Hardikar et al. 2017; Kumkar et al. 2023; Naik et al. 2020; Pasumpon et al. 2023; Patra et al. 2023; Pattanaik et al. 2019; Sahoo and Swain 2023; Vase et al. 2018). The Gulf of Khambhat is also home to chemical and pharmaceutical companies, as well as Alang and Sosiya, the world's biggest ship-breaking yard, where half of the world's ships are disassembled. The main objective of the study was the assessment of seasonal variation in physico–chemical parameters and dissolved heavy metal along the Bhavnagar coast; extraction of key environmental indicators using multivariate statistical tools i.e., corelation analysis, hierarchical cluster analysis (HCA), principal component analysis/factor analysis (PCA/FA). However, to the best author's knowledge there aren't many investigations of coastal water physico–chemical parameters and dissolved heavy metal pollution in the Bhavnagar coast, Gulf of Khambhat, Gujarat, India, have been conducted. This would assist policymakers and stakeholders in developing plans for effective environmental management of studied coastal regions.

Materials and Methods

Study Area

The study area lies in the western belt of the Gulf of Khambhat, Gujarat along the west coast of India in the Arabian Sea. Bhavnagar is a coastal district in Gujarat, located at 21.7645°N 72.1519°E. The Gulf of Khambhat has an average elevation of 8 m above mean sea level. The Gulf is 130 km in length, 70 km in width, and has an average depth of 30 m (Misra and Balaji 2015). The establishment of a large number of diamond-cutting-polishing facilities, agro–based, salt–marine chemicals, cotton textile, woolen, silk, artificial thread-based, chemical, mineral-based, plastics, shipbuilding, and ship–breaking companies has taken place in the Bhavnagar district (MSME-GOI). Energy, petrochemical, agrochemical, metal–mining, auto components, textile, pharmaceutical, effluent treatment, and port industries were located on the outskirts of the research region (MM&FICCI 2019; Rai 2020). The Gulf of Khambhat is a unique tropical coastal marine habitat with a significant continental influence. The region is rich in natural variety and an important ecologically sensitive area. The industrial zone discharges either treated or untreated wastewater into the Gulf of Khambhat. Pollution from industrial effluent discharge is a major problem on the Gujarat Coast (Singh et al. 2022). On the Bhavnagar coast, Alang and Sosiya have the world's biggest shipbreaking yard, which actively dismantles decommissioned ships along the shore; the Ghogha coast has ferry services as well as relatively small ship maintenance businesses. Tourism has an impact on Mithivridi, Kuda, and the Gopanth coast, and Sartanpar is a fish landing hub. Fishing and sand extraction activities can be witnessed at all sampling locations (Table 1).

Rivers such as the Narmada, Tapi, Mahi, Sabarmati, Shetrunji, Ambika, and Purna flow from the terrestrial region and mix to form estuary deltas in the Gulf of Khambhat. The bottom depth in an upstream region of the Gulf of Khambhat ranges between 10 and 30 m. As compared to the whole Indian coastline, the Gulf of Khambhat's tidal current reaches a maximum of 10 m high during spring tide, resulting in a massive tidal current of more than 3 m/s during high tide (Gosai and Mankodi 2023). The Gulf of Khambhat shoreline has extremely dynamic climatic and environmental circumstances. The Gulf of Khambhat area is located in a semi–arid zone with a hot bioclimate, a very high average annual temperature range of roughly 12 °C, and an annual rainfall of 900 mm. In Bhavnagar, annual rainfall averaged 570 mm. The temperature in the Gulf of Khambhat varies greatly, with the lowest being around 10 °C in January and the warmest being over 43 °C in May. The Gulf of Khambhat has dry tropical monsoon climate conditions. This region's soil characteristics are primarily brackish, sandy, and saline to hypersaline, with soil that is typically blackish in colour and a muddy–clayey–silty intertidal zone (Singh et al. 2022).

Sample Collection, Analysis, and Processing

The current investigation includes seven monitoring sites for the evaluation of coastal water from the Bhavnagar coast, Gulf of Khambhat. The sampling points includes

S1–Ghogha, S2–Kuda, S3–Mithivirdi, S4–Sosiya, S5–Alang, S6–Sartanpar, and S7–Gopnath as shown in Table 1. Figure 1 depicts the location map of sampling sites. During the year 2022, a total of 63 coastal water samples (21 samples × 3 seasons) were collected during low tide 500 m apart for hydrochemistry and dissolved heavy metal evaluation of the Bhavnagar coast, Gulf of Khambhat. The study examines the influence of various industries during different seasons i.e., pre–monsoon, monsoon, and post–monsoon. The coastal water samples were collected in triplicates from all the sampling locations. The water sample bottle was properly cleansed with labolene and rinsed with distilled water before sampling. The sample bottles were stored in an ice container and transported to the laboratory (Department of Environmental Studies, The Maharaja Sayajirao University of Baroda, Vadodara) for refrigeration at – 20 °C and analyzed within 48 h. The data quality was ensured through careful standardization, procedural blank measurements, and triplicate sample analysis.

For the determination of dissolved heavy metal, the method from APHA (2012) was used. The coastal water samples were first filtered through 0.45 µm pore glass fiber filters (GF/F, Whatman), and then acidified to pH 1.5–2.0 using HNO_3. The filter coastal water sample was kept in the refrigerator until the analysis. The PerkinElmer ICP – MS NexION 2000 instrument was used for the heavy metal analysis. To achieve accurate and reliable analysis, standard solutions were produced using high–quality analytical–grade chemicals supplied from Merck and deionized water. Before usage, plasticware and glasses were thoroughly cleaned by soaking them in 14% (v/v) nitric acid (HNO3) for at least 24 h and then washing them with distilled water (Jones and Laslett 1994). After testing the blank and calibration solutions under optimal circumstances, the devices developed calibration curves automatically. Spiked coastal water samples were examined to assess the procedure's accuracy, with metal recovery rates ranging from 88 to 95%. Physico–chemical parameters of coastal water samples i.e.,

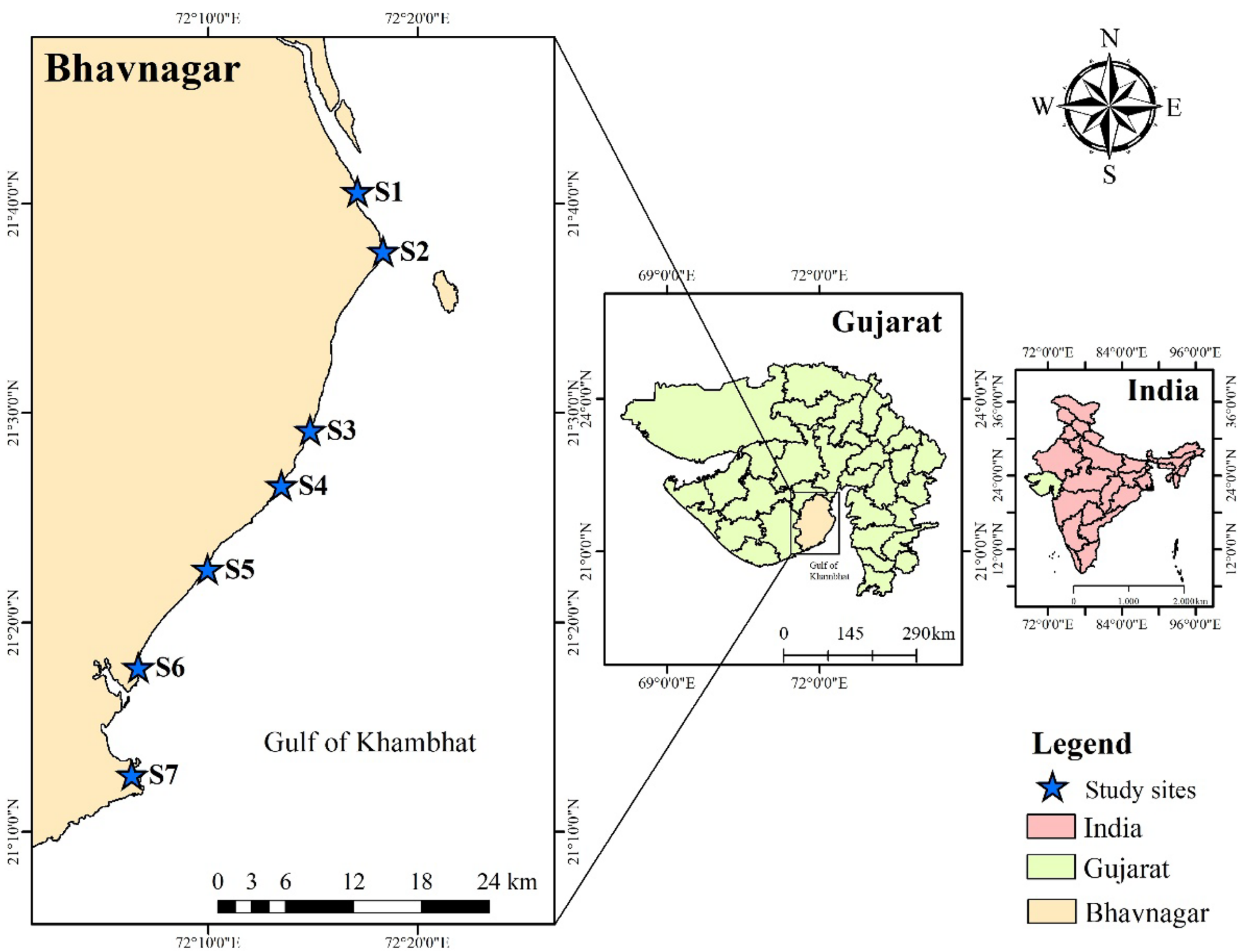

Fig. 1 Geographical distribution of the sampling sites in the Bhavnagar coastal region, Gulf of Khambhat

Table 1 Geographical location of sample sites

Site	Latitude	Longitude	On–site observation
S1	21°40’36.0"N	72°17’07.1"E	A muddy shore with ferry service, ship painting–welding, sand extraction can be seen at site.
S2	21°37’44.7"N	72°18’21.1"E	A sandy shore having tourism, sand extraction and fishing activity.
S3	21°29’11.6"N	72°14’51.2"E	Sandy shore having tourism, sand extraction, shrimp farming, fishing
S4	21°26’34.0"N	72°13’29.2"E	Rocky with muddy nature of shore having shipbreaking, tourism, sand extraction activity can be seen at site.
S5	21°22’34.0"N	72°09’58.3"E	Rocky with muddy nature of shore having shipbreaking, tourism, sand extraction.
S6	21°17’52.6"N	72°06’39.3"E	A muddy shore which having Fish landing center and sand extraction activities.
S7	21°12’44.3"N	72°06’20.5"E	Rocky with muddy shore which having tourism, fishing and domestic waste

temperature, pH, conductivity, total dissolved solids (TDS), total suspended solids (TSS), total hardness (TH), calcium hardness (Ca^{+2}), chloride (Cl), salinity, dissolved oxygen (DO), 5th –day biochemical oxygen demand (BOD), and chemical oxygen demand (COD) were all investigated. The physico–chemical parameters were analyzed as per the standard method (APHA 2012; Grasshoff et al. 1999; Strickland and Parsons 1972).

Multivariate and Statistical Analysis

The entire data set was computed using R–studio and SPSS–v23 for statistical analysis of water parameters such as descriptive statistics, correlation coefficient analysis, component analysis/factor analysis (PCA/FA), and hierarchical cluster analysis (HCA) (Abdulsalam et al. 2022; Panseriya et al. 2021, 2023). To evaluate the degree of correlation Spearmen’s correlation is used with the help of R-studio software. As this coefficient approaches its maximum value of 1, the degree to which it influences the relationship between the parameters becomes increasingly significant (Moscarelli 2023). PCA was performed using Varimax with Kaiser normalization in SPSS–v23 (Abdulsalam et al. 2022). The principal component analysis (PCA) was used to identify the key variable that influences the hydrochemistry of the Gulf of Khambhat. In HCA analysis, the mean concentrations of each parameter were utilized to compare the water quality along the numerous sampling stations. Ward’s approach was used to calculate the clustering analysis for checking interrelationships between the sampling sites (Konare et al. 2022).

Results and Discussion

Comprehensive Hydrochemistry of Coastal Water along the Bhavnagar Coast

Physico–chemical parameters are described as one of the most essential aspects capable of influencing the marine environment, with wide temporal and geographical variations. All of the physico–chemical characteristics demonstrated distinct seasonal trends, which are typical of the tropical marine environment. The current study results were compared with previous studies conducted on the Gujarat coast to understand the variation of data with their study (Table 2).

The physico–chemical seasonal fluctuation of the coastal water is depicted in Figs. 2 and 3 for all sample stations along the Bhavnagar coast, Gulf of Khambhat. The temperature fluctuated from 27 to 33 °C among all the studied sites. The seasonal variations in the average temperature of coastal water was 33.3 ± 0.5 °C, 29.24 ± 0.4 °C, and 27.7 ± 0.3 °C during pre–monsoon, monsoon, and post–monsoon, respectively (Fig. 2). A similar trend in the temperature of surface water was also reported by various researchers on the Gujarat coast (Table 2). Seasons, air circulation, evaporation, insolation, freshwater mixing, solar radiation intensity, and water currents all influence surface water temperature (Cronin et al. 2019). The pH of water is a key component in determining its feasibility for aquatic life. The pH among all the stations ranged from 8.04 to 8.74. It was discovered that seasonal variation was not significant as the average value of pH found were 8.58 ± 0.04, 8.38 ± 0.17, and 8.29 ± 0.15 for pre–monsoon, monsoon, and post–monsoon, respectively. The present study pH demonstrates an alkaline character, which is a typical feature of the marine environment around the shore. According to USEPA (1989), The pH of this study is appropriate for marine biota. Similarly, the pH range of 7.59–8.24 from the Saurashtra coastal region of Gujarat was noted by Sharma et al. (2021). Pandit and Fulekar (2017) also reported a similar pH range of 5.4–9.16 from the Gulf of Kutch, Gujarat, India.

The movement of suspended sediments and fronts is greatly influenced by tides. The Gulf of Khambhat has a wide tidal range, resulting in strong tidal currents and a mechanism for the transport of suspended sediments (Gosai and Mankodi 2023). TSS determines the state of suspended solids. In the current study, TSS levels were discovered to be in the range of 1813–2950 mg/L from all the study sites. The average TSS of the coastal water samples

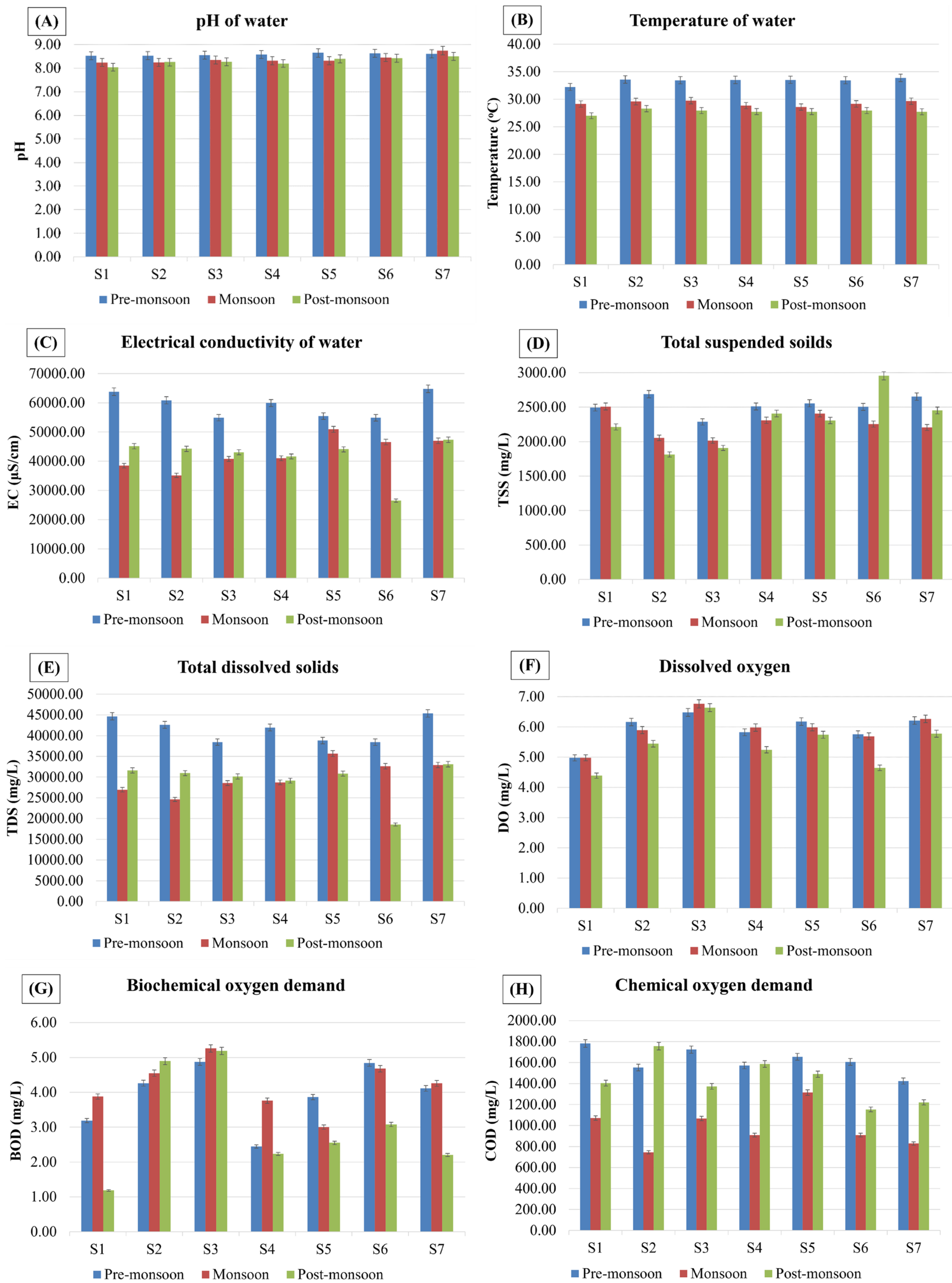

Fig. 2 Seasonal variation of coastal water parameters **A** pH, **B** Temperature, **C** EC, **D** TSS, **E** TDS, **F** DO, **G** BOD and **H** COD at study sites

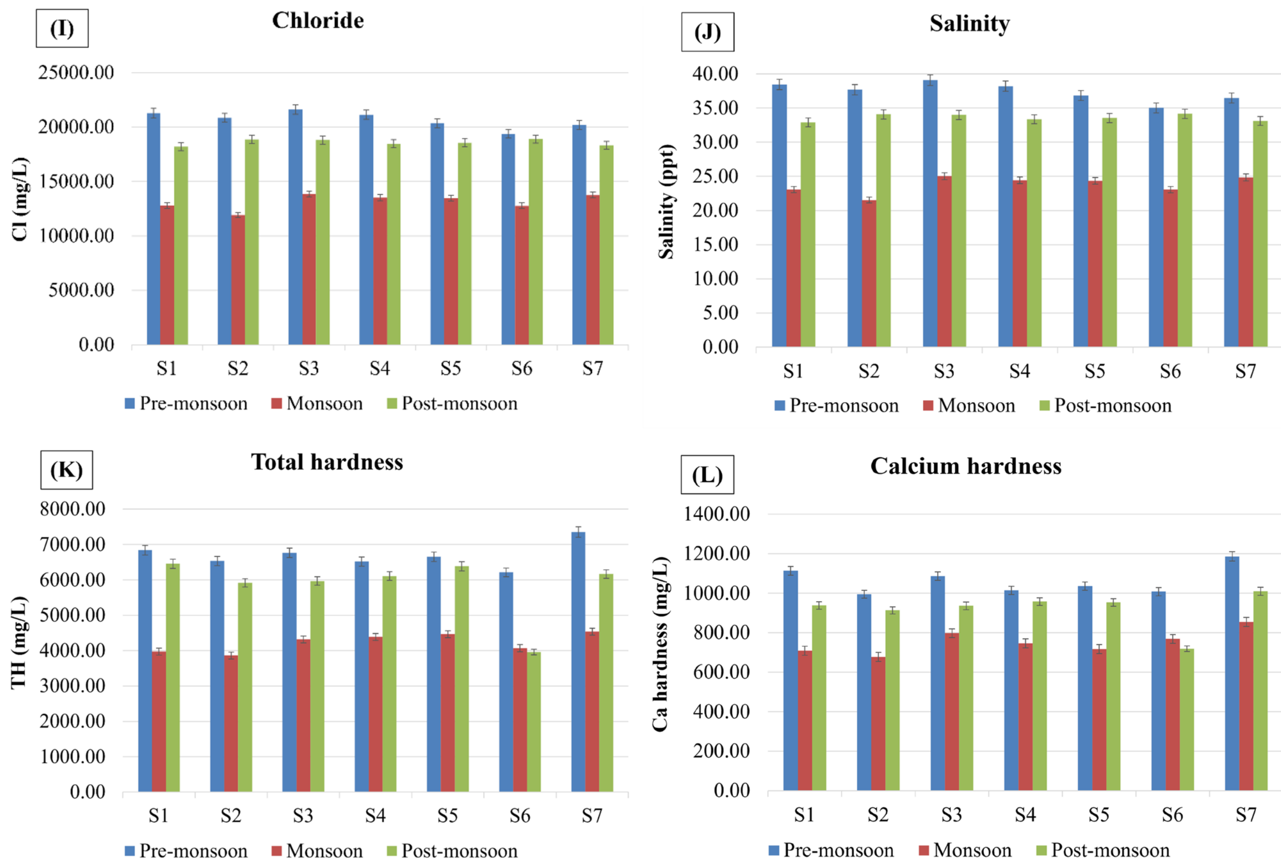

Fig. 3 Seasonal variation of coastal water parameters **I** Chloride, **J** Salinity, **K** TH, **L** Ca hardness at study sites

varied from 2528.0 ± 130.5 mg/L, 2250.8 ± 178.2 mg/L, and 2294.1 ± 379.1 mg/L during pre–monsoon, monsoon, and post–monsoon, respectively. A similar result was also reported by researchers along the Gujarat coast which at the ASSBY coast of Bhavnagar Patel et al. (2014) reported a TSS level of 4000–70,000 mg/L and at Diu coast Patale and Tank (2022) noted 400–2500 mg/L. TDS levels ranged from 18,000 to 45,000 mg/L across all research stations. The average TDS results were found to be 41460.4 ± 2957.9 mg/L, 30002.0 ± 3856.8 mg/L, and 29207.5 ± 4852.7 mg/L at pre–monsoon, monsoon, and post–monsoon, respectively. The variation in TDS may be due to the tidal activity along the coast. On the Gujarat coast, Sharma et al. (2021) reported 37,900 mg/L TDS level at the Somnath coast and 38,800 mg/L at the Dwarka coast from Saurashtra coastal region. The elevated TDS in coastal water samples may be suspected to be a result of direct influence of seawater.

The variation in salinity and total dissolved solids (TDS) have a significant impact on the electrical conductivity of water (Maliki et al. 2020). The measurements of electrical conductivity varied between 26,000 and 64,000 µS/cm. The average electrical conductivity readings along the Bhavnagar coast ranged from 59229.2 ± 4225.6 µS/cm, 42860.0 ± 5510.8 µS/cm, and 41,725 ± 6932.5 µS/cm during pre–monsoon, monsoon, and post–monsoon, respectively. Pre–monsoon had the highest average conductivity levels at the majority of the research sites, whereas post–monsoon had the lowest average conductivity values at all of them. The elevated anthropogenic activity during the pre–monsoon season may be the cause of the high conductivity levels (Clifford et al. 2021). Similar results were reported by researchers on the Dahej coast, Diu coast, and Dumas coast of Gujarat (Table 2). The investigation carried out by Zheng et al. (2018) on seawater, noted a conductivity range of 30,000–60,000 µS/cm, and Tyler et al. (2017), observed the EC 33,100 ± 2300 µS/cm, respectively.

The capacity of water to precipitate insoluble calcium and magnesium salts of different acids from solutions is measured as total hardness. The most frequent cations that cause hardness are calcium, magnesium bicarbonate, carbonate, chloride, and sulphates (Boyd 2015). The hardness levels fluctuated from 3800 to 7100 mg/L at all the sampling locations. The average total hardness level of 6697.3 ± 353.9 mg/L, 4231.0 ± 261.5 mg/L, and 5851.8 ± 857.4 mg/L was reported for pre–monsoon, monsoon, and post–monsoon, respectively. The calcium

Table 2 Comparison of physico–chemical parameters with other studies in the Gujarat region

Parameters	Bhavnagar coast	Gulf of Kutch	Dahej coast	Dumas coast	Diu coast	Gulf of Kutch	ASSBY coast
pH	8.04–8.74	7.90–8.79	7.88–7.97	7.71–7.87	7–9	7.9–8.6	–
Temp (°C)	27.73–33.88	32.70–34.10	29.42–30.74	26.40–30.58	22–37	24.7–33.9	22–40
EC (µS/cm)	26,512–64,807	6300–9900	38,630–39,740	38,800–40,200	13,000–34,000	3300–9700	–
TSS (ppm)	1813–2955	1880–6980	–	–	400–2300	400–5200	4000–70,000
TDS (ppm)	18,558–45,365	48,520–74,520	22,970–28,680	24,000–25,360	1500–8200	45,300–71,600	34,000–42,000
Ca (mg/L)	677–1185	–	–	–	3–11	–	–
Cl (mg/L)	11,913–21,625	–	24,960–28,260	6800–10,810	–	–	–
Salinity (ppt)	21.52–39.07	36–51	23.22–26.94	15.42 – 25.48	–	36.5–52	–
DO (mg/L)	4.39–6.76	2.43–6.91	4.42–6.25	3.29–7.23	5–22	3–11.7	–
BOD (mg/L)	1.18–5.26	1.63–4.49	10.17–12.93	3.11–15.25	2–15	1.8–7.3	870–3160
COD (mg/L)	745–1782	–	107–317	92–354	40–350	–	1690–7000
Reference	*	a	b	b	c	d	e

*Present study

[a]Panseriya et al. (2023)

[b]Singh et al. (2022)

[c]Patale and Tank (2022)

[d]Panseriya et al. (2021)

[e]Patel et al. (2014)

concentration ranged from 677 mg/L to 1185 mg/L. average calcium content of 1062.7 ± 69.4 mg/L, 752.7 ± 60.1 mg/L, and 917.69 ± 92.7 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. Lower concentrations during the monsoon season are affiliated with the dilution effect caused by stream discharge into the ocean (Harrison and Elsworth 1958). Comparable research carried out by Bhadja and Kundu (2012) of Dwarka coastal water, Gulf of Kutch, Gujarat found a total hardness of 5702.5 mg/L and calcium hardness of 422.5 mg/L, respectively. Patale and Tank (2022) found 3–11 mg/L calcium hardness from Diu coastal water of Gujarat. Increased temperature during the summer due to high evaporation might be linked to a rise in the content of calcium, magnesium, and other salts, triggering the hardness of the surface water (Jayakumar et al. 2013).

The Bhavnagar district is well known for salt production contributor in Gujarat state of India (Rakhasiya et al. 2023). The chloride levels measured in this study varied from 11,913 to 21,625 mg/L among all the stations. The average chloride levels were 20692.2 ± 765.7 mg/L, 13150.3 ± 697.8 mg/L, and 18591.4 ± 276.3 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. Seasonal variations in chloride levels are discernible, which might be attributed to natural processes such as water moving through natural salt deposits in the ground, weathering formations, and pollution from household use (Abbasnia et al. 2019; Allan 1995). The salinity levels varied from 28 to 39 ppt. The average salinity levels were 37.3 ± 1.3 ppt, 23.7 ± 1.2 ppt, and 33.59 ± 0.4 ppt during pre–monsoon, monsoon, and post–monsoon, respectively. In contrast to the monsoon and post–monsoon seasons, considerable salinity was seen during the pre–monsoon season. A significant quantity of freshwater intrusion happens during the monsoon season, which lowers the saline level of coastal water. Similarly, previous research conducted by Sharma et al. (2021), reported 32.3–35.5 ppt salinity of coastal water at Okha Port, Saurashtra coastal region of Gujarat.

The traditional and widely used indicator for the health of the aquatic environment is dissolved oxygen. In the present study, DO varied from 4.39 to 6.76 mg/L for all the seven locations. The average DO seasonal variation was not significant as the average value of DO were 5.9 ± 0.4 mg/L, 5.8 ± 0.5 mg/L, and 5.4 ± 0.7 mg/Ls for pre–monsoon, monsoon, and post–monsoon, respectively. According to Akkajit et al. (2018), oxygen levels of 1–6 mg/L could support the growth of marine organisms. Freshwater intrusion through heavy rainfall or photosynthetic processes by phytoplankton in the coastal water could be a possible reason for a higher dissolved oxygen concentration in coastal water (Hammer et al. 2019). Singh et al. (2022) reported a similar range of DO concentration (4.21–6.56 mg/L) in coastal water in the Gulf of Khambhat region, Gujarat. An earlier study carried out by George et al. (2012) noted DO of 0.1–12.3 mg/L along the Tapi region, Gulf of Khambhat, Gujarat. Many variables impact BOD, including pH, temperature, chemical composition, salinity, incubation period, and oxygen availability (Chaudhuri et al. 1992). BOD levels ranged from 1.18 mg/L to 5.89 mg/L across all locations investigated. The average value of BOD was 3.9 ± 0.8 mg/L, 4.2 ± 0.7 mg/L, and 3.0 ± 1.4 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. This fact is supported by Pandya et al. (2022), who reported a 4.8 mg/L BOD value from the Zanzmer coast, Gulf of Khambhat, Gujarat.

The chemical oxygen demand (COD) varied significantly between 745.44 and 1782.04 mg/L for all the sites. The average value of COD were 1616.3 ± 118.0 mg/L, 977.9 ± 189.4 mg/L, and 1426.1 ± 207.6 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. This fact is also supported by Patel et al. (2014), who reported COD values varied between 1690 and 7000 mg/L in coastal water from ASSBY, Bhavnagar coast, Gujarat. Likewise, a study by Patale and Tank (2022) reported 40–350 mg/L COD levels from Diu coast water, Saurashtra coastal region of Gujarat. Increased COD values might be attributed to the Gulf of Khambhat's difficult hydrodynamics and the potential expansion of several industries such as petroleum, fertilizer, tanning, chemical, cement, steel, gas, oil, ship–breaking, and textile. Companies on both sides of the Gulf of Khambhat discharge huge amounts of treated wastewater into the sea (Gosai and Mankodi 2023). The diluting impact of ions brought on by heavy seasonal rainfall may be the source of the reduced concentration of COD during the monsoon season as compared to the pre–monsoon, and post–monsoon periods.

Distribution of Dissolved Heavy Metal in Coastal Water

The seasonal dissolved heavy metal concentrations trend of coastal water is shown in Fig. 4. The average concentration of dissolved heavy metal among all the sites ranked in the following decreasing order Pb > Cr > Ni > Co > Fe > Cd > Mn > Cu > Zn. The reported concentration of dissolved heavy metal in seawater in studied sites was compared with other regional studies documented in Table 3. In comparison to the monsoon season, the dry season (pre–monsoon & post–monsoon), exhibited higher amounts of dissolved heavy metal in the coastal water. Anthropogenic activities increase during the dry season, which causes a larger build–up of heavy metals in water. However, the dilute impact of freshwater incursion during the wet season leads to a lower amount of heavy metal during the monsoon season (Zhang et al. 2010).

Lead (Pb) concentration among sampling sites, ranged between 0.34 and 0.66 mg/L. The average concentration of Pb was 0.54 ± 0.03 mg/L, 0.46 ± 0.09 mg/L, and 0.41 ± 0.14 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. The concentration of Pb is greater than the acceptable limit. Pb is a nonessential component for animals and plants. It is an accumulative contaminant for the living organism. Pb can be transferred

Table 3 Comparison of dissolved heavy metal concentration with other studies (mg/L)

Region	Ni	Cu	Mn	Cr	Pb	Zn	Co	Cd	Fe
Bhavnagar coast, India*	0.262	0.033	0.048	0.360	0.471	0.028	0.163	0.055	0.145
Sitakunda coast, Bangladesh[a]	0.098	0.176	1.19	0.156	0.078	0.782	0.043	0.005	11.77
Chittagong coast, Bangladesh[b]	0.049	0.288	0.203	0.233	0.099	0.289	–	0.049	1.198
Southern coast, Malasiya[c]	0.347	0.093	–	–	0.18	0.067	–	0.087	0.849
Cuddalore coast, India[d]	0.004	0.004	0.022	0.001	0.012	0.014	0.0008	0.0004	1.021
Dingzi bay, China[e]	–	0.002	–	0.004	0.001	0.023	–	0.0003	–
Nellore coast, India[f]	5.62	10.2	16.3	23.4	3.24	11.9	1.46	4.78	391.6
EG coast, China[g]	–	0.0022	–	0.0012	0.0019	0.014	–	0.0001	–
Coastal zone, Belgian[h]	–	0.003	–	–	0.0001	0.012	–	0.0002	–
Saronikos coast, Greece[i]	–	0.0028	–	–	0.0028	0.004	–	0.0003	–
BIS[j]	0.02	0.05	0.1	0.05	0.01	5	–	0.003	0.3

*Present study
[a]Hasan et al. (2023)
[b]Islam et al. (2021)
[c]Yap et al. (2011)
[d]Jonathan et al. (2008)
[e]Pan et al. (2014)
[f]Jha et al. (2019)
[g]Zhang et al. (2015)
[h]Gao et al. (2013)
[i]Ladakis et al. (2007)
[j]BIS (2012)

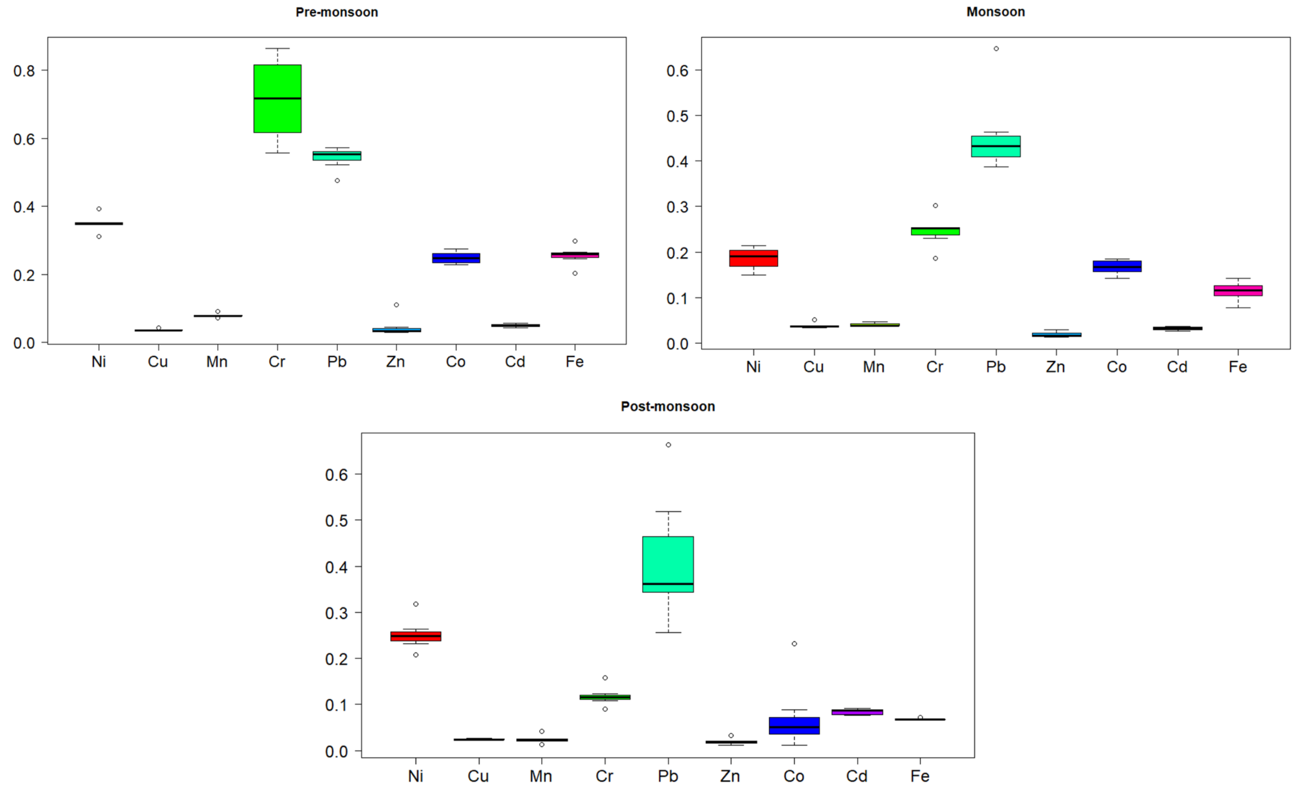

Fig. 4 Seasonal variation of dissolved heavy metal concentration in coastal surface water (mg/L)

via sediments in water and gets precipitated in sediments. Pb has been potentially hazardous to most living organisms (USEPA 1986). The high concentration of Pb in the coastal water might be attributed to the paint and repairing activity of ships at the coast and the release of industrial waste. Considering chromium (Cr) dissolved Cr concentration in water ranged between 0.09 and 0.86 mg/L which was higher than the acceptable limits at all the sites. The average concentration of Cr was 0.72 ± 0.12 mg/L, 0.25 ± 0.03 mg/L, and 0.12 ± 0.02 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. During the sampling period, we observed waste material such as metal ceramics, chrome plating, shiny finish in dye and paint, etc. in the shipbreaking area at the coast of S4 and S5. Cr inputs to the seas are predominantly particulate (river–suspended solids and aerosols). Chromium cycling occurs in the water column as a result of nutrient biogeochemistry (Richard and Bourg 1991).

Nickle (Ni) levels in the water at all sites ranged from 0.14 to 0.39 mg/L. The average concentration of Ni was 0.35 ± 0.02 mg/L, 0.19 ± 0.03 mg/L, and 0.25 ± 0.03 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. Ni levels were higher than BIS standards. The study by Tokatli (2019) and Aydin et al. (2021) suggests that Ni could be associated with sewage sludge, paint – dyes, old batteries breakdown, use of fertilizers, and industrial effluents. The cobalt (Co) concentration in coastal water was noted to be 0.011–0.275 mg/L among the study sites. Co average concentration were 0.25 ± 0.02 mg/L, 0.17 ± 0.02 mg/L and 0.07 ± 0.07 mg/L for pre–monsoon, monsoon and post–monsoon, respectively. Co is present in Earth's crust naturally and is an essential element to fish and other aquatic organisms (Blust 2011). Cadmium (Cd) in the range of 0.026 to 0.090 mg/L in water which is higher than the acceptable limits at all the studied sites. Average Cd concentrations were 0.05 ± 0.004 mg/L, 0.03 ± 0.004 mg/L, and 0.08 ± 0.006 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. The weathering of crust, sewage sludge, ship repairing, agricultural runoff, and industrial effluent releases Cd in soil and aquatic systems (Hutton 1983; Sheppard et al. 2009).

Copper (Cu) ranged from 0.02 to 0.05 mg/L. Cu average concentrations were 0.04 ± 0.003 mg/L, 0.04 ± 0.006 mg/L, and 0.02 ± 0.002 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. Cu concentration in water was found to be within the standard range at sites S2 – S7. Whereas, at S1 site Cu concentration was reported to be slightly higher during post–monsoon season. Elevated Cu could be related to the painting activity and electrical operations for breaking the ships taking place toward the coast. Cu is a common element present in the environment but it has a toxic effect on a living organism (Fatoki et al. 2002). Zinc (zinc), Mn (manganese), and Fe (iron) are the essential micronutrients for most living organisms. These micronutrients can be found in nature in Earth's crust and are involved in metabolic and cellular functions (Hänsch and Mendel 2009). The range of these micronutrients during the study varied as follows 0.01 – 0.11 mg/L for Zn; 0.01 – 0.09 mg/L for Mn; and 0.06 – 0.29 mg/L for Fe among all the researched sites, respectively. Zn average concentrations were 0.04 ± 0.03 mg/L, 0.02 ± 0.01 mg/L, and 0.02 ± 0.01 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. Mn average concentrations were 0.08 ± 0.01 mg/L, 0.04 ± 0.004 mg/L, and 0.024 ± 0.009 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. Fe average concentrations were 0.25 ± 0.03 mg/L, 0.11 ± 0.02 mg/L, and 0.07 ± 0.002 mg/L for pre–monsoon, monsoon, and post–monsoon, respectively. The concentrations of Zn, Mn, and Fe were found to be within permissible limits in all the studied regions. During our field survey, we observed fish catching, fish landing centers, the presence of tourists, boat activities, shrimp pond farms, and shipbreaking industries. Thus, the elevated level of heavy metals is seen in the studied region. The greater concentrations of heavy metal in the research areas might be attributed to agricultural runoff, sewage, painting, chemical industry, and shipbreaking activities (Ali et al. 2022; Basha et al. 2007; Hasan et al. 2023).

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Multivariate and Statistical Tool

Correlation Coefficient among Coastal Water Parameters

The correlation coefficients were calculated between physico–chemical parameters and dissolved heavy metal to distinguish the interdepended of a studied variable. Figure 5 represents the correlation chart of coastal water of all the studied sites. Overall, temperature shows a strong positive correlation with TDS (r = 0.8), EC (r = 0.8), Mn (r = 1.0), Cr (r = 1.0), Co (r = 0.8), and Fe (r = 1.0). As the temperature rises, ion dissolution occurs, resulting in positive correlation. DO and BOD exhibited a positive correlation, which is due to the churning and oxygen mixing that occurs during high tide. COD had a significant correlation with TH (r = 0.8), Ca (r = 0.8), Cl (r = 0.9), and salinity (r = 0.9) respectively. The presence of industry near the shore and its outskirts is the primary source of inorganic waste, which results in excessive BOD, COD, and dissolved heavy metals. The geological components that contain chloride create a high concentration of Cl. The high concentration of Cl indicates high contamination of sewage water, some industrial waste, tides, or any saline water, all of which have a negative impact (AL-Saad et al. 2015). The fact that dissolved heavy metals Cr and Mn exhibited a positive link with Pb, Zn, Co, Ni, and Fe suggested that these heavy metals may have a common source in the coastal region. However, in this study, there were typically positive relationships between dissolved metals and physicochemical factors in coastal water. The connections between heavy metals and physico–chemical parameters were influenced by the chemical properties and migratory forms of the elements, as well as fluctuations in the parameters in situ (Zhang et al. 2015). In the current study, externally driven dissolved heavy metal inputs (terrestrial, anthropogenic, sedimentary) proved to be more relevant than hydrography and natural processes (Gavriil and Angelidis 2005).

Exploration for a Latent Contaminant in Seawater Using Principal Component Analysis

In this study, R–mode factor analysis (Varimax rotation with Kaiser normalization) was performed for principal component analysis. Factor analysis results produced four components that explained the total variance of

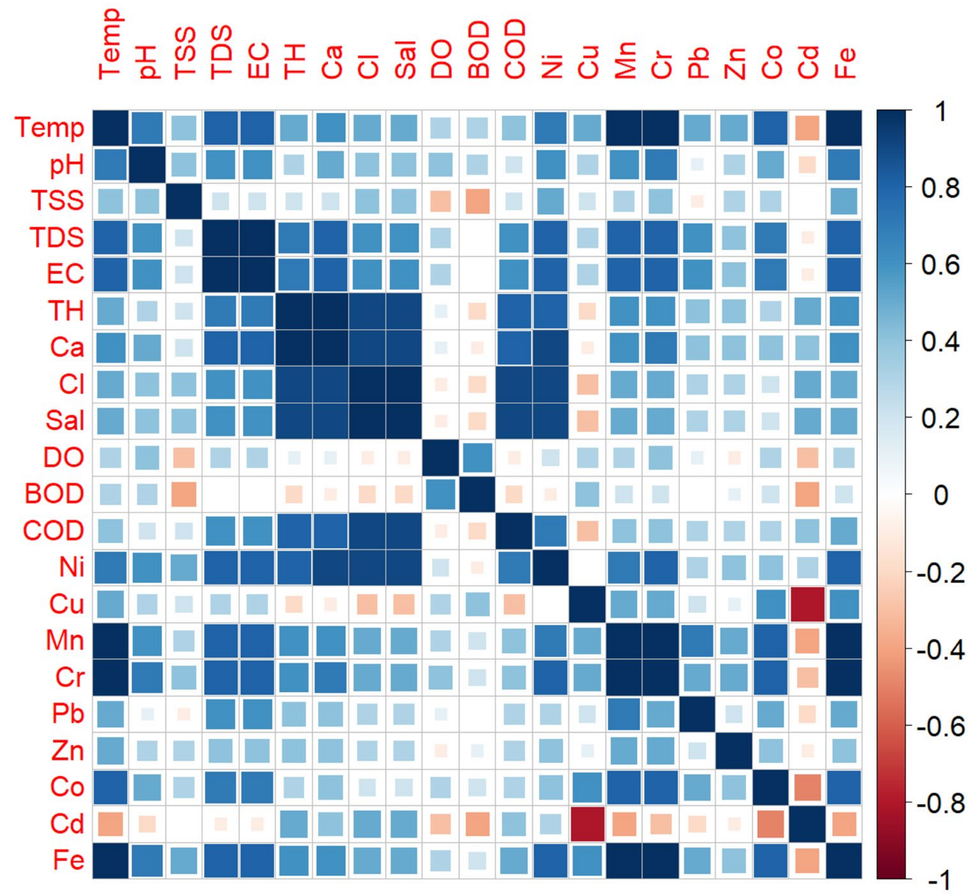

Fig. 5 Pearson correlation coefficient of seawater along the Bhavnagar coast

86.48% (Table 4). **Factor 1** accounts for 37.88% of the variance with strong positive loading of TH, Ca, Cl, Sal, COD, and Ni; and moderate positive loading of TDS and EC. Ions (Ca, Cl) correlated significantly with each other and with COD, suggesting a common source. Positive loading of COD represents anthropogenic impact (Xu et al. 2020). This component could be related to water evaporation and water runoff in the area. **Factor 2** explains 32.63% of the variance with the positive loading of Cu, Mn, Cr, Co, and Fe; and moderate positive loading of TDS, EC, Pb, and Zn. Correlation between heavy metals i.e., Cu, Mn, Cr, Co, Fe found to be significant from the correlation matrix suggests the common source of origin. TDS and EC had a positive significant correlation ($r = 1.0$). This component explains the waste source from anthropogenic activity at the coast and industrialization towards the periphery for dissolved solids and dissolved heavy metals in coastal surface water. **Factor 3** is responsible for 9.35% of the variance with positive loading of the DO and BOD. A significant positive ($r = 0.6$) correlation was found between DO and BOD. DO positive loading related to the warm temperature condition of the study site. DO is a natural process that is affected by tides in coastal water (Pastore et al. 2019). Positive loading of BOD suggests a high loading of dissolved organic matter (Wu et al. 2009) end up in coastal water due to industrial effluent, agricultural activity, and domestic wastewater. Factor 4 contributes 6.6% of the variance with moderately positive loading of pH and TSS. A moderately significant positive correlation was found between pH and TSS ($r = 0.4$). Positive loading of TSS is significantly correlated with soil weathering and subsequent runoff (Singh et al. 2005). This fact is also supported by the study carried out by Ajorlo et al. (2013).

Cluster Analysis

The physico–chemical characteristics of dissolved heavy metal, and anthropogenic/natural inputs of the studied coastal waters have been evaluated using cluster analysis. Employing Ward's technique and Euclidean distances, the HCA was applied to the standardized data set (Zhou et al. 2007). The samples with the highest degree of similarity were first categorized, and then groups of samples were linked together using a linkage rule. The process was repeated until all observations were categorized (Shrivastava et al. 2018). The dendrogram

Table 4 R–mode varimax sorted factor analysis of physico–chemical parameter and dissolved heavy metal of coastal water

Variables	Component			
	Factor 1	Factor 2	Factor 3	Factor 4
Temp		**0.838**		
pH		0.515		0.519
TSS			-0.459	0.740
TDS		0.695		
EC		0.695		
Total hardness	**0.953**			
Calcium	**0.916**			
Chloride	**0.947**			
Salinity	**0.947**			
DO			**0.895**	
BOD			**0.834**	
COD	**0.865**		-0.118	
Nickel	**0.851**			
Copper	-0.430	**0.763**		
Manganese		**0.889**		
Chromium		**0.820**		
Lead		0.591		**-0.630**
Zinc				0.153
Cobalt		**0.877**		
Cadmium	0.633	**-0.723**		
Iron		**0.866**		
Eigenvalue	8.714	7.506	2.152	1.520
Variance %	37.885	32.633	9.356	6.608
Cumulative %	37.885	70.519	79.875	86.483

produced by the cluster analysis showed that seven sample stations throughout three seasons were clustered into four significant clusters (Fig. 6). Cluster I dominated with industrial and tourism activity had three research sites: S4, S5, and S7. The primary sources of pollution at the S4 and S5 research sites are shipbreaking operations along both coast and tourism. In contrast, S7 gets a significant quantity of input from tourism and agricultural runoff. Cluster II included sites S2 and S3, both had rural–residential and tourism sites indicating the domestic nature of anthropogenic loading to coastal water. Cluster III has site S1 at Bhavnagar, where coastal water is affected mostly by saltern pan, small–scale industrial effluent, ferry–service, ship–repair, and tourism activities. Cluster IV included S6. Through the Shetrunji River, S6 water receives domestic waste and agricultural runoff affects coastal water physico–chemical parameters and dissolved heavy metal (Uddin et al. 2020). As a whole, all of the locations are being impacted by the land-based industrial activity inputs on the coast and periphery of the coast. In addition, the Gulf of Khambhat's resilient tidal dynamics, have a significant influence on impacting the coastal water parameters at study sites (Jain et al. 2022; Mitra et al. 2020; Nayak and Shetye 2003). It is clear that the cluster analysis approach is effective in providing reliable categorization of the Bhavnagar coastal waters and will allow for appropriate spatial evaluation in an ideal way.

Future Road Map

Based on the physico–chemical study and dissolved heavy metal analysis of coastal water, it is clear that there are repercussions. It is now critically necessary to investigate the influence of such environmental conditions on the variety of biota (planta, animalia, and microorganisms). The statistical approaches mentioned in the study can be used to forecast the state of an ecosystem in a specific location. Our research and future research will be valuable in developing successful management strategies.

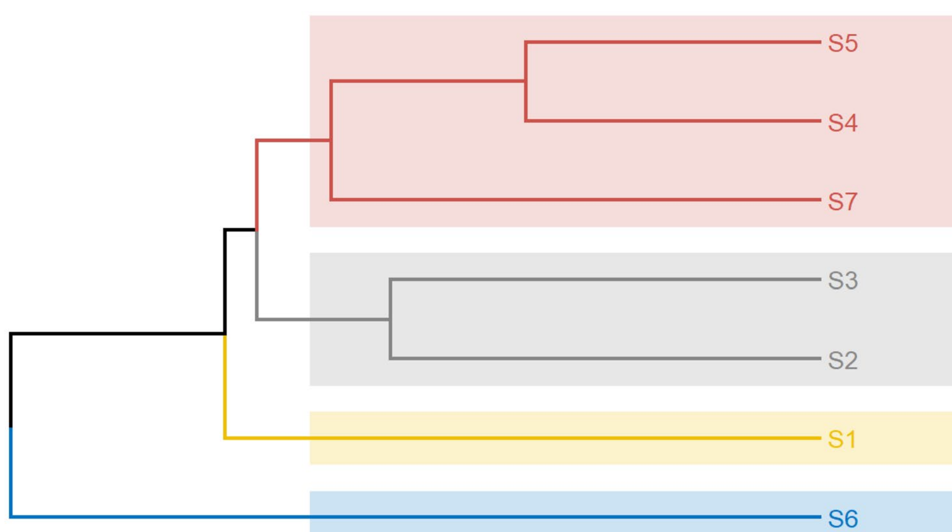

Fig. 6 Ward's method of dendrogram clustering displaying spatial grouping between study locations

Conclusions

This study and its outcomes are important for understanding the current water hydrochemistry and dissolved heavy metal status as an environmental indicator for the biota of Bhavnagar coast, Gulf of Khambhat using correlation analysis, hierarchical cluster analysis, box plot, and principal component analysis/factor analysis. It was discovered that the physico–chemical parameters and dissolved heavy metals of coastal water from study sites of the Bhavnagar coast are considerably different. The findings indicate that land–based anthropogenic activities and tidal dynamics have a significant influence on coastal water. The geographical location of Bhavnagar coast played a major role in pollution load due to the industrial activity at the coast (diamond cutting–polishing, agro–based, salt–marine chemicals, cotton textile, chemical, mineral-based, plastics, shipbuilding, and ship–breaking) and its periphery (energy, petrochemical, agrochemical, metal–mining, auto components, textile, pharmaceutical, effluent treatment, and port), tidal current (10 m high spring tide) and freshwater intrusion could be the primary cause of changes in physico–chemical parameters and source of heavy metal. The seasonal variability in physico–chemical parameters and dissolved heavy metal due to the dilution during monsoon season. The correlation analysis helped in understanding the degree of connection between the measured data, and the box plot enabled an understanding of the seasonal fluctuation of dissolved heavy metal at all study locations. According to PCA/FA analysis, land–based anthropogenic inputs have a considerable impact on parameters like temperature, DO, BOD, COD, Cl, and dissolved heavy metals including Ni, Cu, Mn, and Cr. The similarity between the locations was shown by the hierarchical cluster analysis, which categorized the sites as having anthropogenic (domestic or industrial inputs) and natural (seasonal effect). Overall, the study area showed spatial and temporal variation in water physico–chemical parameters and dissolved heavy metal which appeared to be noticeable and could be harmful to marine ecosystems. This research can be used as a footprint to develop management strategies for the Bhavnagar coast, Gulf of Khambhat, Gujarat, India.

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Author Contributions Hardik Giri Gosai: Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review and editing. Pradeep Mankodi: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – review and editing.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethical Approval and Consent to Participate Not applicable.

Human and Animal Ethics Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

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