RESEARCH ARTICLE

Determining The Impact of Industrial Effluents on Water Quality of Patalganga River Estuary, District - Raigad, Maharashtra State

Salil Dattatreya Save[1*], Rakesh Kumar[2]

DOI: 10.18811/ijpen.v11i01.16

Abstract

Among the 351 polluted river stretches in India, the Patalganga River in Maharashtra has been identified as a polluted river stretch by the Central Pollution Control Board (CPCB). The effluent generated by the selected industries in the Patalganga Industrial Estate is sent to a common effluent treatment plant (CETP). This CETP treats the effluent on behalf of the industries, and the treated effluent is ultimately discharged into the Patalganga River. Parameters such as water temperature, pH, BOD, DO, TSS, PO_4, NO_2, NO_3, and NH_4^+ were measured at the CETP discharge point and at 10 locations for three seasons: pre-monsoon, monsoon, and post-monsoon. The water body stretch was conceptually categorized into five zones: Coastal, estuarine, mixing point, CETP outlet vicinity zone, and riverine zone. The findings reveal significant degradation in water quality near the CETP outlet compared to other areas, with noticeable impacts both upstream and downstream. Dilution emerged as a key factor in pollutant dispersion, particularly evident in coastal zones. Moreover, elevated levels (>11.9 mg l^{-1}) of biochemical oxygen demand exceeded standard thresholds in freshwater areas, indicating potential ecological stress. Correlation analysis conducted between the zones underscores the temporal and spatial variability of water quality dynamics, highlighting the critical influence of CETP discharges. Utilizing cluster analysis, optimization has been conducted for the number of monitoring stations to enhance the efficiency of data collection. The CETP zone exhibited a water quality index (>25), classified as "Very Bad," emphasizing the urgent need for targeted management interventions to address pollution sources, improve water flow during low-flow periods, and promote sustainable resource management practices. These measures are essential for safeguarding ecosystem health in similar aquatic ecosystems.

Highlights

- Pollution in the Patalganga river, identified as a polluted stretch by the CPCB, originated from industries whose effluent is treated by a CETP before discharge.
- Water quality degradation is most pronounced near the CETP outlet, with notable impacts upstream and downstream. This was confirmed through statistical processing of data.
- Elevated biochemical oxygen demand (BOD) levels suggest ecological stress in freshwater areas, urging attention to pollution intervention.
- Spatial and temporal variability in water quality underscores the critical role of CETP discharges, emphasizing the need for targeted interventions and sustainable resource management practices.

Keywords: Patalganga river, CETP effluent, Spatiotemporal variability, Zones, Pollution index, Cluster analysis

International Journal of Plant and Environment (2025); **ISSN:** 2454-1117 (Print), 2455-202X (Online)

Introduction

The total annual water resources in India encompass both surface water and groundwater, estimated to be approximately 1869 billion cubic meters (BCM). However, only around 60% of this volume is considered utilizable due to various geological and topographical constraints. This usable portion includes roughly 690 BCM derived from surface sources. Precipitation, in the form of rainfall and snowfall, contributes an annual influx of approximately 4000 BCM of freshwater resources (Kumar and Padhy, 2015). In the face of climate change and increasing droughts, regional water degradation is a pressing global concern. Efforts to mitigate water shortages focus on understanding and addressing the causes of water scarcity and contamination. Key issues include nutrient, metal, and organic pollutant accumulation in tidal river and estuary sediments, which impact water quality and ecology. Estuaries, among the World's most productive ecosystems, are particularly affected (de Jonge *et al.*, 2002; McLusky & Elliott, 2004; Telesh & Khlebovich, 2010). Approximately 80% of wastewater is discharged into water bodies without undergoing treatment. The poor quality of surface water in lakes and rivers, which are vital sources of drinking water for millions globally, contributes to diarrheal diseases, one of the leading causes of death and

[1*]CSIR-National Environmental Engineering Research Institute, Worli, Mumbai – 400 018, India.

[2]Mission Director CCUS, CSIR- India

***Corresponding author:** Salil Dattatreya Save, CSIR-National Environmental Engineering Research Institute, Worli, Mumbai – 400 018, India., Email: salilsave23@gmail.com

How to cite this article: Save, S.D., Kumar, R. (2025). Determining The Impact of Industrial Effluents on Water Quality of Patalganga River Estuary, District - Raigad, Maharashtra State. International Journal of Plant and Environment. 11(1), 146-154.

Submitted: 18/01/2024 **Accepted:** 17/02/2025 **Published:** 28/03/2025

illness worldwide. In developing countries, pollution upstream can result in reductions of 30 to 40% in annual GDP growth downstream (UN-Water, 2017).

Intensifying human impact on marine environments now extends to the abyssal depths, driven by deep-sea oil and gas extraction, mineral resource retrieval, and bottom trawling in the hadal zone (Barbier, 2023). According to the Central Pollution Control Board of India (CPCB) report (CPCB, 2021), a total of 71,853 million liters per day (MLD) of wastewater, including both sewage and industrial discharge, is released into India's water bodies (Seal *et al.*, 2022). In India, about 44 million m^3d^{-1} of industrial wastewater is being generated and out of which 6.2 billion liters of untreated effluent are discharged in natural water ecosystems (Datta *et al.*, 2021). Water pollution sources such as agricultural runoffs, atmospheric depositions, and urban and rural runoffs contribute significantly to water pollution, which are yet not included in the wastewater management plan (Jadeja *et al.*, 2022). Indian coastal waters bear a substantial pollutant burden from diverse sources, including industrial effluents, untreated sewage, and agricultural runoff, leading to ecological deterioration stretching several kilometers from the shoreline. Notable affected areas include Versova Creek, Mahim Creek, Ulhas Estuary, Thane Creek, and Patalganga Estuary (CSIR-NIO, 2018; Zingde *et al.*, 2000).

The common effluent treatment plant (CETP) concept originated in India in the late 1980s to manage industrial wastewater effectively. It was designed to aid small and medium enterprises (SMEs) that could not afford individual treatment plants, providing cost-effective, collective wastewater treatment. This approach simplified discharge, monitoring, and enforcement for environmental agencies. Government investment in CETPs was justified by significant pollution reduction and environmental benefits (CPCB, 2005; Padalkar and Kumar, 2018). Patalganga river has been identified by CPCB (2008) as one of the most polluted stretches among the 351 polluted river stretches in India. This study focuses on assessing the impact of CETP discharges on the Patalganga ecosystem, encompassing freshwater, estuarine, and coastal zones. The CETP discharge point, situated within the river (Freshwater zone), exacerbates water quality deterioration, extending to the estuarine and coastal zones. To comprehensively evaluate the temporal variability of physicochemical parameters, the water body was conceptualized into five distinct zones. The parameters were monitored due to their significance in assessing water quality and ecological health. pH influences chemical and biological processes in aquatic ecosystems, while high levels of TSS can negatively affect water clarity and aquatic habitats. Similarly, dissolved oxygen (DO) is essential for aquatic organism survival and high biological oxygen demand (BOD) levels indicate organic pollution, potentially leading to oxygen depletion. Excessive nutrient concentrations, particularly nitrogen and phosphorus, can result in eutrophication, further degrading water quality. The water quality index (WQI) was calculated to assess pollution in riverine, estuarine, and coastal areas by combining multiple parameters into a single value for easy comparison. Cluster analysis was carried out to identify similarities among monitoring stations, optimizing spatial coverage and reducing station count, ensuring cost-effective and comprehensive water quality monitoring. Previous investigations have focused on specific regions of the Patalganga river and estuary; a comprehensive analysis of the entire river stretch has been lacking. This study addresses this gap by spanning locations from the upstream of the river to the estuarine and coastal zones, aiming to assess the impact of treated effluent discharged from the CETP on water quality across these zones and seasons.

Materials and Methods

Study Area and Sampling

The Patalganga River, originating from the Sahyadri Hills of the Western Ghats east of the study area, encompasses a catchment area of 328 sq. km. During the non-monsoon period, the river typically maintains a narrow and shallow profile due to water impoundment, experiencing significant flooding during the monsoon season. Upstream of the Patalganga River, approximately 128 MLD of freshwater is extracted for use by the Maharashtra Industrial Development Corporation (MIDC). Additionally, approximately 400 m^3/day of tailrace water is discharged from the Tata Power Station into the river at Khopoli, approximately 32 km upstream of the Patalganga. The Patalganga CETP, situated within the MIDC, has a total treatment capacity of 15,000 m^3/day of effluent (PRIYA, 2004). Effluents from Hindustan Insecticides Limited (HIL) and Hindustan Organic Chemicals (HOC) are also discharged separately into the Patalganga at Apta as shown in Fig. 1. The effluent discharge originating from local Municipal Councils situated in upstream locations represents an additional source of pollution. The combined treated final effluent (CETP Discharge) must comply with norms established by the Maharashtra Pollution Control Board (MPCB), as outlined in the Central Pollution Control Board (CPCB) guidelines of 2006. Transported through a 1 m diameter, 9.2 km long pipeline, the effluent is disposed off into the Patalganga River near Apta Gaon, at coordinates Latitude 18°51′20.11″ N and Longitude 73°07′46.30″ E. The sampling locations of the study area is presented in Table 1.

Table 1: Sampling location at Patalganga river estuary stretch

Zones/Station		*Coordinates*	
Coastal zone	S1	$18^0$49′52.87″ N	$72^0$54′50.26″ E
	S2	$18^0$49′51.80″ N	$72^0$56′33.20″ E
	S3	$18^0$51′23.75″ N	$72^0$58′43.18″ E
Estuarine zone	S4	$18^0$48′14.15″ N	$72^0$59′35.10″ E
	S5	$18^0$48′57.20″ N	$73^0$01′24.30″ E
Mixing zone	S6	$18^0$48′35.80″ N	$73^0$04′17.20″ E
Riverine zone	S7	$18^0$50′19.20″ N	$73^0$05′31.40″ E
CETP outlet	S8	$18^0$51′20.11″ N	$73^0$07′46.30″ E
Riverine zone	S9	$18^0$51′20.28″ N	$73^0$08′34.66″ E
	S10	$18^0$52′27.64″ N	$73^0$09′26.06″ E
	S11	$18^0$53′16.98″ N	$73^0$10′43.52″ E

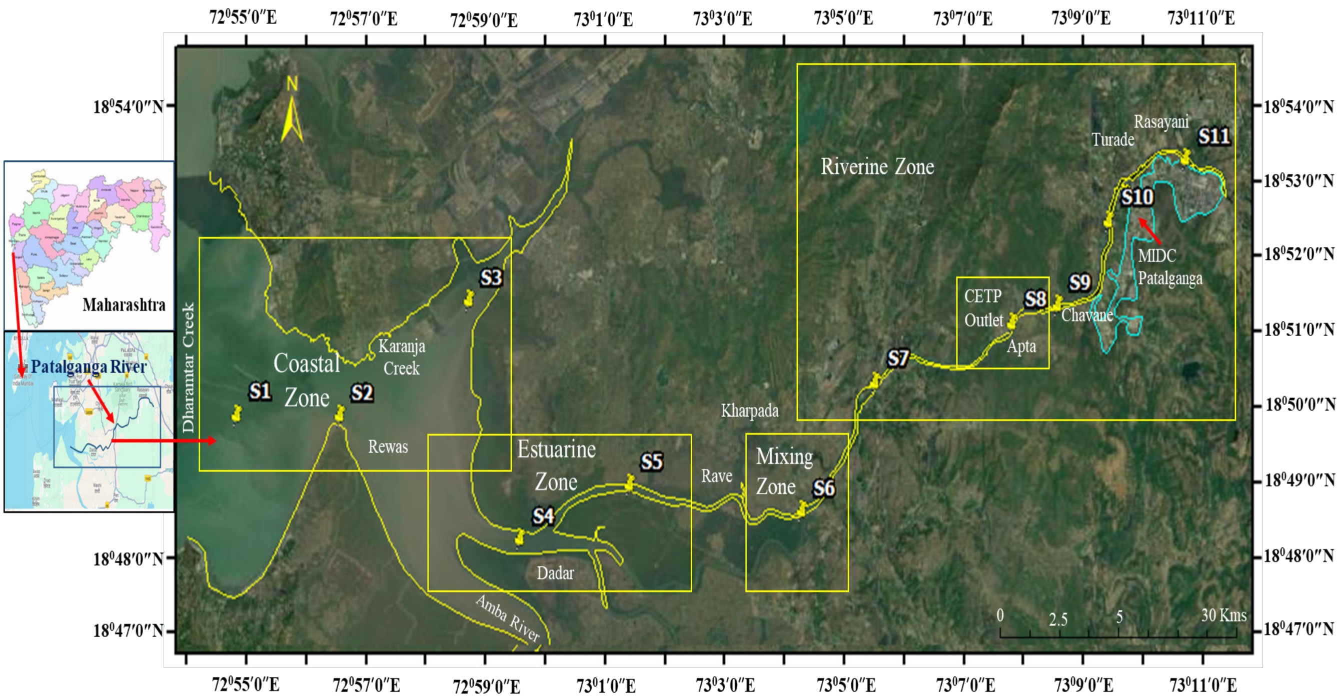


Figure 1: Study area stretch of Patalganga river, riverine, estuary and coastal

Grab sampling was conducted during the pre-monsoon period (April), monsoon season (August), and post-monsoon season (December) to evaluate temporal variability. Water samples were collected at eleven designated locations (S-1–S-11) spanning from the Coastal head to the Estuary across three distinct seasons. Stations S-1 and S-2 remained unmonitored during the monsoon season due to high flood levels and accessibility constraints. The monitored locations were conceptually divided into five zones: Coastal (S-1 to S-3), estuarine (S-4 and S-5), mixing point (S-6), near the common effluent treatment plant (CETP) outlet (S-8), and riverine (S-7 to S-11). The parameters monitored included pH, total suspended solids (TSS), dissolved oxygen (DO), biochemical oxygen demand (BOD), and various nutrients such as phosphates, nitrites, nitrates, and ammonium and silicates.

Analytical Methods

Physicochemical Analysis

Pre-cleaned, acid-washed jerry cans were used for sample collection, and samples were subsequently stored in a refrigerator below 4°C until analysis. Sampling and preservation procedures adhered to guidelines outlined by the Central Pollution Control Board (CPCB, 2017). Field measurements were conducted to assess parameters such as water temperature and pH using standard equipment and procedures. Dissolved oxygen levels were determined using fixed glass bottles, while samples for BOD, total suspended solids (TSS), salinity, and various nutrients (phosphates, nitrites, nitrates, ammonium, and silicates) were preserved according to the methods outlined in the American Public Health Association (APHA, 2012) guidelines.

The Water Quality Index (WQI)

WQI was calculated to evaluate pollution levels in the riverine, estuarine, and coastal regions of the water body. The WQI is a numerical representation of water quality, enabling assessment of changes and trends in a water body's quality. It assigns a unit less value based on measured parameters, utilizing sub-index scores for each parameter to collectively determine the overall index, providing valuable insights into water quality conditions. The water quality index is calculated as proposed by Pesce and Wunderlin, (2000), and further used by Sánchez E. *et al.*, (2007) as follows:

$$WQI = k \frac{\sum_i c_i x P_i}{\sum_i P_i}$$

Where ***k*** is a subjective constant.

It (*k*) represents the visual impression of river contamination. It takes one of the following values according to the river condition. 1.00 = water without apparent contamination (clear or with natural suspended solids)., 0.75 = light contaminated water (apparently), indicated by light non-natural color, foam, light turbidity due to no natural reasons; 0.50 = contaminated water (apparently), indicated by non-natural color, light to moderate odor, high turbidity (no natural), suspended organic solids, etc.; 0.25 = highly contaminated water (apparently), indicated by blackish color, hard odor, visible fermentation, etc.

Ci is the value assigned to each parameter after normalization.

Pi is the relative weight assigned to each parameter. (*Pi* values range from 1 to 4, with 4 representing a parameter that is the most important for aquatic life).

The assigned values of *Ci* and *Pi* for selected parameters of water quality are presented in Table 2. The C*i* and P*i* values, sourced from European standards, differ notably from Indian standards, particularly concerning Nitrite and Ammonia, which contribute 5 to 15% to the overall index. Different k-values were applied across seasons.

Cluster Analysis

Cluster analysis was carried out, using Minitab (14.0) software. Cluster analysis groups samples based on multiple measured variables, producing a dendrogram illustrating relationships among samples according to similarity (Shrivastava *et. al.*, 2015). Some studies, like Ouyang (2005), have used this method to minimize water quality monitoring stations. In this investigation, cluster analysis was applied to station locations as variables.

Coefficient of Correlation Analysis

Correlation measures how two variables are related numerically. It shows how changes in one variable are linked to changes in another. The Karl Pearson Coefficient of Correlation, represented as "*r*," is used to gauge the strength of a linear relationship between two variables. This method, developed by Karl Pearson, helps find the best-fit line through the data points, with "*r*" indicating how closely the data points align with this line. It's a widely used approach in statistics for assessing the correlation between variables (Noori, 2010)**.**

$$r = \frac{Co\,\mathrm{var}\,iance(x,y)}{SD(x) * SD(y)}$$

$$r = \frac{n\sum xy - (\sum x) * (\Sigma y)}{\sqrt{\left[n\sum x^2 - \left(\sum x^2\right)\right]\left[n\sum y^2 - \left(\Sigma y^2\right)\right]}}$$

Where *r* = correlation coefficient and x and y are the two different variables.

The interpretation of *r* has been carried out through the following points:

The value of the coefficient of correlation will always lie between -1 and +1., i.e., $-1 \leq r \leq 1$.

When *r* = +1, it means, there is a perfect positive correlation between the variables.

When *r* = -1, there is a perfect negative correlation between the variables.

When *r* = 0, there is no relationship between the two variables.

Results and Discussion

Physicochemical Parameters Analysis

The results of the parameters monitored are presented in Table 3. pH values observed in all three seasons are well within the standards (6.5–8.5) recommended for drinking water by BIS (2012) (for riverine zone stations). CPCB (1998) has prescribed the coastal water standards (6.5–9.0) and in this study, all the saline zone (coastal and estuarine) samples possessed the range of pH in satisfactory range. As far as zone-wise deviations are considered, the station near the CETP outlet exhibited a maximum deviation from the other 4 zones. This may be due to the relation between the continual discharge of the industrial effluents in the water body with the availability of water volume at that specific season. The standards prescribed for effluents to be discharged in inland water by CPCB (2000), state. The temperature in any segment of the stream within a 15-meter distance downstream from the effluent outlet must not surpass 40°C. Ministry of Environment, Forest and Climate Change- India, through their notification, revealed that the temperature rise should not increase the temperature of the receiving water body by more than 5°C from the ambient (MoEF&CC, 2016). Overall, in all three seasons, the water body exhibits satisfactory levels of temperature-related standards of the effluent discharges.

The DO standard for freshwater/ drinking water is >4 mg l^{-1} (for public water supply, A-II category of freshwater) (MPCB, 2019) and the standard for Coastal/ saline water is >3.5 mg l^{-1} (CPCB, 1998). These standards are prescribed for fish and wildlife propagation. As the present study addresses the coastal

Table 2: The assigned weights of WQI for the selected parameters

Parameter#	*Relative weight (P_i)*	*Normalization Factor (C_i)*										
		100	*90*	*80*	*70*	*60*	*50*	*40*	*30*	*20*	*10*	*0*
Range of analytical value												
pH	1	7	7–8	7–8.5	7–9	6.5–7	6–9.5	5–10	4–11	3–12	2–13	1–14
TSS	4	<20	<40	<60	<80	<100	<120	<160	<240	<320	<400	>400
Amm.	3	<0.01	<0.05	<0.10	<0.20	<0.30	<0.40	<0.50	<0.75	<1.00	<1.25	>1.25
NO_2	2	<0.005	<0.01	<0.03	<0.05	<0.10	<0.15	<0.20	<0.25	<0.50	<1.00	>1.00
NO_3	2	<0.5	<2.0	<4.0	<6.0	<8.0	<10.0	<15.0	<20.0	<50.0	<100.0	>100.0
P-t	1	<0.2	<1.6	<3.2	<6.4	<9.6	<16.0	<32.0	<64.0	<96.0	<160.0	>160.0
BOD_5	3	<0.5	<2.0	<3	<4	<5	<6	<8	<10	<12	<15	>15
DO	4	7.5	>7.0	>6.5	>6.0	>5.0	>4.0	>3.5	>3.0	>2.0	>1.0	<1.0
T	1	21/16	22/15	24/14	26/12	28/10	30/05	32/0	36/–2	40/ 4	45/ 6	>45/<- 6

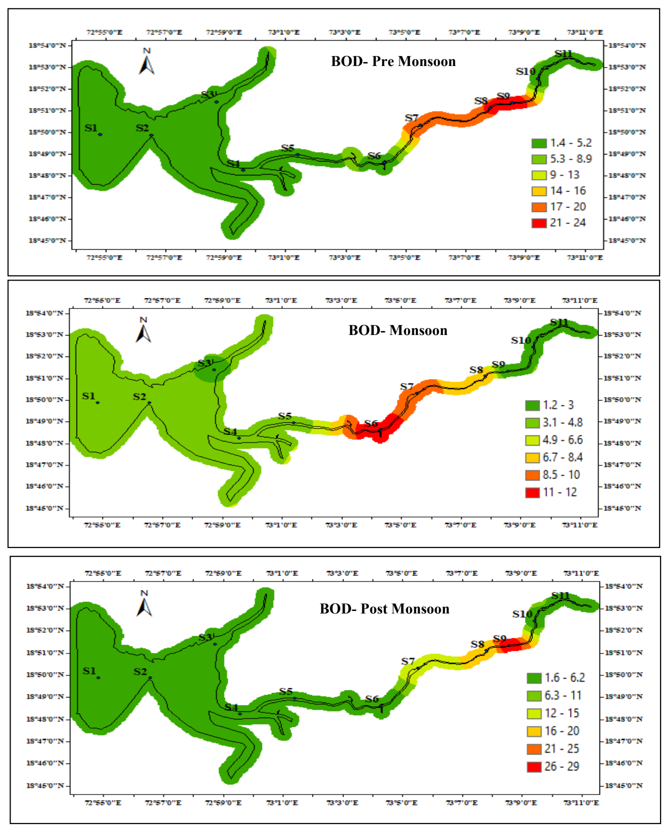
* Sánchez E. *et al.,* (2007), # All values are in mg l-1, pH in pH Un and temperature in ^{0}C.

Table 3: Physicochemical Parameters Monitored for the Three Seasons

Season	*Zone*	*Water Temp (°C)*	*pH*	*Concentrations in mg l^{-1}*							
				DO	*BOD*	*TSS*	*PO_4*	*NO_2*	*NO_3*	*NH_4*	*SiO_2*
Pre-monsoon	Coastal	31.6	8.0	5.2	1.9	30.4	0.239	0.148	0.819	0.026	0.231
	Estuarine	30.9	7.7	5.0	2.1	26.5	0.236	0.324	1.765	0.419	5.102
	Mixing	30.0	7.5	5.1	3.9	23.4	0.209	0.944	1.374	0.527	6.240
	Near CETP	31.0	7.6	2.2	20.4	12.0	0.494	0.285	3.026	0.504	8.520
	Riverine	28.8	7.3	4.4	11.9	13.3	0.083	0.224	0.693	0.286	5.721
Monsoon	Coastal	29.0	7.6	4.8	2.8	42.0	0.110	0.046	0.843	0.032	0.204
	Estuarine	28.0	7.6	5.7	3.7	36.0	0.191	0.069	1.550	0.340	2.910
	Mixing	26.0	7.6	2.1	12.0	20.0	0.272	0.115	2.660	0.364	2.760
	Near CETP	27.0	7.2	4.0	8.0	32.0	0.254	0.189	1.575	0.335	4.560
	Riverine	25.8	7.4	5.6	3.9	21.5	0.199	0.101	1.259	0.227	3.840
Post-monsoon	Coastal	27.1	7.7	6.5	2.1	39.3	0.258	0.189	1.369	0.115	0.517
	Estuarine	29.3	7.6	5.2	1.8	30.8	0.197	0.410	2.466	0.278	1.970
	Mixing	28.5	7.5	3.0	1.7	23.7	0.193	0.458	1.556	0.725	1.222
	Near CETP	25.5	7.3	2.0	16.2	20.0	1.169	0.193	0.794	0.461	2.412
	Riverine	26.3	7.3	4.3	12.5	25.3	0.682	0.170	0.787	0.331	5.276

waters as well as freshwater, both standards need to be taken into consideration. In all three hydrological periods, coastal, estuarine and riverine zones, the observed values of DO were within the specified threshold. However in the monsoon and post-monsoon seasons, the mixing point zone (DO< 3.5 mg l^{-1}) has been observed to be violating the norms. In pre and post-monsoon, near the CETP zone, the concentration of DO was observed to be violating the norms.

In this study, BOD concentrations in the coastal saline zone generally complied with the CPCB-prescribed standard of 3.0 mg l^{-1} during pre-monsoon and post-monsoon seasons, except for the mixing zone in the pre-monsoon, where it reached 3.9 mg l^{-1}. However, during the monsoon season, significantly higher BOD levels, up to 12 mg l^{-1}, were observed at the mixing zone. This increase may be attributed to intensified water flow carrying pollutants downstream, compounded by the restricted water flow and pollutant accumulation characteristics of confluence points (mixing zone). The stagnant water dynamics and prolonged residence time in these areas contribute to elevated pollution levels. Upstream and downstream stations (S-7 and S-9) from the CETP outlet (S-8) in the riverine zone experienced industrial effluent impacts, particularly pronounced in pre-monsoon and post-monsoon seasons due to shallower water columns and reduced dispersion rates. Additionally, stations S-10 and S-11 (Riverine zone) were affected by pollutant loads from upstream sewage released from local Municipal Councils, resulting in BOD concentrations reaching up to 12.5 mg l^{-1}. The spatiotemporal variation of BOD influence on the entire aquatic system is detailed in Fig. 2. This figure represents the individual and stationwise concentrations of BOD. Thus, the pre-monsoon season shows an 80% decrease in BOD from CETP to the mixing point station; while in the post-monsoon season, the percent decrease was 89%. In the monsoon season, 50%



Source: During the monsoon season, observational assessments have not been conducted for Stations S-1 and S-2. The depiction of green hues on the map for Stations S-1 and S-2 has been extrapolated for the purpose of visualization

Figure 2: Spatiotemporal variation of BOD at Patalganga waterbody stretch

rise in BOD values at the mixing point than that of the station near the CETP outlet. In the monsoon season, the coastal region experienced more load of BOD comparatively than in the other two seasons. However, the load of the BOD has minimized up to satisfactory levels and this suggests the proper dispersion and dilution of pollutants as the water body moves from upstream to downstream up to the coastal zone. As far as TSS was considered, in all hydrological periods, estuarine and coastal zones exhibited higher concentration than that of riverine zone. Among the three seasons, the highest value (42 mg l^{-1}) was observed in Monsoon season.

Nutrients Study

In this study, nitrite levels were generally within acceptable limits, yet during the post-monsoon season, notably higher concentrations were detected, particularly in mixing and estuarine regions. Estuaries, recognized as nutrient-rich environments, serve as vital zones for nutrient accumulation from freshwater runoff, as highlighted by previous research (Dame *et al*., 2008)**.** Throughout all seasons and locations, nitrate concentrations remained below the permissible limit of 45 mg l^{-1} as per MPCB (2019)**.** Nitrate levels were observed to be higher near the CETP zone and this may be due to anthropological pressure. Consistently elevated phosphate levels at the CETP outlet suggest industrial effluent influence, while the saline zone showed higher levels possibly due to sediment accumulation in the river-dominated estuary (Watson *et al*., 2018). In the riverine zone, increased phosphate concentrations were observed during monsoon and this may have resulted from untreated sewage disposal by local Municipal Councils. Throughout all seasons, ammonium concentrations varied, with the lowest levels in the coastal zone and the highest in estuarine and mixing zones, attributable to estuarine dynamics where freshwater and seawater converge, aiding nutrient retention and dispersion (Torregroza-Espinosa *et al*., 2020). The highest concentration of silicates near the CETP outlet in the pre-monsoon and monsoon seasons may be due to the presence of numerous food and pharmaceutical industries in the Patalganga Industrial belt (Selvarajan *et al*., 2020; Videira-Quintela *et al*., 2021). Silica, commonly used in industrial applications, could contribute to elevated levels in this area. Additionally, the riverine zone showed increased silicate concentrations in the pre- and post-monsoon season, likely influenced by diffuse sources such as weathering and sewage disposal.

The Water Quality Index (WQI)

During the pre-monsoon season, the CETP Outlet zone was assigned a *k*-value of 0.5 due to observed non-natural coloration, slight odor, and turbidity, while no *k*-value was assigned during the monsoon season. In the post-monsoon season, station S-8 was assigned a *k*-value of 0.75 due to slight non-natural coloration and turbidity. WQI was calculated according to the zones and the results are presented in Table 4 and symbolically represented in Fig. 3. In the pre-monsoon season, the effect of pollution can be experienced up to the estuarine zone, whereas in the other two seasons, the effect was observed to be limited up to the mixing point zone. In the monsoon season, due to substantially elevated water discharge, the riverine part was found to be in the category of 'Good' water quality index. The WQI near the CETP zone varied across seasons, indicating 'Very Bad' (25) in pre-monsoon, 'Bad' (47) in monsoon, and 'Bad' (41) in post-monsoon. Pre-monsoon conditions allow heightened evaporation and lower water discharge, higher residence time which may have exacerbated pollutant concentrations.

On the contrary, the monsoon season brought increased water flow, diluting pollutants downstream. Post-monsoon conditions improved marginally but remained inferior to monsoon levels. Downstream stations consistently showed 'Good' quality, suggesting effective dispersion and dilution. These findings underscore the seasonality and spatial variability of water quality dynamics, emphasizing the need for targeted management interventions.

Cluster Analysis

In the pre-monsoon season analysis, a dendrogram revealed five clusters. The first cluster, representing coastal zones (stations S-1, S-2, and S-3), showed 87% similarity, indicating uniform

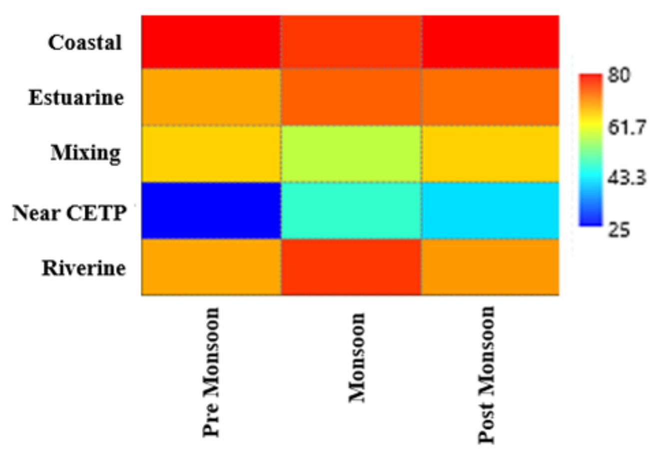
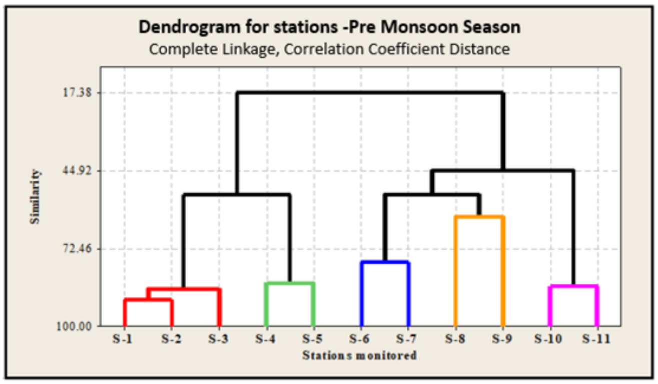


Figure 3: WQI for the three seasons

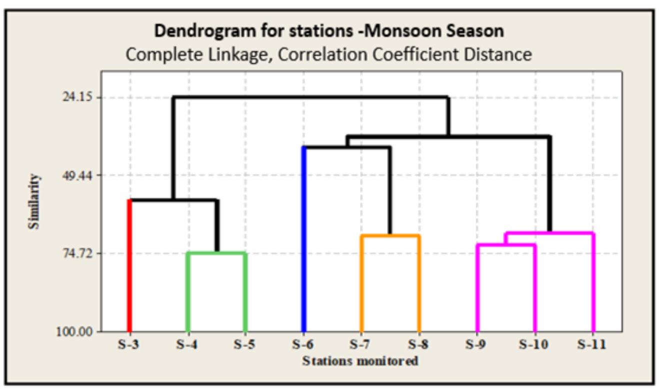
Table 4: WQI for three seasons according to zone

Range		*Zones*	*Pre-monsoon*	*Monsoon*	*Post-monsoon*
00- 25= "Very Bad'		Coastal	80	76	80
26- 50= "Bad"		Estuarine	68	73	72
51- 70= "Medium"		Mixing	65	57	65
71- 90 = "Good"		Near CETP	25	47	41
91-100 = "Excellent"		Riverine	68	76	69

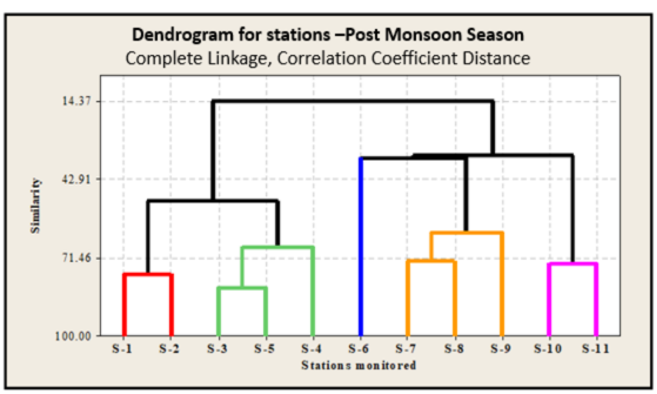
characteristics. The second cluster, observed in the estuarine zone (stations S-4 and S-5), exhibited 85% similarity (Fig. 4a). Further, the third cluster comprised the mixing point (S-6) and riverine (S-7) stations, exhibiting 77% similarity. Stations S-8 and S-9 formed the fourth cluster, sharing 61% similarity in their characteristics. The fifth cluster included riverine stations S-10 and S-11, with an 86% similarity. Based on cluster analysis, monitoring could be focused on five stations (S-1, S-4, S-6, S-8, and S-11) during the pre-monsoon season to represent the overall water body characteristics effectively and the number of monitoring stations may be reduced to five instead of 11 stations in future.



(a) Pre-Monsoon



(b) Monsoon



(c) Post-monsoon

Figure 4 (a to c): Dendrogram for stations - a. Pre-monsoon, b. Monsoon, c. Post-monsoon

As far as the monsoon season is concerned, the coastal and estuarine zone was connected through 57% similarity in their characteristics. Station S-6, being a mixing point station, was observed to be different from all other stations. Station S-7 was a downstream station to CETP outlet (S-8) and the similarity between these two stations was 69%. Riverine zone stations (S-9, S-10, and S-11) were interconnected by 68% similarity in their characteristics (Fig. 4b). Further, in the monsoon season, according to the cluster analysis, the number of stations may be reduced to five and only the stations S-3, S-4, S-6, S-8, and S-11 may be monitored in the future.

Furthermore, in the post-monsoon season, stations S-1, and S-2 are linked with 77.4% similarity, while stations S-3, S-4, and S-5 exhibited a similarity of 67.5%. The mixing point station S-6 was observed to be a separate cluster and linked with a similarity matrix of 35% near CETP outlet station (S-8). Other upstream riverine stations i.e., S-10 and S-11 formed the last cluster with 73.5% similarity. Thus, in the post-monsoon season, according to the cluster analysis, the number of stations may be reduced to five and only stations S-1, S-4, S-6, S-8, and S-11 may be monitored in the future (Fig. 4c).

All five zones were connected through 24% similarity in monsoon season, whereas the pre and post-monsoon seasons were connected through 17 and 14%, respectively. Further, the similarity with other stations in the monsoon season was higher than that of the other two seasons. The amplified hydrological connectivity during the monsoon period, coupled with increased freshwater inflow leading to intensified flushing, likely played a role in this context. Therefore, in light of the spatiotemporal fluctuations, it is imperative to monitor only 4 stations viz. S-4 (Estuarine), S-6 (Mixing), S-8 (Near CETP), and S-11 (Riverine) across three seasons to evaluate the comprehensive representation of the waterbody under investigation.

Coefficient of Correlation Analysis

The zone-wise correlation concerning the parameters analyzed is presented in Table 5. In the pre-monsoon season, significant correlations were found between the coastal zone and the estuarine zone ($r > 0.991$, $p < 0.01$) and also with mixing zones ($r > 0.926$, $p < 0.01$). The coastal zone spans up to 8 kilometers and the estuarine zone extends another 8 kilometers. This similarity in physicochemical parameters between the coastal and estuarine zones may be due to limited water volume and longer resident time, leading to inadequate flushing and tidal water ingress. Additionally, a strong correlation was observed between the estuarine and mixing point zones ($r = 0.955$, $p < 0.01$) due to their adjacent proximity. Similarly, the riverine near the CETP station zone showed a strong positive correlation ($r = 0.902$, $p < 0.01$) due to limited flushing capacity in the pre-monsoon season. However, the coastal zone did not correlate with the CETP outlet and riverine zones, suggesting different characteristics. Similarly, mixing with riverine and CETP outlet zones also showed non-correlated characteristics, indicating distinct physicochemical elements.

During the monsoon season, all zones showed significant correlations (Table 6), assisted by heavy rain increasing river flow, and flushing out pollutants, silt, and algae. The elevated water volume and flow velocity enhance self-cleaning processes like

Table 5: Zone-wise correlation analysis for pre-monsoon season

	Coastal	*Estuarine*	*Mixing*	*Near CETP*	*Riverine*
Coastal	1				
Estuarine	**0.991****	1			
Mixing Point	**0.926****	**0.955****	1		
Near CETP	0.082	0.125	0.307	1	
Riverine	0.345	0.392	0.602	0.902**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Table 6: Zone-wise correlation analysis for monsoon season

	Coastal	*Estuarine*	*Mixing*	*Near CETP*	*Riverine*
Coastal	1				
Estuarine	0.997**	1			
Mixing Point	0.861**	0.877**	1		
Near CETP	0.693*	0.734*	0.803**	1	
Riverine	0.677*	0.722*	0.753*	0.980**	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 7: Consolidated zone-wise correlation analysis for post-monsoon season

	Coastal	*Estuarine*	*Mixing*	*Near CETP*	*Riverine*
Coastal	1				
Estuarine	0.998**	1			
Mixing Point	0.932**	0.938**	1		
Near CETP	0.463	0.463	**0.652***	**1**	
Riverine	0.598	0.603	**0.802****	**0.940****	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

dilution, sedimentation, and aeration, improving water body homogeneity. Strong water currents prevent solids deposition, while proximity between adjacent zones correlates more significantly than distant ones.

Table 7 shows correlations among zones during the post-monsoon season. Similar to the pre-monsoon season, strong correlations were found between the coastal zone and the estuarine ($r > 0.998$, $p < 0.01$) and also with mixing zones ($r > 0.932$, $p < 0.01$), as well as between the estuarine and mixing point zones ($r = 0.938$, $p < 0.01$), likely due to their proximity and reduced water velocity and volume compared to the rainy season. Unlike the pre-monsoon season, correlations were observed between the mixing zone and the near CETP and riverine zones, possibly due to increased water volume levels during the post-monsoon season leading to similar characteristics among these adjacent zones.

Limitations of the study

In the monsoon season, the monitoring was not able to be conducted at S-1 and S-2 stations due to high flood levels and accessibility constraints.

Conclusion

The study investigates the spatiotemporal dynamics of water quality in the Patalganga river, particularly in relation to discharges from the CETP, exhibiting distinct seasonality and spatial heterogeneity.

- Pre-monsoon assessments highlight a severe degradation in water quality at station S-8 proximal to CETP, persisting upstream at S-9, yet witnessing betterment downstream at S-7 and S-6 during the monsoon period. Post-monsoon observations indicate a marginal enhancement, with downstream stations consistently depicting 'Good' water quality.
- Analytical examination reveals seasonal and spatial variations in pollution impacts, with pre-monsoon contamination extending to the estuarine zone, while monsoon and post-monsoon effects are mainly confined to the mixing point. The cluster analysis reveals the rationalization of monitoring stations to 4 strategic locations (S-4, S-6, S-8, and S-11) optimizes resource allocation, ensuring comprehensive coverage, and thus crucial for the representativeness of physicochemical parameters. These methodologies are economically feasible river water quality management, and useful for maintaining ecosystem integrity.
- Correlation analyses revealed consistent patterns among riverine, mixing point, and estuarine zones, contrasting with distinct characteristics in the coastal zone. Robust correlations between coastal and estuarine/mixing zones were evident pre-monsoon, while mutual correlations spanned all zones during monsoon. Riverine, mixing point, and estuarine zones exhibited significant pollution loads, while post-monsoon analyses showed a strong correlation between estuarine and mixing point zones, possibly due to decreased water velocity and volume, highlighting the complexity of pollutant dispersion across seasons.

The study highlights industrial and sewage effluents as major contributors to Patalganga River's water quality decline. Furthermore, the current placement of the CETP discharge outlet lies within a non-tidal freshwater zone, positioned 8 km away from the middle estuary. This imprecise placement has led to approximately 8 km of the total 12 km of the area being subjected to pollution pressure, primarily within the riverine zone. Accordingly, relocating the CETP discharge outlet approximately 8 km downstream, within the saline zone, is recommended. Understanding pollution dynamics is crucial for effective interventions, emphasizing source reduction and increased water flow during low-flow periods for sustainable water management in the Patalganga river.

Acknowledgments

I wish to express gratitude to the CSIR - National Environmental Engineering Research Institute, Mumbai and CSIR- National Institute of Oceanography, Mumbai for their logistical support and provision of essential laboratory resources, which were instrumental in conducting this study. Additionally, sincere appreciation is extended to the Maharashtra Pollution Control Board for their assistance in facilitating my research efforts.

Conflict of Interest

The authors declare that they do not have any conflict of interest

Authors Contributions

All authors contributed equally

References

American Public Health Association (APHA). (2012). Standard Methods for the Examination of Water and Wastewater. 22nd Edition, Washington, DC.

Barbier, E. B. (2023). Greening the Ocean Economy. Frontiers in Environmental Economics, 2, 1096303. doi: 10.3389/frevc.2023.1096303.

Bureau of Indian Standards (BIS-10500). (2012). Specification for Drinking Water, Indian Standards Institution, New Delhi, 1-5.

Central Pollution Control Board (CPCB). (1998). Water Quality Standards for Coastal Waters. https://cpcb.nic.in /wqm/ coastal_water_standards.pdf.

Central Pollution Control Board (CPCB). (2000). Environmental Standards for Ambient Air, Automobiles, Fuels, Industries and Noise. Pollution Control Law Series PCLS/4/2000-2001.

Central Pollution Control Board (CPCB). (2005). Performance Status of Common Effluent Treatment Plants in India. https://cpcb.nic.in/openpdffile php?id = UmVwb3J0RmlsZXMvODQ4XzE1NTU0MDc4MjFfbWVkaWFwaG90bzMxNDQwLnBkZg.

Central Pollution Control Board (CPCB). (2006). Pollution Control Acts, Rules and Notifications, Central Pollution Control Board, issued thereunder, New Delhi, 1131.

Central Pollution Control Board (CPCB). (2008). Polluted River Stretches in India (Criteria & Status). https://cpcb.nic.in/wqm/RS-criteria-status.pdf.

Central Pollution Control Board (CPCB). (2017). Guidelines for Water Quality Monitoring. https://cpcb.nic.in/wqm/Guidelines_Water_Quality_Monitoring_2017.pdf

Central Pollution Control Board (CPCB). (2021). National Inventory of Sewage Treatment Plants. March 2021, 183. https:// cpcb. nic. in/ status- of- stps/

CSIR-National Institute of Oceanography (CSIR-NIO). (2018). Monitoring of Coastal Marine and Estuarine Ecology of Maharashtra. Phase-I.

Dame, R.F. (2008). Encyclopedia of Ecology. Estuaries. 1407-1413. Charleston SC, USA. @ Elsevier B.V.

Datta, D., Arya, S. and Kumar, S. (2021). Industrial Wastewater Treatment: Current Trends, Bottlenecks, and Best Practices. Chemosphere, 285, 131245. https://doi.org/10.1016/j.chemosphere.2021.131245

de Jonge, V.N., Elliott, M. and Orive, E. (2002). Causes, Historical Development, Effects and Future Challenges of a Common Environmental Problem: Eutrophication. Hydrobiologia, 475, 1-19. doi:10.1023/A:1020366418295

Jadeja, N., Banerji, T., Kapley, A., and Kumar, R. (2022). Water pollution in India -Current scenario. Water Security (16), 100119. https://doi.org/10.1016/j.wasec.2022.100119

Kumar, M. and Padhy, P. K. (2015). Discourse and Review of Environmental Quality of River Bodies in India: An Appraisal of Physico-chemical and Biological Parameters as Indicators of Water Quality. Curr. World Environ., 10(2). http://dx.doi.org/10.12944/CWE.10.2.20

Maharashtra Pollution Control Board. (2019). Water Quality Standards for Best Designated Usages. https://www.mpcb.gov.in/water-quality/standards-protocols/ water-quality-standards_1

McLusky, D.S. and Elliott, M. (2004). The Estuarine Ecosystem: Ecology, Threats and Management. Oxford University Press, Oxford, UK.

Ministry of Environment, Forest and Climate Change (MoEF&CC). (2016). Notification-New Delhi. 1st January, 2016. S.O. 4(E)e. Environment (Protection) Amendment Rules, 2015.

Noori, R., Sabahi, M.S., Karbassi, A.R., Baghvand, A. and Taati Zadeh, H. (2010). Multivariate Statistical Analysis of Surface Water Quality Based on Correlations and Variations in the Data Set. Desalination, 260 (1–3), 129-136. doi: 10.1016/j.desal.2010.04.053.

Ouyang, Y. (2005). Evaluation of River Water Quality Monitoring Stations by Principal Component Analysis. Water Research, 39(12), 2621-2635. doi: 10.1016/j.watres.2005.04.024.

Padalkar, A. and Kumar, R. (2018). Common Effluent Treatment Plant (CETP): Reliability Analysis and Performance Evaluation. Water Science and Engineering, 11(3): 205-213. https://doi.org/10.1016/j.wse.2018.10.002

Patalganga & Rasayani Industries' Association (PRIYA). (2004). Brochure, Overall View of Common Effluent Treatment Plant (CETP).

Pesce, S. F., and Wunderlin, D. A. (2000). Use of Water Quality Indices to Verify the Impact of Córdoba City (Argentina) on Suquía River. Water Research, 34(11), 2915-2926. doi:10.1016/S0043-1354(00)00036-1.

Sánchez, E., Colmenarejo, M. F., Vicente, J., Rubio, A., García, M. G., Travieso, L., and Borja, R. (2007). Use of the Water Quality Index and Dissolved Oxygen Deficit as Simple Indicators of Watersheds Pollution. Ecological Indicators, 7(2), 315-328. doi: 10.1016/j.ecolind.2006.02.005

Seal, K., Chaudhuri, H., Pal, S., Srivastava, R. R., and Soldatova, E. (2022). A Study on Water Pollution Scenario of the Damodar River Basin, India: Assessment of Potential Health Risk using Long Term Database (1980- 2019) and Statistical Analysis. Environmental Science and Pollution Research, 29(35), 53320-53352. https://doi.org/10.1007/s11356-022-19402-9

Selvarajan, V., Obuobi, S., and Ee, P. L. R. (2020). Silica Nanoparticles- A Versatile Tool for the Treatment of Bacterial Infections. Frontiers in Chemistry, 8, 602. doi: 10.3389/fchem.2020.00602

Shrivastava, A., Tandon, S. A., and Kumar, R. (2015). Water Quality Management Plan for Patalganga River for Drinking Purpose and Human Health Safety. International Journal of Scientific Research in Environmental Sciences, 3(2), 0071-0087. http://dx.doi.org/10.12983/ijsres-2015-p0071-0087

Telesh, I. V. and Khlebovich, V. V. (2010). Principal Processes within the Estuarine Salinity Gradient: A Review. Marine Pollution Bulletin, 61(4-6), 149-155. doi: 10.1016/j.marpolbul.2010.02.008

Torregroza-Espinosa, A. C., Restrepo, J. C., Correa-Metrio, A., Hoyos, N., Escobar, J., Pierini, J., and Martinez, J. M. (2020). Fluvial and Oceanographic Influences on Suspended Sediment Dispersal in the Magdalena River Estuary. Journal of Marine Systems, 204, 103282. https://doi.org/10.1016/j.jmarsys.2019.103282

UN-Water. (2017). Wastewater: The Untapped Resource. United Nations World Water Development Report. https://www.unwater.org/publications/world-water-development-report-2017

Videira-Quintela, D., Martin, O., and Montalvo, G. (2021). Emerging Opportunities of Silica Based Materials within the Food Industry. Microchemical Journal, 167, 106318. https://doi.org/10.1016/j.microc.2021.106318

Watson, S. J., Cade-Menun, B. J., Needoba, J. A., and Peterson, T. D. (2018). Phosphorus Forms in Sediments of a River-dominated Estuary. Frontiers in Marine Science, 5, 302. doi: 10.3389/fmars.2018.00302

Zingde, M. D. and Govindan, K. (2000). Health Status of the Coastal Waters of Mumbai and Regions Around, Edited by: Sharma, V.K., in Environmental Problems of Coastal Areas in India. Bookwell Publications, New Delhi, 119- 132.