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ORIGINAL ARTICLE

One health and contaminated estuarine ecosystems: a critical review of the status of Thane Creek, Mumbai, India

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Abstract

Estuaries are critical components in the environmental risk assessment of anthropogenic contamination. They funnel the emissions from upstream terrestrial catchments and are often within historically established population and industrial centers. They are sensitive and biodiverse and increasingly acknowledged be subject to increasing risks and hazards from urban development and climate change. To understand these effects, regular monitoring is essential but needs to be appropriate to allow impact assessment and direct long-term mitigation strategies, building resilience under the advancing impacts of climate change. A One Health approach to environmental assessment is needed to counter the emergence of global public health threats, such as antimicrobial resistance (AMR) supporting the interaction between estuarine ecology, humans and the environment. We focus on Thane Creek, Mumbai, India as a critical case being recently designated a RAMSAR site and India's only urban RAMSAR wetland. The necessity of a robust environmental monitoring system for regulatory policy development reflects impacts from historic and emerging pollution sources. It is a particularly sensitive environment, and one of the largest creeks in Asia, with ecosystem function identified to be highly vulnerable to the impacts of climate change. Rapid urbanization, causing alterations to creek geometry over relatively short timescales, has impinged on wetland habitats. Data from governmental monitoring and previous studies of environmental quality in Thane Creek are compared to data for other Indian estuaries. Overall, there is evidence of contamination from sources including domestic sewage and nearby industries, which may have chronic impacts on the ecosystem. Dissolved oxygen was lower, biochemical oxygen demand higher, and coliform counts similar in Thane Creek compared to other estuaries. The influence of tidal dynamics and sediment movement is likely to develop seasonal variation in AMR within water and sediments with potential impact on a rich and diverse ecology, especially for migratory birds. Subsets of organic contaminants and potentially toxic elements are currently monitored infrequently in water but have been found enriched in the creek's sediments. These key geochemical parameters are likely to have significant impacts on environmental health and highlight the need for wider assessment of environmental stressors and the development of more robust estuarine health indicators. Given both the ecological and geographical sensitivity of the region focusing on one health is a more appropriate monitoring strategy to address the emerging ecosystem challenges.

Keywords Anthropogenic contamination · Estuary · One health · Pollution control · RAMSAR · Water quality · Sediment

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Introduction

The United Nations' Sustainable Development Goal 6 is "Clean Water and Sanitation", with Target 6.3 setting out the following aim: "By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally" (United Nations, accessed Jan 2024). With wider estuarine health and protection of biodiversity, the lack of control standards for water and pressure from climate change, we need holistic approach to environmental systems in the protection of public health. To develop policies in support of this goal and measure progress towards it, regular water quality monitoring must take place, and the right parameters must be measured. The ecology of these systems has often been well studied but we still need to deal with spatial and temporal pressures and how the system responds to climatic variation is a critical part. The potential proximity of physicochemical and biological indicators to threshold limits needs to be considered in building conservation strategies (Elliot et al., 2019). The relevance of estuarine ecological status and the need for adequate water quality monitoring is highlighted for a sensitive estuarine case in India.

Selection and measurement of water quality parameters is an ever-changing process as new contaminants and analysis techniques emerge (Behmel et al. 2016). The UN's core parameters for estimating water quality of rivers are dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), electrical conductivity (EC), total dissolved solids (TDS), salinity, total oxidized nitrogen (TON), total nitrogen (TN), ammoniacal nitrogen, nitrite, orthophosphate, total phosphorus (TP), and pH (Kirschke et al. 2020). Additional commonly measured water parameters include turbidity, temperature, chloride, total hardness, total solids (TS), and total suspended solids (TSS) (Ahmed et al. 2020). Commonly observed contaminants such as potentially toxic elements (PTEs) and organic compounds, such as polycyclic aromatic hydrocarbons (PAHs), may be monitored less frequently than other parameters or only at certain sites. Microbiological monitoring of water is typically focused on total coliforms and faecal coliforms, which act as indicators for sewage contamination and increased likelihood of pathogen presence (Cohen and Shuval 1973). In some reports, several parameters are used to calculate a Water Quality Index (WQI), as no single parameter is representative (Ahmed et al. 2020). Correlations between parameters may mean that monitoring can be optimized by removing some parameters from measurement regimes (Behmel et al. 2016). There are calls for estuarine indices to have a more ecological focus (Mulik et al. 2020) and provide link between anthropogenic intervention, resident and migratory species and environmental quality, introducing the core components of One Health. A collaborative approach to the health of people, animals and the environment.

Values of physico-chemical parameters in water are impacted by the presence of anthropogenic pollution and they in turn impact other water quality parameters and local ecology. For example, high BOD results in lower DO, due to increased aerobic breakdown of organic content. Suspended solids act as carriers for pollutants including hydrocarbons and PTEs, and high concentrations of solids may also block light and negatively impact the health of fish and aquatic plants, particularly benthic organisms (Aryal et al. 2010; Ferrier et al. 2005; Kennedy et al. 2016; Müller et al. 2020; Siddhesh et al. 2016). High concentrations of nutrients like nitrogen and phosphorus cause algal blooms, which reduce light and oxygen concentrations, and may also produce toxins that can damage the human brain, kidneys, and liver (Erickson et al. 2013; Pal et al. 2014). PTEs are persistent in the environment and can cause organ damage (e.g. cadmium, lead, zinc), may be carcinogenic (e.g. chromium, arsenic) (Bearcock et al. 2017; Nieder et al. 2018), or become toxic at high concentrations (e.g. nickel, iron) (Gurav et al. 2013). Low pH can result in release of PTEs bound to sediment and an increase in PTE bioavailability. Hydrocarbon compounds can be acutely toxic at high concentrations, and some (including PAHs) are also carcinogenic or mutagenic and may cause heritable genetic damage (Kennedy et al. 2016; Liu et al. 2018; Rodgers et al. 2019; Tiwari et al. 2017).

The World Health Organization's Guidelines for Drinking-Water Quality (GDWQ) are a non-binding set of parameters and standards on which many countries base their own drinking water legislation. No global set of recommendations equivalent to the GDWQ exists for surface water, leading to high levels of heterogeneity in monitored contaminants and regulatory limits between different regions, particularly for organic contaminants (Van Winckel et al. 2021). The provision of a set of global guidelines and limits for surface water would enable a more unified approach to environmental protection and regulation of contamination sources. Standardized approaches to monitoring would support the development and implementation of these guidelines.

To facilitate guideline development, monitoring should be cost-effective and easily adaptable to emerging contaminants or changing risks, and data resulting from monitoring must be of high quality and readily accessible (Lovett et al. 2007). Identifying relationships between parameters may allow more streamlined and cost-effective monitoring. To ensure that policy developed from monitoring data is adequate, sufficient parameters must be examined. A better understanding of the behavior of and risks posed by contaminants in the environment is required. Data should not be limited to only laboratory-based experiments. This includes both well understood contaminants like PTEs that have been researched for many years, and emerging contaminants including pesticides, per- and polyfluoroalkyl substances, and antibiotics, which may have differing impacts in varied environments alongside other contaminants.

The growing interest in better assessment of indicators for estuarine health beyond standard physicochemical and biological contaminants, targets other indicators such as disease (Tallam and White 2023). More representative assessment to protect and develop indicators of estuarine health bring forward the potential to incorporate of One Health principles could benefit environmental monitoring and more resilient management of sensitive estuarine ecosystems (Adams et al. 2020). One Health is a holistic, transdisciplinary view that considers the connections between human, animal, and environmental health (Ogunseitan 2022). Engagement with stakeholders from each of these areas would provide a strong basis on which to build regulatory guidelines, ensuring that they tackle not only environmental contamination from a purely ecological perspective, but also incorporating broader impacts to health including the spread of zoonotic diseases or antimicrobial resistance (AMR). Monitoring is essential but climate change drives ever changing baselines, making detection of natural and/or anthropogenic disruptions challenging without evaluating alternative strategies (Elliot et al., 2019).

For example, although current water quality guidelines may be sufficient in preventing direct health and ecosystem impacts by contaminants, they may not be stringent enough to avoid applying selection pressures that promote environmental AMR. Gullberg et al. (2014) found that minimum selective concentrations (MSCs) for various antibiotics and PTEs were well below the minimum inhibitory concentrations (MICs) with the maximum difference being arsenic's MSC – 140-fold lower than its MIC. Synergistic effects were identified between some antibiotics and PTEs (Gullberg et al. 2014), suggesting that selective pressures leading to AMR could occur even in the presence of very low concentrations of contaminants. Therefore, regulatory standards may have to be altered or alternative parameters such as antibiotics could be included in routine monitoring.

Thane Creek, Mumbai India is a contaminated estuary, subject to dynamic change. It holds significant ecological and environmental status as an important coastal mangrove system. These systems across India are projected to show a cumulative loss of 60% by 20,230 (Sharma et al. 2022) yet are crucial in coastal zone protection and ecosystem services (Asari et al. 2021). Thane Creek receives waste from industries including automotive, metallurgical, and pharmaceutical companies, as well as untreated or partially treated domestic sewage from several highly populated areas. Impact assessments of the threat from climate change have identified sensitive zones of mangrove forest within the tidal creek system, vulnerable to sea level rise, impacting on the wider urban resilience to flooding (Murali et al. 2020). A detailed analysis of land use and land cover change (LULC) predicts important changes in river channel dynamics with increasing urbanization. There are consequences for vegetation on the creek banks and wider biodiversity over relatively a short term (Vijay et al. 2020). The local designation of surrounding land as a Special Economic Zone in 2005 resulted in the loss of > 130 acres of mangrove by 2022 (Sharma et al. 2022). The addition of Thane Creek to the National Waterways Bill in 2015, places it further within a zone of potential disruption as a transport route subject to development and maintenance activities (Dharmadhikary and Sandbhor 2017). Contamination in the creek has the potential to affect not only local people but also flora and fauna (including mangrove wetlands and a flamingo sanctuary) and the microbial community. As such, Thane Creek represents a tropical estuary impacted by anthropogenic activity, considering contaminant pressures, the relationships between them, and factors that should be considered when designing monitoring schemes and quality standards, particularly from a One Health perspective.

Thane Creek, India – a multi-pollutant receptor

Overview

Estuaries and creeks are often subject to urbanization, industrialization, shipping activity, and the discharge of waste, as tidal flushing should theoretically result in lower long-term impacts on the ecosystem (Athalye et al., 2012; Rodgers et al. 2019; Vijay et al. 2020). They perform critical functions and provide up to $5.4 trillion in multiple ecosystem services, with pressures driven by dredging/draining, habitat change, toxins and nutrients and pathogens and invasive species (Talam & White, 2023). However, through their naturally dynamic nature, the resuspension of sediment and changes in salinity due to tidal flow leads to cyclical adsorption and release of contaminants, resulting in pulses of exposure that can impact fish, invertebrates, algae, and the microbial community (Roberts 2012; Rodgers et al. 2019).

Thane Creek is a tidal estuary in the Indian state of Maharashtra. The creek extends from the Ulhas River in the north to the Arabian Sea in the south and is bordered by the populous cities of Mumbai in the west, Navi Mumbai in the east, and Thane to the north. The section of Thane Creek that lies between Vashi Bridge and Airoli Bridge is also known as Vashi Creek. The state of Maharashtra accounts for more than a quarter of India's textiles, chemicals, metallurgy, and transport production (Jaiswar et al. 2018). Navi Mumbai is a hub for industries including pharmaceutical, electronics and petrochemical manufacturing, and contains the Thane-Belapur Industrial Belt – at one time Asia's largest industrialized region (Siddhesh et al. 2016; Tambe and Gotmare 2017). At the seaward end of Thane Creek are Mumbai Port and Jawaharlal Nehru Port, both major sites for import/export of cargo including crude oil, fertilizer, food, chemicals (Jaiswar et al. 2018).

The creek is approximately 27 km long with a minimum depth of 0.5 m, so factors such as monsoon season rainfall, effluent discharges, and tidal flushing have significant impacts on water quality (Jaiswar et al. 2018; Singare 2012; Thomas et al. 2022). The flushing time of an estuary/creek impacts its long-term ecosystem health – faster flushing reduces the chance of negative impacts e.g. from waste discharges. Thane Creek joins to the Ulhas River in the north but receives very little freshwater input except during the monsoon season due to the narrowness of the creek's connection to the river (100 m width) (Thomas et al. 2022). The creek is funnel-shaped, reaching a width of 9000 m at the seaward end and a maximum depth of 12 m (Pradhan et al. 2021). Modelled tidal simulation has projected this seasonal variation with semi diurnal ebb and flood dynamics, varying from the mouth northwards, changing sediment erosion and deposition conditions, critical for the mixing/dispersal of contaminant discharges (Thomas et al. 2019). Recent analysis (Ragkkasagi et al., 2024) of all costal Ramsar sites in India, have highlighted Thane Creek as high risk in terms of extreme rainfall – on the basis of return levels and extreme precipitation events. In addition, widespread flooding is also predicted as a significant risk potentially enhanced climatic oscillations.

It is bordered on both sides by mudflats and mangroves, which play important ecosystem roles including cycling of nutrients (phosphorus, nitrogen, carbon), providing habitats for wildlife, retention of PTEs, and reducing coastal erosion and flood risk (Abdul Azeez et al. 2022; Fernandes et al. 2012). There has been a 40% reduction in mangrove cover around Mumbai in the last 10 years (Abdul Azeez et al. 2022), due to anthropogenic activities including the use of mangrove wood as fuel or the creation of space for developments such as aquaculture (Borkar et al. 2007).

It was designated a Ramsarsite (a wetland site of international importance under the Ramsar convention (https://www.ramsar.org/) in 2022 (Ramsar accessed 21 June 2024) hosting ~ 20% of the Indian mangrove species and has been declared as the "Thane Creek Flamingo Sanctuary" and an important part of the Central Asian Flyway for bird migration. The forests providing an important buffer to storms and other coastal extreme events. With over 400 faunal species it ranks 25th out of 75 RAMSAR sites in India, acknowledged to need further assessment to understand the significance of faunal structure (Bannerjee et al., 2023). A rich flora and fauna have been described in some locations and includes diverse resident and migratory bird species in addition to mammals, amphibians, reptiles, invertebrates and other species (Khan and Gupta 2024).

Industrialization around Thane Creek began in the 1960s, with the development of the Trans-Thane Creek region from 44 industrial units in 1971 to 3800 in 2006 (Athalye et al., 2012). Studies of the creek environment over this period found increased silt content, increased silicate concentrations, increased PTE content in water, sediments, and fish, and a decrease of DO to less than 2.5 mg/l (considered hypoxic). By 2012, DO at several points in the creek was 0 mg/l. In the 1980s, fish catch as far north as Thane was plentiful and diverse but by 2002 fishing was limited to the mouth of the creek apart from during monsoon season (Athalye et al., 2012). Fish yield in Thane Creek has fallen dramatically since the 1980s, with 1999–2000's yield only 4% of that in 1981-82 (Nikam et al. 2008). Commercial fishing in the creek has become less and less viable more recently due to factors including the clogging of fishing nets with solid waste and litter, and fish death due to the discharge of toxic chemicals and waste (Goldin and Athalye 2012).

The area around Thane Creek has undergone significant change over the last several decades. Since 1972 there has been a 7.1% increase in built-up land cover in the areas of Mumbai, Navi Mumbai, and Thane that surround the creek (Vijay et al. 2020). Due to a combination of shifting mangrove growth patterns (towards the creek ward side) and the frequent discharge of domestic and industrial waste, the creek's width has now decreased significantly. Between 1972 and 2016, the width of the lower, seaward region of the creek has decreased by 13.2%, while the upper region has decreased by 46% (Vijay et al. 2020). The construction of Vashi Bridge in 1996 has also led to narrowing of the creek and a change in water currents and tidal flushing. As a result, more plastic waste such as bags, bottles, and fibers has become trapped in the creek (Rathod, 2020).

Development of the area around Thane Creek has been relatively rapid and industrialization is still ongoing, leading to a sharper increase in pollution burden and perhaps greater risk from emerging contaminants in comparison to estuaries that experienced slower, longer-term exposure to contamination followed by declines in population and industrial activity (e.g. the River Clyde in Glasgow (Rodgers et al. 2019). As a result of this, stress on the ecosystem may be greater in Thane Creek than in other estuaries. Waste discharged into the creek includes pharmaceutical waste, which has potential to increase AMR in environmental microorganisms including pathogens. The impact of rapid urbanization, the threat of AMR impacting human health as well as other anthropogenic contamination affecting Thane Creek's high biodiversity (including mangroves and flamingos), make this area an important case to consider a One Health approach to estuarine health under increasing ecosystem pressures. Assessing the relevance of indicators for the ecological status of estuaries is more straightforward for locations with high pollution and salinity loading but less clear in intermediate zones (Mulik et al. 2020). This limitation needs to drive new strategies for monitoring and regulating impact from industrialization.

Local treatment & monitoring

Currently, there are seven sewage treatment plants in Mumbai, providing primary treatment to sewage before its discharge into the environment. By 2030, it is expected that seven more treatment plants will be constructed, each of which will treat 2,464 million litres of sewage per day to secondary or tertiary level (Chitnis 2023). In Thane, sewage is treated by eight plants, six of which were constructed within the last five years (Pol 2019). In the Navi Mumbai industrial area, larger industries have their own full treatment plants. Small industries have individual primary effluent treatment plants (ETPs) then shared Common Effluent Treatment Plants (CETPs) where additional treatment occurs before discharge of effluent into Thane Creek. There are seven sewage treatment plants in Navi Mumbai as well as a solid waste landfill site (Athalye et al., 2012). Sewage plumes at discharge points into Thane Creek can be seen using remote sensing (Sasamal et al. 2007). Sewage enters the creek directly from open drains (untreated), or from treatment plants (either partially treated or having undergone secondary treatment) (Vijay et al. 2014).

Water quality monitoring in India is overseen by the Central Pollution Control Board (CPCB), under the Water (Prevention and Control of Pollution) Act 1974 (Bhardwaj 2005). As of 2022, the CPCB's monitoring network consisted of 4484 stations covering surface freshwater, coastal water, and groundwater (Central Pollution Control Board, n.d.-b). According to CPCB guidelines, water quality at "Trend" stations (used to demonstrate how water quality at a certain point varies over time due to geogenic and anthropogenic factors) is monitored monthly for the following 25 parameters: colour, odour, temperature, pH, EC, DO, turbidity, TDS, ammoniacal nitrogen, nitrite & nitrate nitrogen, total phosphate, BOD, COD, total coliforms, faecal coliforms, fluorine, boron, and the ions sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), chloride (Cl^-), and sulphate (SO_4^{2-}). In addition, pesticides are monitored once yearly (pre-monsoon), toxic metals twice yearly (pre- and post-monsoon, subset of metals monitored based on location), and specific organic compounds including PAHs are monitored only if deemed necessary for a specific site (Central Pollution Control Board 2017).

Apart from the CPCB, each state has its own pollution control board. Maharashtra Pollution Control Board (MPCB) is responsible for regulating the management of wastewater generated in industries. As the treated industrial wastewater is discharged into Thane Creek, the creek's water quality is tested regularly by the MPCB. Water quality is tested at Kalwa Bridge in the far north of the creek, Elephanta Island towards the south, at Ghansoli Jetty along the Trans Thane Creek arm of the creek, and at Vashi Bridge and Airoli Bridge in Vashi Creek (Fig. 1).

Water quality parameters and trends

A subset of these measurements is published annually in the MPCB's water quality status report – namely pH, DO, BOD and faecal coliforms (FC) (Maharashtra Pollution Control Board, n.d.). Table 1 shows the average annual pH, DO, BOD, and FC at each site since 2013 (Maharashtra Pollution Control Board, n.d.). In addition, the CPCB publishes the minimum and maximum values measured each year for the following parameters: temperature, DO, pH, EC, BOD, nitrate & nitrite nitrogen, faecal coliforms, and total coliforms (Central Pollution Control Board, n.d.). Figure 2 summarizes the annual monitoring data from 2013 to 2021. Broadly stable annual maxima are seen in temperature, dissolved oxygen (and to an extent BOD), and conductivity generally shows the influence of salt water towards the mouth of the creek. Other microbial and chemical parameters more indicative of pollution inputs are much more variable, indicating the influence of pollution point sources along the creek. While average annual values of DO are generally above the minimum limit set by CPCB for SW-II class waters (4 mg/l) (Table 2), minimum values in many of the samples fall below this. Values of BOD exceed the CPCB's maximum limit in all samples while faecal coliform counts exceed limits in many of the samples, though they vary quite significantly between sites and sampling times.

Governmental monitoring is an important source of data on environmental contamination, as it is standardized, long-term, and regular. Ideally, all government data should be made readily available to inform future monitoring strategies and allow comparison with academic studies, which may be focused on narrower areas, different time points, or specific contaminants. As Thane Creek is currently

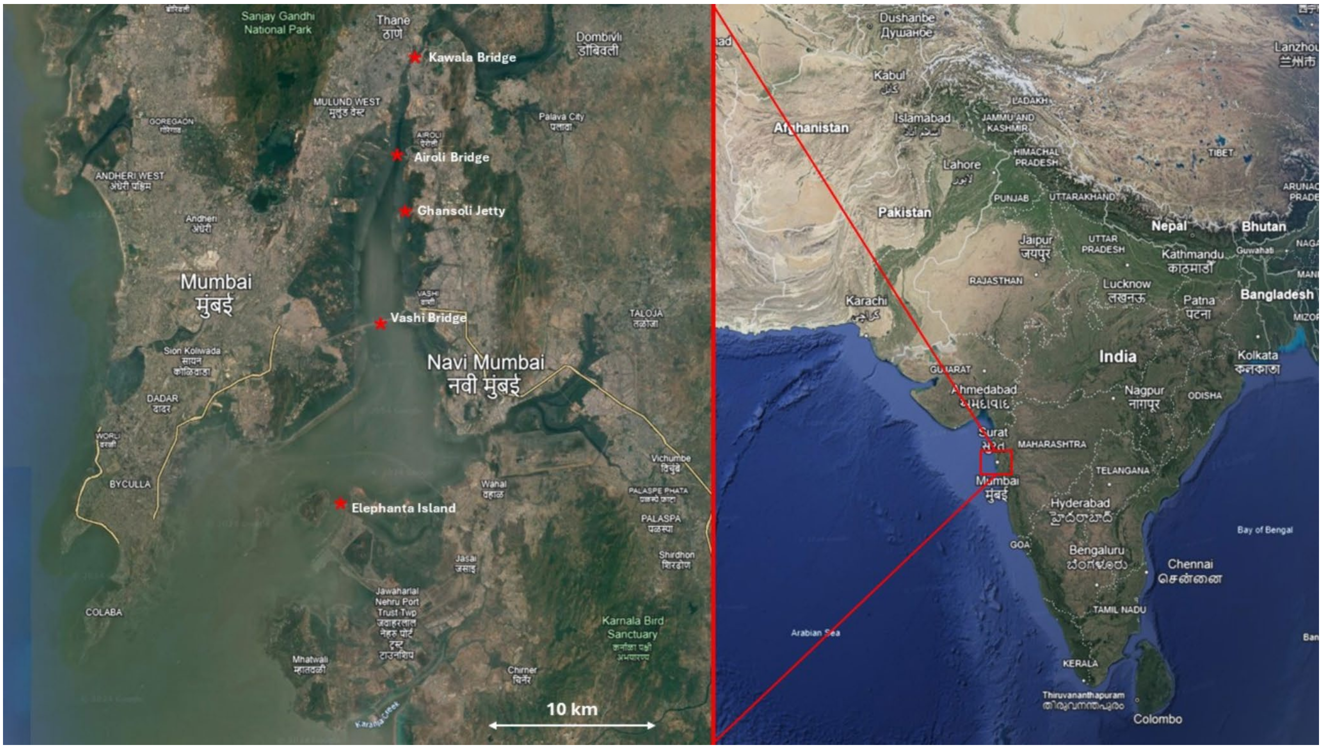

Fig. 1 Map showing geographical context of Thane Creek, Mumbai in India with Maharashtra Pollution Control Board (MPCB) water quality monitoring sites marked. Map source: Google Maps, 2024, E. Asia, available at https://earth.google.com/web/@19.0061701,72.88464728,30.71182698a,81868.294717d,35y,0 h,0t,0r/data=CgRCAggBOgMKATA (accessed 11/09/2024)

monitored regularly by the CPCB and MPCB, we consider opportunities where additional parameters or monitoring strategies may be necessary.

Contamination in Thane Creek

Thane Creek experiences contamination from a broad range of sources. An estimated 28,750 m^3 of treated and untreated waste are discharged into the creek daily from surrounding industries and their associated effluent treatment plants (Siddhesh et al. 2016), along with around 1260 megalitres of domestic sewage per day (Jaiswar et al. 2018). Almost 85% of pollution loading occurs north of the Ghatkopar outfall, close to Vashi Bridge (Sasamal et al. 2007).

Water standards set by CPCB for marine coastal outfalls and by the Bureau of Indian Standards (BIS) for drinking water and surface water are shown for reference in Table 2.

Water quality in Vashi Creek was measured by Tambe and Gotmare (2017) measured during July & August 2016 and compared to drinking water standards set by the Indian Council for Medical Research (ICMR), WHO, and BIS. They found that mean pH, chloride, TDS, and sulphate concentrations were within permissible limits but that BOD, COD, and TSS exceeded these limits. BOD was very high, which is of concern as high BOD can result in low oxygen concentrations in the water, leading to fish death, odour, and reduced decomposition (Tambe and Gotmare 2017). A study by Chordiya et al. (2021) examined Vashi Creek water quality data from the ENVIS Centre on Control of Pollution Water, Air, and Noise database, relating to 2008–2019. Similarly, they found that in some years BOD and DO did not meet the drinking water standards set by the ICMR (5 mg/l for both BOD and DO).

Additionally, dissolved oxygen levels in the upper part of the creek (Vashi Bridge and north) often fall below the CPCB's lower recommended limit of 4 mg/l. Nikam et al. (2008) found DO concentrations of only 0.9 mg/l in the northern region of Thane Creek between Balkum and Kalwa Bridge, increasing further south to 2.2 mg/l between Kalwa Bridge and Airoli Bridge, and to 3.1 mg/l between Airoli Bridge and Vashi Bridge. Most samples from this region also exceed the recommended BOD limit of 3 mg/l, which is likely a contributing factor to the low DO concentrations. Jaiswar et al. (2018) and Vijay et al. (2014) found DO was dependent on tides, with concentrations <3 mg/l in the upper creek at low tide (Jaiswar et al. 2018) and during low tide from middle of the creek upwards and in the upper region during high tide (Vijay et al. 2014). Additionally, BOD was again above CPCB standards (Vijay et al. 2014).

Faecal coliforms were identified above CPCB standards by Chordiya et al. (2021) and Vijay et al. (2014, 2015) with maximum concentrations of 1×105 MPN/100 ml, 5.9×105

Table 1 Average annual values of pH, dissolved oxygen (DO), biological oxygen demand (BOD), and faecal coliforms in sites along Thane Creek. Data: Maharashtra Pollution Control Board, n.d

Location	Year	pH	DO (mg/l)	BOD (mg/l)	Faecal Coliforms (CFU/100 ml)
Elephanta Island	2013–2014	7.7	5.1	7.8	666
	2014–2015	7.86	-	9.56	463
	2015–2016	7.9	4.8	9.7	558.25
	2016–2017	-	-	-	-
	2017–2018	7.2	3.9	12.6	33.8
	2018–2019	7.2	4.2	12.5	327.9
	2019–2020	7.3	4.4	11.7	205.6
	2020–2021	7.27	4.23	10.44	113.78
Vashi Bridge	2013–2014	7.6	4.6	8	688
	2014–2015	7.63	4.81	18	437
	2015–2016	7.6	5	8.1	198
	2016–2017	-	-	-	-
	2017–2018	7.2	4.5	10.9	29.8
	2018–2019	7.3	4.6	10.4	69
	2019–2020	7.2	4.9	9.8	48.3
	2020–2021	7.35	4.61	9.91	46.73
Airoli Bridge	2013–2014	7.5	4.7	7.4	600
	2014–2015	7.65	4.92	17.6	400
	2015–2016	7.5	4.7	8.2	266.5
	2016–2017	-	-	-	-
	2017–2018	7.2	4.3	9.9	30.6
	2018–2019	7.2	4.5	11.6	95.5
	2019–2020	7.4	4.6	31.5	74
	2020–2021	7.43	4.61	10.18	98.42
Kalwa Bridge	2013–2014	7.4	3.7	10.1	481
	2014–2015	7.51	4.18	17.3	208
	2015–2016	7.5	4.7	8.5	143
	2016–2017	-	-	-	-
	2017–2018	7.2	4.5	10.3	48.4
	2018–2019	7.3	4.7	8.9	82.6
	2019–2020	7.3	4.8	9.5	39.1
	2020–2021	7.23	4.38	9.3	104.75
Ghansoli Jetty	2013–2014	-	-	-	-
	2014–2015	-	-	-	-
	2015–2016	7.2	5	8.9	361.67
	2016–2017	-	-	-	-
	2017–2018	7.2	4.3	11	55.9
	2018–2019	7.1	4.5	16.3	103.1
	2019–2020	7.4	4.5	9.9	41.3
	2020–2021	7.4	4.79	8.95	45.82

MPN/100 ml, and 965 MPN/100 ml respectively. The presence of faecal coliforms is indicative of domestic sewage pollution in Thane Creek. Vijay et al. (2015) also found high BOD, ammoniacal nitrogen, and phosphate, as well as low DO concentrations – all of which are additional indicators of sewage contamination. Water quality was lower pre-monsoon, at low tide, and in the upper regions of the creek, suggesting that dilution by tidal flow and monsoon input is an important factor in contamination control (Vijay et al. 2015).

Generally, previous studies of Thane Creek suggest that contamination, likely from discharge of sewage, is impacting water quality, particularly oxygen levels. For comparison to other, similar locations Table 3 shows water quality parameters for selected estuaries across India. Average DO values in these estuaries meet CPCB standards, except for the Uppanar Estuary, which is close to a cluster of chemical processing plants (Gopal et al. 2018). Data analysed by Chordiya et al. (2021) found average BOD of 20.3 mg/l at Airoli Bridge and 19.9 mg/l at Vashi Bridge. In both cases this is significantly higher than BOD measured in other estuaries (Chakraborty et al. 2021; Mitra et al. 2018; Thasneem et al. 2018). Faecal coliforms in Hugli Estuary were measured by two studies (Chakraborty et al. 2021; Mitra et al. 2018), both also above the CPCB limits, with maximum concentrations of 7338 MPN/100 ml (Chakraborty et al. 2021) and 5615 MPN/100 ml (Mitra et al. 2018). These maximum concentrations are significantly higher than Thane Creek concentrations presented by Chordiya et al. (2021) but significantly lower than those measured by Vijay et al. (2015). Overall, comparisons to other estuarine water in India indicate that Thane Creek experiences sewage contamination as seen in other estuaries, leading to similar coliform presence, but that additional contamination from industry is further negatively influencing water quality in Thane Creek. Data from the creek can therefore be considered representative of contaminated estuaries affected by sewage and/or industrial waste.

Sediment quality

Sediment quality in Indian estuaries is not subject to regular government monitoring, but several studies have measured concentrations of metals and organics in Thane Creek. Analysis of sediment alongside water provides additional insights into contamination, as many pollutants including PTEs, PAHs, and antibiotics can accumulate within the sediment and persist for many years. Concentrations of pollutants in sediment tend to be higher and more stable over time than in water (Fernandes and Nayak 2012) and can be re-suspended due to tidal movements, dredging, or storms (Roberts 2012). Therefore, analysis of creek sediment demonstrates the long-term conditions to which local plants, animals, and microbes are exposed. This may reveal contaminants that are not currently monitored in water yet are having a significant impact on ecosystem health.

Samples of sediment from ten locations in Thane Creek, as well as additional samples of seawater, during May and November 2014 were analysed by Tiwari et al. (2017). They found that sediment PAH concentrations (USEPA 16) were

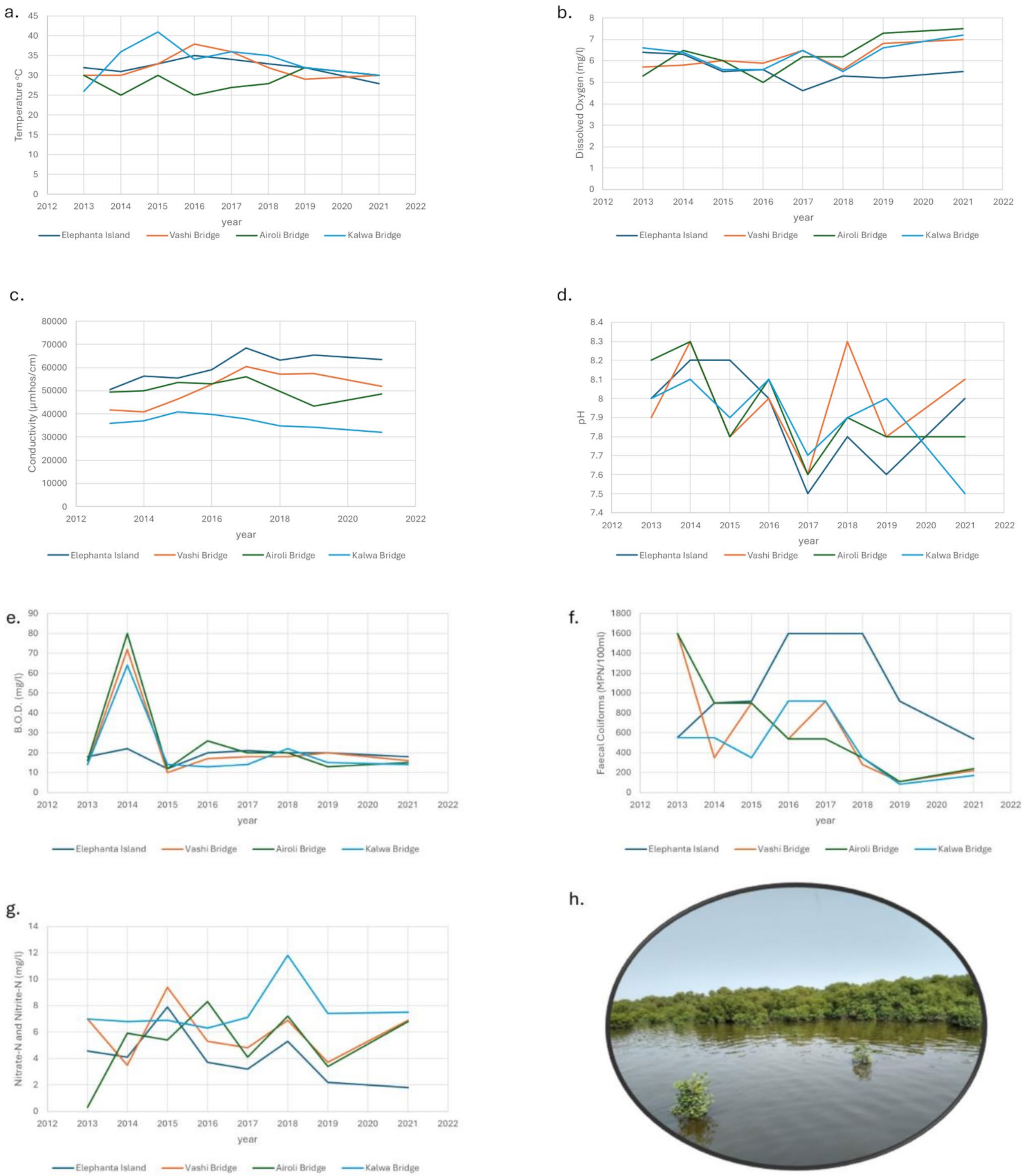

Fig. 2 Maximum annual values (2013–2021) for water quality parameters along Thane Creek Mumbai: (**a**) temperature, (**b**) DO, (**c**) conductivity, (**d**) pH, (**e**) BOD, (**f**) faecal coliforms, and (**g**) (nitrate + nitrite) nitrogen, f. shows general view of mangrove forest along Than Creek. Data: Central Pollution Control Board, n.d.-a

Table 2 CPCB standards for marine coastal outfalls (Central Pollution Control Board, n.d.-c) and BIS standards for drinking water (IS 10500:2012 and surface water (IS 2296:1992)

	CPCB SW-II (For Bathing, Contact Water Sports and Commercial Fishing)	CPCB SW-III (For Industrial cooling, Recreation (non-contact) and Aesthetics)	BIS Drinking Water	BIS Surface Water Quality (Class B – Outdoor Bathing)
pH	6.5–8.5	6.5–8.5	6.5–8.5	6.5–8.5
DO (minimum)	4 mg/l	3 mg/l	-	5 mg/l
Coliforms	100/100 ml (Faecal)	500/100 ml (Faecal)	0/100 ml (Faecal)	500/100 ml (Total)
BOD	3 mg/l	3 mg/l	-	

Table 3 Water quality data for selected estuaries across India

Location	Type	pH	DO (mg/l)	BOD (mg/l)	Faecal coliforms (MPN/100 ml)	Reference	Notes
Uppanar Estuary	Surface water	8.2	2.4		-	Gopal et al. 2018	Means of 25 sampling points
Hugli Estuary	Surface water	7.9	4.55	1.38	3306	Mitra et al. 2018	Means of 8 sites over 3 seasons
Cochin Estuary	Surface and bottom water	7.25	6.2	2.42	-	Thasneem et al. 2018	Means over 9 stations over 24 months
Hugli Estuary	Surface water	7.48	5.16	2.68	4561	Chakraborty et al. 2021	Means of 8 sampling points, 2 sampling times (before and during lockdown)
Ashtamudi Estuary	Surface and bottom water	7.92	5.86		-	Babu et al. 2010	Means of 30 locations over 2 seasons

2–3 times higher in winter than in summer, with a winter mean of 1391 ng/g compared to 317 ng/g in summer. This pattern was also seen in the seawater samples, with a winter mean of 706 ng/l and summer mean of 337 ng/l. When compared to quality guidelines, most PAHs were above the threshold effect level (TEL) in winter, but all samples were below the probable effect level (PEL) in both seasons. High winter PAH concentrations could be due to rainfall in the previous monsoon season transporting PAHs to the creek from the surrounding area leading to build-up in sediment, or due to low temperatures slowing degradation rates (Tiwari et al. 2017). Sukhdhane et al. (2015) found that sediment in Thane Creek (around the Vashi Bridge area) was moderately polluted with PAHs, with concentrations ranging from 902 to 1,643 ng/g, while Basavaiah et al. (2017) found that PAH concentrations were greater in the upper layers of sediment and identified a nearby solid waste burning site as a likely potential source of these PAHs. Further work by Nair et al. (2024) revealed a spatially varying balance between petrogenic and pyrogenic inputs, with the lower parts of Thane Creek most affected and PAH concentrations (USEPA 16) showing similar ranges (16.53-1,317.02 ng/g dw) over 10 years since the previous study (Sukhdhane et al. 2015).

Soil taken from near Kalwa Bridge, at the northern end of Thane Creek, was analyzed by Singare et al. (2010). They found seasonal differences in pH, PTE concentrations, conductivity, alkalinity, and chloride concentrations – all of which were higher during the pre-monsoon season than during the monsoon. Sediment from fourteen locations in the creek, the majority coming from south of Vashi Bridge, was analyzed by Maity et al. (2017). Most of the PTE concentrations were highest at the sample site just north of Vashi Bridge, on the east side of the Creek – close to the industrialized area of Navi Mumbai and factories producing chemicals, textiles, pharmaceuticals, and fertilizer. Additionally, Maity et al. (2017) found that PTE concentrations were higher in sediments with a greater proportion of fines. Increasing siltation in the creek due to anthropogenic contamination may therefore also lead to higher concentrations of PTEs and associated negative impacts on the ecosystem. However, at other locations in the creek, the impact of water current on sediment transport during tidal cycles can disrupt associations of PTEs with sediment and generate contradictory associations. For example, in "sluggish" parts of Thane Creek channel, preferential removal of fine-grained materials by current action can enhance the relative association of PTEs with coarser grain size fractions (Lonkar et al. 2022) and higher silt loadings.

A study analysing PTE distribution in mudflat and mangrove sediments(Fernandes and Nayak 2012) identified depth variation in in PTE where, in both sediments, copper concentration increased with depth while lead concentration fell. Many PTEs in Thane Creek mudflat and mangrove sediments correlate with each another, suggesting that they may have arisen from the same source or are exhibiting the same behaviour once they enter the creek. Correlations between PTEs and iron/manganese suggest that redox interactions are occurring in the sediment. Iron and manganese are redox-sensitive and their oxides/hydroxides readily bind to other PTEs and therefore play a key role in controlling their distribution (Fernandes et al. 2012). Copper concentrations correlated with organic matter, so industrial effluent or domestic sewage could be the primary source of copper contamination (Fernandes and Nayak 2012).

Concentrations of PTEs in Thane Creek soil and sediment appear to be heavily influenced by season and location. Proximity to industrial facilities and sewage discharges are likely to lead to higher PTE levels, although heavy rains during the monsoon period may cause changes in concentrations across the year. Local geology is an important factor in PTE concentration, as varying soil types (whether formed naturally or through anthropogenic activity) and mineralogy influence binding strength of many toxic elements.

Table 4 shows concentrations of PTEs in sediment in other Indian estuaries. Although manganese was the only element which was highest in concentration in Thane Creek, concentrations of other PTEs in the creek were generally comparable with the more contaminated of the other estuaries. Again, highlighting the relevance of Thane Creek as a model estuary for anthropogenic impacts on tropical Indian estuaries. .

Discussion

Although chemical parameters such as PTEs and organic compounds are often included in monitoring strategies, they may not be monitored frequently enough. The review of data for Thane Creek demonstrates contamination in sediment parallels many other estuaries across India and is significantly impacted by seasonal changes. Consequently, the current approach of once- or twice-yearly monitoring of subsets of these contaminants in water may not be sufficient to develop an accurate picture of the threats they pose. More significantly the tidal cycle is an important influence on the abundance of *E. Coli* in water. With increasing salinity as flow tides rise, incoming water dilutes contamination (Baliarsingh et al. 2021). In other Indian estuaries whilst the influence of monsoonal water dynamics improves water quality through dilution, microbial isolates from monsoonal sediments and waters exhibit multiple antibiotic resistance which has been attributed to increased flushing of terrestrial contamination (Toraskar et al., 2022). This aspect of estuarine dynamics has yet to be fully evaluated in terms of dispersal or deposition of suspended contaminated sediments in lower energy locations such as the mangrove forests. The indications of differential sediment transport in sections of Thane creek and coupled with the high risk of disruptive rainfall events, flushing material from terrestrial systems into the estuary, are more subtle features of pollutant dynamics beyond estimates of discharge loadings. It shows more detailed assessment needs to be linked to estuarine health and the inclusion of sediment monitoring or more frequent water monitoring is key in understanding current contamination levels. Whilst the dynamic nature of estuaries defines them, it is still unclear as to the implications of these dynamics on the propagation of e.g. AMR through the food chain and influence on the resident and migratory animals within these important wetland habitats.

This narrative has been based on assessment more conventional pollution indicators and data is lacking for emerging contaminants such as antibiotics, microplastics, and Per- and polyfluoroalkyl substances (PFAs) in Thane Creek, all of which have significant potential to harm the Vashi Creek ecosystem and impact human health either directly or indirectly through the spread of AMR and zoonoses. There is likely to be an increased risk as more waste treatment capacity is introduced in the catchment as many of these emerging substances are weakly removed in conventional processes. Appropriate monitoring techniques and regulatory standards must be developed for these contaminants, which will require a greater understanding of their behaviour in the environment and relationships with other contaminants and the ecosystem itself all part of the collaborative needs for the implementation of a One Health approach.

Alternative parameters may need to be considered to develop a full picture of contamination and risk. For example, while faecal coliforms are generally better indicators than total coliform count (Dutka 1973; Ramteke et al. 1992), they may still be inadequate as a measure of contamination and health risk, particularly in tropical waters (Hazen 1988).

Testing for alternative microorganisms such as faecal streptococci (Cohen and Shuval 1973) or carrying out DNA sequencing may therefore be required to fully understand microbiological quality of water. The presence of AMR is another important consideration that is currently overlooked in global environmental monitoring. Again, this may require DNA sequencing or susceptibility tests to be added to the current monitoring profile. However, the monitoring of additional chemical parameters such as antibiotic concentrations may be a sufficient indicator for AMR risk.

Conclusions

To develop policies for environmental protection that incorporate One Health principles and safeguard human, animal, and ecosystem health, a strong base of monitoring and data is required. As such, the effect of each parameter on all areas of the human-animal-environment interaction must be considered when creating standards and guidelines. Ecosystem health indicators need to be robust and reflect the multiple stressors and their sensitivity to direct anthropogenic impacts and those of climate change. Parameters must be chosen to maximize information gained from monitoring while remaining cost-effective. By determining

Table 4 Mean PTE concentrations (in ppm) in sediment samples from selected estuaries across India

Location	Type	Al	As	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn	Reference	Notes
Khonda Creek	Surface sediment	63,800	-	-	54.9	-	91.9	58,500	-	1420	121	55.8	98	Volvoikar and Nayak 2013	Section 3 means
Dubh Creek	Surface sediment	90,800	-	-	51.5	-	148	99,900	-	1721	156	62.7	211	Volvoikar and Nayak 2013	Section 3 means
Kavvayi Estuary	Surface sediment	-	-	-	78.1	206.4	23.09	-	-	280.2	83.8	17.6	60.2	Kumar et al. 2022	Averages of 21 sampling points
Kallar Estuary	Surface sediment	-	7.3	3.61	1.38	10.12	27.43	34,125	0.2	356.25	33.78	29.11	320.38	Magesh et al. 2013	Averages of 8 sampling points
Korampallam Creek	Surface sediment	-	5.06	5.29	5.11	26.85	98.1	23,663	0.238	357.5	33.99	67.38	190.38	Magesh et al. 2013	Averages of 8 sampling points
Punnakayal Estuary	Surface sediment	-	5.69	10.4	3.65	9.34	30.98	28,363	0.331	277.63	21.2	28.13	231	Magesh et al. 2013	Averages of 8 sampling points
Cochin Estuary	Surface sediment	-	-	5.07	13.75	133.7	26.74	31,784	-	273.78	31.12	21.91	386.08	Salas et al. 2017	Averages of 15 sampling points over 3 monsoons, 2 pre-monsoon, 2 post-monsoon events
Hugli Estuary	Surface sediment	83,595	7.7	0.45	17.1	84	36	42,462	-	813	45.4	27.8	83.8	Watts et al. 2017	
Mandovi Estuary	Sediment core	-	-	-	24.4	147.7	47.3	192,500	-	1541	-	24.5	66.6	Veerasingam et al. 2015	Average of 3 locations
Ulhas Estuary	Sediment core	-	-	-	79	239	173	90,200	-	2077	190	82	180	Fernandes and Nayak 2012	
Thane Creek	Sediment core	-	-	-	49	90	110	78,300	-	2290	101	41	100	Fernandes and Nayak 2012	
Thane Creek	Surface Surface	73,000 71,000			32.9 32.4	137 129	82.4 81.7	81,000 82,000	190 234.7	845 917	72.5 67.6	14.3 15.1	98.4 95.3	Lonkar et al. 2022	Grab samples, surface sediment, estuary mouth, near cargo lanes

how chemical and microbiological parameters relate to one another and to risks including AMR, zoonoses, and ecosystem damage, reduced or targeted groups of analytes can be developed and streamlined for more frequent monitoring.

Thane Creek provides an important opportunity to highlight the significance of estuarine system dynamics and the physical processes driving ecological status under the pressures of climatic shift and urban sprawl. The system is under pollution stress and developments in urban infrastructure are likely to increase this. The enhanced national ecological status and as an example of a contaminated estuary, future pressures are likely to be exacerbated by the shifting estuarine dynamics driven by climate change, with high risk from extreme weather events. The creek receives domestic and industrial waste and shows evidence of contamination including faecal coliforms and PTEs in its water and sediment and a similar status to a number of other Indian estuaries.

There are clear monitoring challenges intrinsic to the dynamics and diversity of the estuarine ecosystem, legacy pollution exposure and physical disruption. A stronger understanding of environmental contamination in estuaries is required as the neglect of key geochemical and microbiological parameters could have significant implications for human and animal health and beyond. This is particularly important as many organic compounds are emerging contaminants that are poorly understood and many PTEs are associated with the spread of AMR. An improved understanding is applicable not only to this local case but to a broad range of industrialized coastal environments and working to build more resilient wetland habitats has positive repercussions for human residents in these locations and supports the wider mitigation of increased anthropogenic pressures on ecosystems.

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Declarations

Competing interests The authors declare no competing interests.

References

Abdul Azeez S, Gnanappazham L, Muraleedharan KR, Revichandran C, Sebin J, Seena G, Jubin T (2022) Multi-decadal changes of mangrove forest and its response to the tidal dynamics of Thane Creek, Mumbai. J Sea Res 180. https://doi.org/10.1016/j.seares.2021.102162

Adams J, Whitfield A, Van Niekerk L (2020) A socio-ecological systems approach towards future research for the restoration, conservation and management of southern African estuaries. Afr J Aquat Sci 45(1–2):231–241. https://doi.org/10.2989/16085914.2020.1751980

Ahmed U, Mumtaz R, Anwar H, Mumtaz S, Qamar AM (2020) Water quality monitoring: from conventional to emerging technologies. Water Supply 20(1):28–45. https://doi.org/10.2166/ws.2019.144

Aryal R, Vigneswaran S, Kandasamy J, Naidu R (2010) Urban stormwater quality and treatment. Korean J Chem Eng 27(5):1343–1359. https://doi.org/10.1007/s11814-010-0387-0

Asari N, Suratman MN, Ayob MNA, Hamid ANH (2021) Mangrove as a natural barrier to environmental risks and coastal protection. In: Rastogi, R.P., Phulwaria, M., Gupta, D.K. (eds) Mangroves: ecology, biodiversity and management. Springer, Singapore. https://doi.org/10.1007/978-981-16-2494-0_13

Athalye RP, Gokhale KS, Quadros G (2012) Environmental management strategies for creeks and estuaries: a case study of Thane creek, India. Eco Revolution. https://www.researchgate.net/publication/257940318

Babu KN, Omana PK, Mohan M (2010) Water and sediment quality of Ashtamudi estuary, a Ramsar site, southwest coast of India-a statistical appraisal. Environ Monit Assess 165(1–4):307–319. https://doi.org/10.1007/s10661-009-0947-0

Baliarsingh SK, Lotliker AA, Srichandan S, Basu A, Nair TMB, Tripathy SK (2021) Efect of tidal cycle on *Escherichia coli* variability in a Tropical Estuary. Bull Environ Contam Toxicol 106:622–628. https://doi.org/10.1007/s00128-021-03106-w

Banerjee D, Bharti D, Kumar S, Mitra A, Joshi R, Gupta D (2023) Faunal composition of Ramsar wetlands from India: an analysis. Records Zoological Surv India 123(1S):01–15. https://doi.org/10.26515/rzsi/v123/i1S/2023/172458

Basavaiah N, Mohite RD, Singare PU, Reddy AVR, Singhal RK, Blaha U (2017) Vertical distribution, composition profiles, sources and toxicity assessment of PAH residues in the reclaimed mudflat sediments from the adjacent Thane Creek of Mumbai. Mar Pollut Bull 118(1–2):112–124. https://doi.org/10.1016/j.marpolbul.2017.02.049

Bearcock JM, Smedley PL, Fordyce FM, Everett PA, Ander EL (2017) Controls on surface water quality in the River Clyde catchment, Scotland, UK, with particular reference to chromium and lead. Earth Environ Sci Trans Royal Soc Edinb 108(2–3):249–267. https://doi.org/10.1017/S1755691018000397

Behmel S, Damour M, Ludwig R, Rodriguez MJ (2016) Water quality monitoring strategies — a review and future perspectives. Sci

Total Environ 571:1312–1329. https://doi.org/10.1016/j.scitotenv.2016.06.235
Bhardwaj RM (2005) Water Quality Monitoring in India - Achievements and Constraints. IWG-Env, International Work Session on Water Statistics, Vienna, June 20–22 2005
Borkar MU, Quadros G, Athalye RP (2007) Threats to the mangroves of Thane Creek and Ulhas River Estuary, India. J Coastal Dev 11(1):49–57. https://ejournal.undip.ac.id/index.php/coastdev/article/view/5553 [accessed 11 September 2024]
Bureau of Indian Standards (2012) Drinking Water - Specification. https://www.indiawaterportal.org/articles/Indian-standard-drinking-water-bis-specifications-10500-2012-second-revision accessed 25/06/2024
Central Pollution Control Board. (n.d.-b). NWMP Monitoring Network. Retrieved January 19 (2024) from https://cpcb.nic.in/nwmp-monitoring-network/
Central Pollution Control Board. (n.d.-a). NWMP Data. Retrieved January 19 (2024) from https://cpcb.nic.in/nwmp-data/
Central Pollution Control Board (2017) Guidelines for Water Quality Monitoring. https://cpcb.nic.in/wqm/Guidelines_Water_Quality_Monitoring_2017.pdf accessed 25/06/2024
Central Pollution Control Board. (n.d.-c). Water Quality Standards for Coastal Water Marine Outfalls. Retrieved January 19 (2024) from https://cpcb.nic.in/wqm/coasteal_water_standards.pdf accessed 25/06/2024
Chakraborty S, Sarkar K, Chakraborty S, Ojha A, Banik A, Chatterjee A, Ghosh S, Das M (2021) Assessment of the surface water quality improvement during pandemic lockdown in ecologically stressed Hooghly River(Ganges) Estuary, West Bengal, India. Mar Pollut Bull 171. https://doi.org/10.1016/j.marpolbul.2021.112711
Chitnis P (2023), January 18 Mumbai set to have network of 7 key sewage treatment plants. Why it took almost 20 yrs. The Print. https://theprint.in/india/mumbai-set-to-have-network-of-7-key-sewage-treatment-plants-why-it-took-15-yrs/1319285/ accessed 25/06/2024
Chordiya S, Bankar P, Shitole M (2021) Water quality assessment of Vashi Creek (Maharashtra) of India by Nemerow pollution index. Int J Environ Ecol Res 3(2):14–19. http://www.cpcbenvis.nic.in/
Cohen J, Shuval HI (1973) Coliforms, Fecal coliforms and Fecal Streptococci as indicators of Water Pollution. Water Air Soil Pollution 2:85–95. https://doi.org/10.1007/BF00572392
Dharmadhikary S, Sandbhor J (2017) National Inland Waterways in India: A Strategic Status Report published by SRUTI, New Delhi and Manthan Adhyayan Kendra, Pune & Badwani available: https://www.sruti.org.in/news/national-inland-waterways-in-india-a-strategic-status-report/ (accessed 17/12/2024)
Dutka BJ (1973) Coliforms are an inadequate index of Water Quality. J Environ Health 36(1):39–46
Elliott M, Day JW, Ramachandran R, Wolanski E (2019) A synthesis: what is the future for coasts, estuaries, deltas and other Transitional habitats in 2050 and Beyond? Coasts Estuaries. https://doi.org/10.1016/B978-0-12-814003-1.00001-0
Erickson AJ, Weiss PT, Gulliver JS (2013) Impacts and Composition of Urban Stormwater. Optimizing Stormwater Treatment practices: a handbook of Assessment and maintenance. Springer Science & Business Media. Springer, New York, NY, pp 11–22. https://doi.org/10.1007/978-1-4614-4624-8_2
Fernandes L, Nayak GN (2012) Heavy metals contamination in mudflat and mangrove sediments (Mumbai, India). Chem Ecol 28(5):435–455. https://doi.org/10.1080/02757540.2012.666527
Fernandes L, Nayak GN, Ilangovan D (2012) Geochemical assessment of metal concentration in mangrove sediments along Mumbai Coast, India. Int J Civil Geol Eng 6. https://www.researchgate.net/publication/268786073 [accessed 11 September 2024]
Ferrier RC, D'arcy BJ, MacDonald J, Aitken M (2005) Diffuse Pollution - what is the nature of the Problem? Water Environ J 19:361–366. https://onlinelibrary.wiley.com/doi/abs/ https://doi.org/10.1111/j.1747-6593.2005.tb00574.x[accessed 11 September 2024]
Goldin Q, Athalye RP (2012) Decline of fish diversity in the anthropogenically polluted Thane Creek along the Central West Coast of India. Int Res J Biol Sci 1(4):17–21 www.isca.in
Gopal V, Shanmugasundaram A, Nithya B, Magesh NS, Jayaprakash M (2018) Water quality of the Uppanar estuary, Southern India: implications on the level of dissolved nutrients and trace elements. Mar Pollut Bull 130:279–286. https://doi.org/10.1016/j.marpolbul.2018.03.046
Gullberg E, Albrecht LM, Karlsson C, Sandegren L, Andersson DI (2014) Selection of a Multidrug Resistance plasmid by sublethal levels of Antibiotics and Heavy metals. MBio 5(5). https://doi.org/10.1128/mBio.01918-14
Gurav MN, Dayaram P, Kale N, Rokade L (2013) Bioaccumulation of some heavy metals in indigenous fishes found in Vashi Creek and an insight on socioeconomic status of local fishermen. Proceedings of the National Conference on Biodiversity: Status and Challenges in Conservation – 'FAVEO' 2013, 148–152. https://vpmthane.org/sci/FAVEO/r24.pdf [accessed 11 September 2024]
Hazen TC (1988) Fecal coliforms as indicators in tropical waters: a review. Toxic Assess 3(5):461–477. https://doi.org/10.1002/tox.2540030504
Jaiswar ARS, Rakesh PS, Fulke AB, Sautya S Assessment of impact of release of effluents on ecology of inshore and coastal areas of Maharashtra and their management. NIO/SP- 42/2017 SSP2964, Gupta SM (2018) (2024) Biodiversity Exploration: Winter Walking Trails Around Bhandup Pumping Station Eco. Env. & Cons. 30 (October Suppl. Issue) pp. (S550-S557) available: https://www.envirobiotechjournals.com/ecology-environment-and-conservation/ (accessed: 17/12/2024)
Kennedy P, Allen G, Wilson N The management of hydrocarbons in stormwater runoff: a literature review. Report number: Auckland Council Technical Report, TR 2016/010Affiliation: Golder Associates (NZ), Limited (2016) https://www.researchgate.net/publication/309036974_The_management_of_hydrocarbons_in_stormwater_runoff_a_literature_review accessed 25/06/2024
Khan AS, Gupta SM (2024) Biodiversity exploration. winter walking trails around Bhandup pumping station
Kirschke S, Avellán T, Bärlund I, Bogardi JJ, Carvalho L, Chapman D, Dickens CWS, Irvine K, Lee SB, Mehner T, Warner S (2020) Capacity challenges in water quality monitoring: understanding the role of human development. Environ Monit Assess 192(298). https://doi.org/10.1007/s10661-020-8224-3
Kumar VV, Rimjhim S, Garagu SA, Valappil NN, Rakhavan RP (2022) Heavy metal contamination, distribution and source apportionment in the sediments from Kavvayi Estuary, South-West coast of India. Total Environ Res Themes 3–4. https://doi.org/10.1016/j.totert.2022.100019
Liu A, Hong N, Zhu P, Guan Y (2018) Understanding benzene series (BTEX) pollutant load characteristics in the urban environment. Sci Total Environ 619–620:938–945. https://doi.org/10.1016/j.scitotenv.2017.11.184
Lonkar S, Pradhan UK, Ram A, Udayakrishnan PB, Sahu B (2022) Geochemistry of metals in grain size fractionated sediments from estuarine and coastal regions along Mumbai: a baseline information. Indian J Geo Mar Sci 51(12). https://doi.org/10.56042/ijms.v51i12.4290
Lovett GM, Burns DA, Driscoll CT, Jenkins JC, Mitchell MJ, Rustad L, Shanley JB, Likens GE, Haeuber R (2007) Who needs environmental monitoring? In Frontiers in Ecology and the Environment (Vol. 5, Issue 5, pp. 253–260). https://doi.org/10.1890/1540-9295(2007)5[253:WNEM]2.0.CO;2
Magesh NS, Chandrasekar N, Kumar K, S., Glory M (2013) Trace element contamination in the estuarine sediments along Tuticorin

coast - Gulf of Mannar, southeast coast of India. Mar Pollut Bull 73(1):355–361. https://doi.org/10.1016/j.marpolbul.2013.05.041
Maharashtra Pollution Control Board. (n.d.). Maharashtra Water Quality Reports. Retrieved January 19 (2024) from https://mpcb.gov.in/focus-area/reports-documents/water
Maity S, Sahu SK, Pandit GG (2017) Trace metals distribution and their dependence on some physico-chemical parameters in creek sediment. Toxicol Environ Chem 99(2):209–222. https://doi.org/10.1080/02772248.2016.1176170
Mitra S, Ghosh S, Satpathy KK, Bhattacharya BD, Sarkar SK, Mishra P, Raja P (2018) Water quality assessment of the ecologically stressed Hooghly River Estuary, India: a multivariate approach. Mar Pollut Bull 126:592–599. https://doi.org/10.1016/j.marpolbul.2017.09.053
Mulik J, Sukumaran S, Dias HQ (2020) Can the ecological status of three differentially impacted monsoonal tropical estuaries in NW India, be adequately assessed by a common estuarine benthic index? Ecol Indic Volume 119:106807. https://doi.org/10.1016/j.ecolind.2020.106807
Müller A, Österlund H, Marsalek J, Viklander M (2020) The pollution conveyed by urban runoff: a review of sources. Sci Total Environ 709:136125. https://doi.org/10.1016/j.scitotenv.2019.136125
Murali RM, Riyas MJ, Reshma KN, Kumar SS (2020) Climate change impact and vulnerability assessment of Mumbai city, India. Nat Hazards 102(2):575–589. https://doi.org/10.1007/s11069-019-03766-2
Nair MN, Sreeraj MK, Rakesh PS, Thomas J, Kharat PY, Sukumaran S (2024) Distribution, source and potential biological impacts of polycyclic aromatic hydrocarbons in the core sediments of a networked aquatic system in the northwest coast of India – A special focus on Thane Creek Flamingo Sanctuary (Ramsar site) Regional Studies in Marine Science Volume 70, 103377 https://doi.org/10.1016/j.rsma.2024.103377
Nieder R, Benbi DK, Reichl FX (2018) Role of Potentially Toxic Elements in Soil. In Soil Components and Human Health. Springer. https://doi.org/10.1007/978-94-024-1222-2_8
Nikam VS, Kumar A, Lalla K, Gupta K (2008) Conservation of Wetlands and Mangroves in Thane Creek and Ulhas River Estuary, India. Proceedings of Taal2007: The 12th World Lake Conference, 1635–1642. https://www.researchgate.net/publication/49645029 accessed 25/06/2024
Ogunseitan OA (2022) One health and the Environment: from conceptual Framework to implementation science. Environment: Sci Policy Sustainable Dev 64(2):11–21. https://doi.org/10.1080/00139157.2022.2021792
Pal A, He Y, Jekel M, Reinhard M, Gin KY-H (2014) Emerging contaminants of public health significance as water quality indicator compounds in the urban water cycle. Environ Int 71:46–62. https://doi.org/10.1016/j.envint.2014.05.025
Pol M (2019), October 31 New sewage treatment plant in Thane to be ready by 2020. www.hindustantimes.comaccessed25/06/2024
Pradhan UK, Ram A, Sahu B, Lonkar BUP, S., Kumbhar L (2021) Multivariate assessment of outflow water quality in highly urbanized creek system: implication of natural and anthropogenic processes. Environ Sci Pollut Res 28:49725–49742. https://doi.org/10.1007/s11356-021-14128-6/Published
Rakkasagi S, Goyal MK, Jha S (2024) Evaluating the future risk of coastal Ramsar wetlands in India to extreme rainfalls using fuzzy logic. J Hydrology Volume 632:130869. https://doi.org/10.1016/j.jhydrol.2024.130869
RAMSAR Thane Creek, India, Site number: 2490 https://rsis.ramsar.org/ris/2490 accessed 21 June 2024
Ramteke PW, Bhattacharjee JW, Pathak SP, Kalra N (1992) Evaluation of coliforms as indicators of water quality in India. J Appl Bacteriol 72(4):352–356. https://doi.org/10.1111/j.1365-2672.1992.tb01846.x
Rathod S Plastic Peril on Species Diversity and Fish Catch: A Zone-wise Comparative Assessment between Ulhas River Estuary and Thane Creek. In Prof. S. G., Bapat DSB, Kulkarni P. (Mrs.), Meshram SS (2020) Mrs. Savita Dange, Prof. (Mrs.) S. S. Meshram, Dr. (Mrs.) U. B. Gokhe, Prof. A. A. Koli, Prof. A. S. Dani, Prof. N. V. Nandi, Prof. G. S. Tawde, & Prof. S. S. PawarProf. H. H. Tadwalkar (Eds.), Proceedings of Two Day National Conference on Materials and their Applications: A Broad Perspective. Department of Physics, V.P.M's B. N. Bandodkar College of Science. ISBN: 978-81-923628-7-8 https://zenodo.org/records/7538959
Roberts DA (2012) Causes and ecological effects of resuspended contaminated sediments (RCS) in marine environments. Environ Int 40(1):230–243. https://doi.org/10.1016/j.envint.2011.11.013
Rodgers K, McLellan I, Peshkur T, Williams R, Tonner R, Hursthouse AS, Knapp CW, Henriquez FL (2019) Can the legacy of industrial pollution influence antimicrobial resistance in estuarine sediments? Environ Chem Lett 17:595–607. https://doi.org/10.1007/s10311-018-0791-y
Salas PM, Sujatha CH, Kumar R, C. S., Cheriyan E (2017) Heavy metal distribution and contamination status in the sedimentary environment of Cochin estuary. Mar Pollut Bull 119(2):191–203. https://doi.org/10.1016/j.marpolbul.2017.04.018
Sasamal SK, Rao KH, Suryavansi UM (2007) Sewage and industrial pollution in and around Thane Creek, Mumbai using high resolution IRS data. Int J Remote Sens 28(19):4391–4395. https://doi.org/10.1080/01431160500354039
Sharma D, Rao K, Ramanathan AL (2022) A systematic review on the impact of urbanization and industrialization on Indian Coastal Mangrove Ecosystem Ch 8 in Coastal Ecosystems, Coastal Research Library 38, S. Madhav (eds.). https://doi.org/10.1007/978-3-030-84255-0_8
Siddhesh B, Benjamin S, Vaz J, Tripathi A, Gujarpadhaye P, Athalye RP, Azeez PA, Mylswamy M, Shirish S, Quadros G (2016) Conducting baseline studies for Thane Creek. https://docslib.org/doc/243658/conducting-baseline-studies-for-thane-creek accessed 25/06/2024
Singare PU (2012) Study of some Major Non-biodegradable Solid Wastes along Thane Creek of Mumbai. World Environ 2(3):24–30. https://doi.org/10.5923/j.env.20120203.01
Singare PU, Lokhande RS, Pathak PP (2010) Soil Pollution along Kalwa Bridge at Thane Creek of Maharashtra, India. J Environ Prot 1(2):121–128. https://doi.org/10.4236/jep.2010.12016
Sukhdhane KS, Pandey PK, Vennila A, Purushothaman CS, Ajima MNO (2015) Sources, distribution and risk assessment of polycyclic aromatic hydrocarbons in the mangrove sediments of Thane Creek, Maharashtra, India. Environ Monit Assess 187(274). https://doi.org/10.1007/s10661-015-4470-1
Tallam K, White E Jr (2023) The role of diseases in unifying the health of global estuaries. Front Mar Sci 10:1185662. https://doi.org/10.3389/fmars.2023.1185662
Tambe E, Gotmare S (2017) Pollution Monitoring Study of Water samples collected from Vashi Creek by determining Water Quality Index. Int J Innovative Res Sci Eng Technol 6(4):6501–6508. https://doi.org/10.15680/IJIRSET.2017.0604062
Thasneem TA, Nandan B, S., Geetha PN (2018) Water quality status of Cochin Estuary, India. Indian J Geo Mar Sci 47(5):978–989
Thomas J, Velamala SN, Prasad KVSR (2019) Numerical Simulation of Tidal constituents in Thane Creek and the Ulhas Estuary, West Coast of India. J Coastal Res 35 2:376–388. https://doi.org/10.2112/JCOASTRES-D-17-00189.1
Thomas J, Naidu VS, Shanas PR, Bhaskaran P, Naidu CV (2022) Influence of river inflow and its impact on the salinity variations and flushing time in a networked system, northwest coast of India. J Earth Syst Sci 131(2). https://doi.org/10.1007/s12040-022-01837-w

Tiwari M, Sahu SK, Pandit GG (2017) Distribution of PAHs in different compartment of creek ecosystem: Ecotoxicological concern and human health risk. Environ Toxicol Pharmacol 50:58–66. https://doi.org/10.1016/j.etap.2017.01.008

Toraskar AD, Manohar CS, Fernandes CL, Ray D, Gomes AD, Antony A (2022) Seasonal variations in the water quality and antibiotic resistance of microbial pollution indicators in the Mandovi and Zuari estuaries, Goa, India Environ Monit Assess 194:71. https://doi.org/10.1007/s10661-021-09679-7

United Nations. (n.d.). UN Sustainable Development Goals. Retrieved January 19 (2024) from https://sdgs.un.org/goals/goal6#targets_and_indicators

Van Winckel T, Cools J, Vlaeminck SE, Joos P, Van Meenen E, Borregán-Ochando E, Van Den Steen K, Geerts R, Vandermoere F, Blust R (2021) Towards harmonization of water quality management: a comparison of chemical drinking water and surface water quality standards around the globe. J Environ Manage 298. https://doi.org/10.1016/j.jenvman.2021.113447

Veerasingam S, Vethamony P, Mani Murali R, Fernandes B (2015) Depositional record of trace metals and degree of contamination in core sediments from the Mandovi estuarine mangrove ecosystem, west coast of India. Mar Pollut Bull 91(1):362–367. https://doi.org/10.1016/j.marpolbul.2014.11.045

Vijay R, Khobragade PJ, Sohony RA, Kumar R, Wate SR (2014) Hydrodynamic and water quality simulation of Thane Creek, Mumbai: an impact of sewage discharges. Indian J Geo-Mar Sci 43(10):1891–1898. https://nopr.niscpr.res.in/handle/123456789/34541 [accessed 11 September 2024]

Vijay R, Khobragade PJ, Dhage SS, Gupta A, Wate SR (2015) Tidal and seasonal variations in water quality of Thane Creek, Mumbai, India: a statistical analysis. Indian J Geo-Mar Sci 44(6):808–817. https://nopr.niscpr.res.in/handle/123456789/34815 [accessed 11 September 2024]

Vijay R, Dey J, Sakhre S, Kumar R (2020) Impact of urbanization on creeks of Mumbai, India: a geospatial assessment approach. J Coastal Conserv 24(4). https://doi.org/10.1007/s11852-019-00721-y

Volvoikar SP, Nayak GN (2013) Depositional environment and geochemical response of mangrove sediments from creeks of northern Maharashtra coast, India. Mar Pollut Bull 69(1–2):223–227. https://doi.org/10.1016/j.marpolbul.2012.12.013

Watts MJ, Mitra S, Marriott AL, Sarkar SK (2017) Source, distribution and ecotoxicological assessment of multielements in superficial sediments of a tropical turbid estuarine environment: a multivariate approach. Mar Pollut Bull 115(1–2):130–140. https://doi.org/10.1016/j.marpolbul.2016.11.057