

Chapter 9

Coastal Pollution



Guizhi Wang , Xiaolin Li , Marc Humphries , Venkatesh Chinni ,
Khanittha Uthaipan , and Minhan Dai 

Abstract Coastal pollution has been one of the most pressing issues at both regional and global levels due to intense pressures from human development, especially in recent decades. This chapter presents general scientific knowledge of classic nutrient-induced coastal eutrophication, heavy metal pollution, organic pollutants such as oil and plastics, and radionuclide pollution, followed by representative cases of coastal pollution from developing countries—China, South Africa, India, and Thailand—to demonstrate how science can improve understanding and tackle the problems and impacts of coastal pollution on blue economies. The case studies of pollution presented here show examples of the blue economy sectors that can be impacted, including human health, fisheries, and tourism. The multiplicity of pollutants, their complex interactions, as well as their impact and potential exacerbation due to climate change pose challenges that can be confronted by blue economic policies based on a better scientific understanding of the issue involved.

Keywords Eutrophication · Metal pollution · Oil spills · Radionuclides · Marine plastics

G. Wang (✉) · X. Li · K. Uthaipan · M. Dai
State Key Laboratory of Marine Environmental Science and College of Ocean and Earth Sciences,
Xiamen University, Xiamen, China
e-mail: gzhwang@xmu.edu.cn

X. Li
e-mail: xlli@xmu.edu.cn

M. Dai
e-mail: mdai@xmu.edu.cn

M. Humphries
School of Chemistry, University of the Witwatersrand, Johannesburg, South Africa

V. Chinni
CSIR-National Institute of Oceanography, Dona Paula, Goa, India

9.1 Introduction

As the gateway between the land and ocean, the coastal zone is home to over 50% of the world's human population and produces almost 50% of its gross domestic product (GDP).¹ However, this vital region has undergone intensified pressures from human development ever since the Industrial Revolution. These pressures are further amplified by climate change, loss of biodiversity, and pollution (Winther et al. 2020), which have adversely impacted human society and impaired the coastal ocean's and, by extension, the global ocean's, sustainability. Coastal pollution is one of the most pressing issues at both regional and global levels (Halpern et al. 2008). In the marine environment, pollutants comprise a wide variety of physical, chemical, and biological agents, introduced to the coastal ocean via the following pathways. Pollutants (both point-source and diffuse) from land may be carried into the coastal ocean via surface runoff and rivers, and groundwater, as well as direct discharges of waste waters. Pollutants in the marine environment can also result from human activities at sea and deposition from the atmosphere (Jickells et al. 2017). The origins of pollutants and their distributions are highly spatially and temporally variable around the globe, with megacities at the coast emerging as a major source for pollution (Cabral et al. 2019). This chapter will focus on the general scientific knowledge of classic nutrient-induced coastal eutrophication, heavy metal pollution, organic pollutants (with oil spill and plastics singled out for special attention), and radionuclide pollution. This general information will be followed by representative cases of coastal pollution from China, South Africa, India, and Thailand to demonstrate how science can improve understanding and help tackle the problems and impacts of these coastal pollutants on blue economies.

9.2 Coastal Eutrophication

Eutrophication is a global phenomenon, primarily caused by the excessive addition of nutrients, especially compounds of nitrogen (N) and phosphorus (P) to coastal ecosystems. It results in excess phytoplankton production with undesirable disturbance to the community structure and to water quality (Rabalais et al. 2009; Malone and Newton 2020).

9.2.1 *Global Patterns and Trends*

In the past few decades, coastal eutrophication has dramatically increased worldwide, especially in the Northern Hemisphere, along the western margins of the Atlantic and Pacific oceans, and in European coastal waters (Steffen et al. 2015). Nitrogen is

¹ Data source: <https://www.citypopulation.de/en/world/bymap/Coastlines.html>.

seen to be the primary cause of eutrophication in most coastal marine ecosystems, although phosphorus also plays a role in this process (Howarth 2008; Howarth and Paerl 2008). Global anthropogenic N input to the environment is now greater than the natural N-fixation in the ocean (140 teragrams (Tg) N yr⁻¹) by 20 Tg N yr⁻¹ (Steffen et al. 2015). Anthropogenic nutrients are mainly sourced from municipal wastewater, fertilizers, the combustion of fossil fuels, and food-related industries, among which the largest source are synthetic fertilizers (Table 9.1).

Most anthropogenic N inputs to the coastal ocean are via river runoff fueled by anthropogenic inputs to coastal watersheds, wet deposition within watersheds, and riverine transport from watersheds and atmospheric deposition derived from both agricultural sources and fossil fuels (Jickells et al. 2017). Direct atmospheric deposition contributes about 14% of the total (Malone and Newton 2020), while the exports of nutrients from submarine groundwater discharge vary greatly from one coastal system to another (Santos et al. 2021), in which the anthropogenic fraction is poorly known.

Table 9.1 Global sources of anthropogenic nutrients (N)

Source	Magnitude (Tg N yr ⁻¹)	Regional contribution (%)						Reference
		Southern Asia		North America	Europe	South America		
Synthetic fertilizer	118	71		11	7	6		Johnson and Harrison (2015), Lu and Tian (2017)
		30		20	17	12		
Combustion of fossil fuels	25–40	30		20	17	12		Lamsal et al. (2011)
		34.2	17.6	14.2	13.3	11.6	9.2	
Manure	18	34.2		17.6	14.2	13.3	11.6	Zhang et al. (2017), Malone and Newton (2020)
		30		20	17	12		
Emission of ammonia from agriculture	10	–						Bouwman et al. (2013)
Sewage	9	–						Malone and Newton (2020)
Finfish aquaculture	2.6	–						

9.2.2 Patterns in Developing Countries

Coastal eutrophication in developing countries is found mainly in East and Southeast Asia, off the Iranian coast of the Caspian Sea, off the coasts of the Red Sea, and on the African and South American coasts (Fig. 9.1). In terms of the major nutrient sources, fertilizer use more than doubled from 2002 to 2012 in Latin America, South Asia, East Asia, and Oceania (Malone et al. 2021), with East Asia, especially China, being the hotspot of fertilizer use in the early Twenty-first Century (Fig. 9.2). China contributed 30.5 Mt synthetic nitrogen in 2016, which was about 30% of the global use (Yu et al. 2019). Consequently, eutrophication has been widely observed along Chinese coasts, with a slow development from the 1970s to the 1990s and a fast increase after 2000 (Wang et al. 2021). Additionally, wastewater discharges may facilitate algal blooms and hypoxia in some regions (Table 9.2). For example, a sharp increase in nutrient concentrations was observed from 2001 to 2019 in Jakarta Bay, Indonesia, related to the increase in human population in the adjacent river basin and direct discharge of 60–80% of untreated domestic wastewater (Prayitno and Afdal 2019; Damar et al. 2020). Moreover, groundwater and atmospheric deposition, as well as shrimp farm and harbor effluents, may also be sources of nutrients. For example, off the coast of Mexico, dissolved inorganic nitrogen (DIN) levels were 35–80 times higher than baseline levels of $< 0.2 \mu\text{M}$ of five decades ago and soluble reactive phosphorus (SRP) levels increased from $0.1 \mu\text{M}$ in the 1970s to the 2000s by eightfold (González-De Zayas et al. 2020).

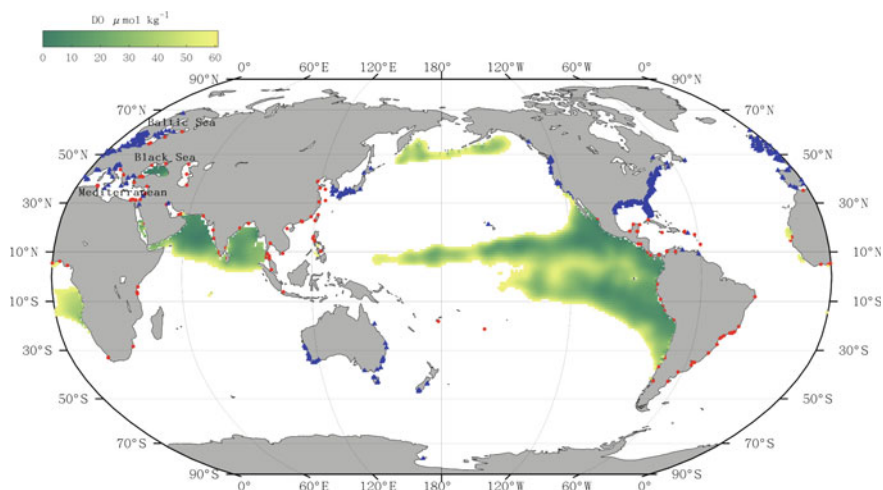
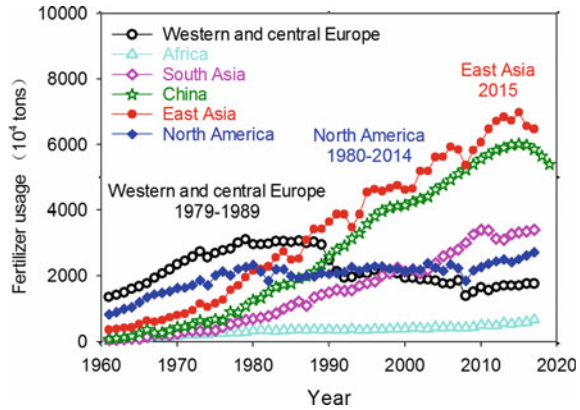


Fig. 9.1 Global sites of observed coastal eutrophication, with those in developing countries in dots and in other countries in triangles (*Data source* Diaz et al. [2011] and references in Table 9.2). The shaded areas have dissolved oxygen (DO) level less than $61 \mu\text{mol kg}^{-1}$ at the depth of 300 m (*Data source* World Ocean Atlas 2018 [www.ncei.noaa.gov]). Note that countries with more data available may show relatively more eutrophic areas compared to countries with less data

Fig. 9.2 Fertilizer use in different regions around the globe since 1960. Figure revised from Wang (2022) with data available from the International Fertilizer Association (<http://ifadata.fertilizer.org/ucSearch.aspx>)



9.2.3 Impacts of Eutrophication

The most noticeable consequences of coastal eutrophication include the occurrence and/or expansion of hypoxic (oxygen concentration $\leq 61 \mu\text{mol kg}^{-1}$), or even anoxic, areas when excess organic matter produced in surface waters sinks below the pycnocline, where its remineralization consumes oxygen, resulting in associated organismal, fisheries, and geochemical effects (Rabalais et al. 2014). Additionally, coastal acidification may be induced by CO_2 produced as a byproduct of aerobic respiration (Wallace et al. 2014). Eutrophication can also increase harmful algal bloom (HAB) occurrence and intensity and may reduce oxygenated habitat and harm biodiversity, ecosystem function, and human well-being. Furthermore, changes in nutrient composition and stoichiometry (nutrient ratios) have been observed in many coastal waters where eutrophication occurs, including increases in the concentration of ammonium and bioavailable organic nitrogen and phosphorus, and increases in elemental ratios of nitrogen to phosphorus and nitrogen to silicate. For example, in the Bohai Sea the ratios of inorganic N:P and N:Si increased from 2–45 and 0.1–1.26, respectively during the 1980s–1990s to 20–87 and 0.68–2.89 in the 2000s (Wang et al. 2021). Globally, coastal eutrophication areas with associated hypoxia coincide with major population centers and watersheds that deliver large amounts of nutrients (Diaz and Rosenberg 2008). Largely as a consequence of land-derived anthropogenic N inputs, surface chlorophyll-a (as a proxy of phytoplankton production) increased by 10% in the coastal ocean in 1998–2003 and the frequency of HABs appears to be increasing, for which eutrophication is at least partially responsible (Malone and Newton 2020).

Since 1950, coastal hypoxic areas have spread exponentially worldwide to over 500 known systems in 2015, with many more systems likely being affected, especially in developing countries, where monitoring may be sparse even in waters with untreated human and agricultural waste (Breitburg et al. 2018). Most marine ecosystem services are likely to be negatively affected by hypoxia, although to varying degrees (Laffoley and Baxter 2019). More than 10% of the worldwide coral reefs are at elevated risks of hypoxia (Altieri et al. 2017). Coral bleaching in the

Table 9.2 Selected coastal eutrophication in developing countries

Country	Site	Phenomenon reported	Sources of nutrients	Reference
China	Chinese coasts	Eutrophication, harmful algal blooms, hypoxia, and acidification	River inputs, atmospheric deposition, sewage discharge, and submarine groundwater discharge	He et al. (2014), Zhao et al. (2020), Wang et al. (2021)
Iran	Iranian coast of the Caspian Sea	Ecosystem shift from oligotrophic to mesotrophic/meso-eutrophic	Terrestrial inputs of N	Basatnia et al. (2018), Saravi et al. (2019)
India	Tapi Estuary	Hypoxia during monsoon and anoxia during post- and pre-monsoon seasons	Agricultural fertilizers and sewage inputs	Ram et al. (2014)
	Coastal margins off west India	Eutrophication	Upwelling, rivers and land drainage	Chauhan et al. (2011), George et al. (2012), Durga Rao et al. (2017), Sivasankar et al. (2018)
Indonesia	Jakarta Bay	Eutrophication, hypoxic water, algal blooms, and mass mortality of aquatic biota	Discharge of untreated domestic wastewater	Prayitno and Afdal (2019), Damar et al. (2020)
	Coastal waters of Bitung, Keunekai, Mimika, and Bintan Island	Eutrophication	–	Baohong et al. (2016), Wishu et al. (2018), Hamuna et al. (2019), Syakti et al. (2019)
Thailand	Southern coastal waters	Nutrient enrichment	River water	Yoshikawa et al. (2017)
Philippines	Bolinao and Anda maricultural areas	Eutrophication	Extensive use of low-quality fish feeds	Ferrera et al. (2016)
	Manila Bay	Eutrophication and hypoxia	Urban wastewater flow	Sotto et al. (2014)
Malaysia	Coastal water of Tioman Island	Eutrophication	Residential wastes discharge	Rahman et al. (2015)
	Semerak River	Eutrophication	Aquaculture activity	Er et al. (2018)

(continued)

Table 9.2 (continued)

Country	Site	Phenomenon reported	Sources of nutrients	Reference
Vietnam	Klang Estuary Saigon-Dongnai River system	Hypoxia Eutrophication, algal blooms, and hypoxia	Elevated river flow Untreated domestic discharges	Lee et al. (2020) Nguyen et al. (2019)
United Arab Emirates	Coastal waters of Abu Dhabi in Arabian Gulf	Eutrophication, algal blooms, and hypoxia	Treated sewage discharge, industrial effluents, aeolian dust	Rajan et al. (2020)
South Africa	Algoa Bay	Algal blooms and hypoxia	Wastewater discharge	Lemley et al. (2019)
Nigeria	Coastal lagoons	Hypoxia	Nutrients loading associated from anthropogenic and agricultural activities	Akagha et al. (2020)
Mexico	Coastal areas	Nutrient enrichment	Groundwater, sewage, runoff, atmospheric deposition, and shrimp farm and harbor effluents	Herrera-Silveira et al. (2004), González-De Zayas et al. (2020), Pérez-Gómez et al. (2020)
Brazil	Coastal waters	Hypertrophic, low oxygen level	Waste discharge, agricultural, and aquaculture effluents	de Carvalho Aguiar et al. (2013), Ciotti et al. (2018), Mourão et al. (2020)
Fiji Islands	Laucala Bay	Nutrient enrichment	–	Singh et al. (2009)
Saudi Arabia	Coastal waters	Ammonium enrichment	Sewage effluents	Ei Sayed et al. (2013), Al-Amri et al. (2020)
Vanuatu	Coastal areas of Port Vila	Nutrient enrichment	Non-treated sewage and stormwater runoff	Devlin et al. (2020)

Great Barrier Reef is promoted by eutrophication (Malone et al. 2021). Land-derived nutrient inputs are one of the main drivers of expanding hypoxia in the Baltic Sea, leading to the creation of the largest man-made hypoxic area in the world, extending almost 70,000 km² in 2019 (Carstensen and Conley 2019). The resultant cyanobacteria blooms produce toxins that affect recreation and fisheries in this region. Oyster landings in the Chesapeake Bay (USA) declined by up to sixfold from 1950 to 2000, corresponding with a tripling of the hypoxic water volume (Tian 2020).

In Chinese coastal waters, phytoplankton blooms have appeared with increasing spatial extent and frequency in the Bohai Sea, the Yellow Sea, the inner shelf of the East China Sea, and the northern shelf of the South China Sea. Persistent summer hypoxia appeared as early as the late 1950s on the inner shelf of the East China Sea off the Yangtze River estuary and the spatial extent expanded from about 1,800 km² in 1959 to > 15,400 km² in 2006, which has been attributed to elevated nutrient input due to fertilizers used in the Yangtze watershed (Malone and Newton 2020). Reported toxic algal blooms along the coast increased from none in the 1950s to more than a total of 100 in the 1990s due to an increase in the nutrient input from the Yangtze River (Yan et al. 2002), which adversely impacted local aquaculture and other marine services. In Algoa Bay, South Africa, wastewater discharges are the dominant source of inorganic nutrients to the nearshore environment, representing 71% of total DIN and 62% of dissolved inorganic phosphorus (DIP) loads, which has yielded, in part, increased algal blooms and hypoxia (Lemley et al. 2019).

9.3 Heavy Metal Pollution

Heavy metals are a group of naturally occurring elements with a density greater than 4 g cm⁻³, including metals and metalloids such as arsenic (Duffus 2002). Heavy metal pollution is a serious issue because of the toxicity, persistence, and non-biodegradable nature of these metals. Such pollution is usually most severe in coastal areas adjacent to highly industrialized and urbanized regions. Anthropogenic activities have dramatically increased concentrations of metals in coastal zones, with zinc, copper, chromium, lead, nickel, mercury, and cadmium being of most concern.

9.3.1 Global Patterns

Heavy metals in coastal environments originate from natural and anthropogenic sources. The lowest metal concentrations are observed in North America and the Arctic. The most metal-polluted region is observed along the Egyptian Mediterranean coast due to metals from industries, sewage, irrigation, and urban runoff. The concentrations of heavy metals vary greatly in coastal systems around the globe (Lu et al. 2018). Unlike eutrophication, however, a consistent temporal trend of metal contamination on a global scale is lacking, although metal concentrations show a

decrease for lead in surface waters by nearly an order of magnitude compared to ~ 200 picomol kg^{-1} during the 1970s (Boyle et al. 2014) and a slight increase for mercury in higher trophic level organisms (Ebinghaus et al. 2021).

Natural sources of heavy metals include weathering of rocks and volcanic activities. For example, in the Red Sea-Gulf of Aqaba coast of Saudi Arabia, iron, manganese, cadmium, copper, zinc, and chromium are mostly of terrestrial origin, derived from weathering of nearby pre-Cambrian basement rocks, and Tertiary and Quaternary sedimentary rocks (El-Sorogy et al. 2020). The major anthropogenic sources of heavy metals include reclamation and dredging (which mobilize heavy metals to elevated levels relative to sediment quality guidelines), traffic emissions, agricultural and sewage discharges, and industrial effluents in countries with rapid industrial growth. In particular, lead pollution arises from aerosol deposition and ship moorings, and lead levels may be maintained because of semi-closed characteristics and circulation pattern of coastal embayments (Gao and Chen 2012; Zhuang and Gao 2014). In the Arabian Gulf countries, heavy metals mainly derive from activities related to oil refining and petrochemical industries, desalination plants, coal combustion, and oil pollution due to oil spills from cargo ships and oil tankers, as well as from drilling platforms (Pekey 2006; Naser 2013; El-Sorogy et al. 2020). Fishing trawler and shipping activities, such as repairing, fueling, greasing and painting of ships, may aggravate metal contamination in coastal areas (Jilani 2015). Each individual metal may enter the environment from various sources in different regions and some may have the same sources in the same region (Lu et al. 2018).

As metals in coastal waters tend to be bound by suspended particles and sink to the seafloor, coastal sediments are generally the major reservoirs of heavy metals and overlying seawater may have low levels of dissolved heavy metals (Liu et al. 2021). For the same reason, estuaries serve as sink locations of past metal contamination (Ridgway and Shimmield 2002). In downstream areas, however, estuarine dynamics such as waves and tidal currents may promote re-suspension of bottom sediments, leading to desorption and release of heavy metals in the suspended particles from sediments into the water column. Sediments comprised of fine particles tend to have relatively high metal concentrations due to their high specific surface area in surface adsorption and ionic attraction (Zhuang and Gao 2014).

9.3.2 *Patterns in Developing Countries*

In various countries, different regions may be dominated by different metals. For example, iron is the most abundant heavy metal in surface sediments of the Red Sea-Gulf of Aqaba coast of Saudi Arabia, along the coast of Pakistan, and in the coastal waters of Nigeria with a range from 1,413–3,374 $\mu\text{g g}^{-1}$, although still about an order of magnitude lower than in the Brisbane River, Australia (Olaifa 2005; Saher and Siddiqui 2016; El-Sorogy et al. 2020). In the surface sediments of Ulsan Bay, Korea, zinc is the most abundant metal, with a mean concentration of 362 $\mu\text{g g}^{-1}$, higher near industrial complexes; however, mercury and cadmium with

mean concentrations of 0.16 and 0.40 $\mu\text{g g}^{-1}$, respectively are the metals posing a very high potential ecological risk (Ra et al. 2014). The Bay of Bengal, Bangladesh is highly polluted by cadmium, chromium, copper, mercury, nickel, lead, and uranium, mainly due to agricultural, domestic and industrial wastes directly discharged into the waterways (Kibria et al. 2016). In the surface sediments in Mejillones Bay, Chile, cadmium is the only metal whose values are high relative to the average concentration in Earth's crust (Valdes et al. 2005).

The metal hotspots in China are usually located in estuaries and nearshore regions where industrial and domestic sewage discharge and the metal concentrations decrease sharply with the distance offshore or away from the estuary (Gao and Chen 2012; Rui et al. 2013; Liu et al. 2021). Metal pollution of copper, nickel, lead, and zinc in the Bohai Sea, surrounded by highly industrialized regions, is more serious than in the South Yellow Sea and the Changjiang River Estuary, while less severe than in the Pearl River Estuary. The metal concentrations in the Bohai Sea are comparable to those in heavily polluted coastal areas in European countries (Lu et al. 2018). Likely related to industrial wastes, cadmium pollution is the most serious in coastal areas of the Bohai Sea. In southern China, the coastal sediments of Guangdong province are enriched in lead, zinc, and cadmium, due to development of nearby industrial sectors and rapid urbanization in these areas, while metal levels in the coastal sediments of Guangxi and Hainan provinces are relatively low (Wang et al. 2013).

9.3.3 Impacts of Heavy Metals on Coastal Ecosystems

Some metals (such as iron, copper, zinc, manganese, nickel) are essential for organisms, but are toxic when their concentrations are above certain thresholds. A few other metals—such as mercury, lead, silver, and cadmium—are toxic to marine organisms even when present in minute amounts. For example, in the Baltic Sea the established threshold concentration of mercury is 20 $\mu\text{g kg}^{-1}$ in fish muscle, of lead is 26 $\mu\text{g kg}^{-1}$ in fish liver, and of cadmium is 137.3 $\mu\text{g kg}^{-1}$ in mussel tissues (Ebinghaus et al. 2021). Heavy metals have diverse negative effects on marine organisms including, but not limited to, increased energy demand and impaired development and reproduction, which depend on metal concentration, speciation, interactions with receptor sites, uptake into the organisms, and other factors (Cabral et al. 2019). Since metals are not degradable during biological uptake and release, they tend to accumulate through food webs in higher trophic levels, especially in top predators (Vareda et al. 2019). For example, in the coastal sediments near Santa Rosalía, Mexico, metal pollution due to copper mining and smelting over the past century has caused accumulation of metals in a local seaweed (Rodríguez-Figueroa et al. 2009). In the Persian Gulf, concentrations of arsenic, cadmium, lead, and mercury exceeded the maximum allowable levels in international commerce in fish muscles (Cunningham et al. 2019). Thus, metal contamination in coastal systems may render water and sediments unsuitable for marine aquaculture, which

potentially reduces seafood stocks and affects the blue economy of the region, and bioaccumulation of metals through the trophic chain poses risks to human health.

9.4 Oil Spills

Oil spill pollution results from the leaking of crude oil or oil products from work sites or reservoirs to natural environments due to the accidents or regular operations during petroleum exploration, development, refining, storage and transportation (Ramseur 2017).

9.4.1 Global Patterns

The major sources of oil spill pollution include oil tanker accidents, offshore oil exploration leaks and blowout accidents. Long-term input sources include oily sewage discharge from port and ship operations, natural seabed leakage, and erosion of oily sedimentary rocks (Guo 2004). From the 1970s to 2020, statistics from oil transportation activities show that there were 1,847 oil spills (more than 7 tons) from oil tankers, and the total amount of oil spills reached 5.86 million tons.² Among them, there were 11 oil spills with more than 100,000 tons leakage in each incident, including the oil spill of Atlantic Express off Tobago, West Indies, which leaked 287,000 tons in 1979; the oil spill of ABT Summer at 700 nautical miles off Angola, which leaked 260,000 tons in 1991; and the oil spill of Castillo De Bellver off Saldanha Bay, South Africa, which leaked 252,000 tons in 1983. The statistics also demonstrate that the frequency of spills greater than 7 tons from tankers has decreased over the past 50 years. As the region with the highest oil production in the world, oil spills occur frequently in the Middle East. From 1967 to 2010, accidental oil spills in the Arabian Sea amounted to about 1 million tons of oil, which is about 10 times as much as the annual long-term oil spills of the entire Persian Gulf region (Danish 2010).

In addition, crude oil spills caused by drilling platform accidents are also an important source of marine oil spill pollution. In 1979, an outburst occurred in the exploratory well of Kestock 1 in the Gulf of Mexico, and approximately 140 million gallons of crude oil was discharged into the sea. In 2010, about 300 barrels of crude oil leaked from a drilling platform of the American Mobil Oil Company in Nigeria. On April 20, 2010, due to the explosion of BPs Deepwater Horizon drilling rig in the Gulf of Mexico, a large amount of oil spilled over a period of nearly three months. The maximum daily oil spill volume reached 126,000 tons, covering 2,500 square

² Data source: www.itopf.org/fileadmin/data/Documents/Company_Lit/Oil_Spill_Stats_publication_2020.pdf.

kilometers of seawater, making it the most serious oil spill in American history (Beyer et al. 2016).

9.4.2 Pattern in Developing Countries

The developing countries of South and West Asia are adjacent to the Indian Ocean, which is the main route connecting the Pacific Ocean, the Middle East and the Mediterranean Sea. Oil spills occur frequently in this region. The following were large oil spills in the Indian Ocean from 2017 to 2018: Chennai oil spill, Sharjah oil spill, Al Khiran oil spill, and Mubarak village oil spill (Naz et al. 2021). Nigeria is the 11th largest oil producer in the world, and the extraction and processing of oil in this area have caused significant oil spill pollution (Sam et al. 2016). In the past 50 years, approximately 10–13 million tons of oil have been spilled into the Niger Delta due to oil spills, of which only 33% have been recovered (Nwilo and Badejo 2006; Kadafa 2012). In China, from 1990 to 2010, about 22,035 tons of oil flowed into Chinese waters due to oil tanker accidents. The average annual loss is 1,049 tons, and more than 70 accidents have leaked more than 50 tons of oil each (Xiong et al. 2015). In 2018, there was a major oil spill from the oil tanker of Sanchi offshore Shanghai due to a ship collision and 111,510 tons of condensate oil leaked (Pan et al. 2021).

9.4.3 Impacts of Oil Spills

Marine oil spills are mainly composed of crude oil and its derivatives in a flammable, explosive, and complex toxic chemical mixture. These pollutants released to the environment on a short-term and limited spatial scale may cause adverse impacts on marine and coastal environments such as beach contamination and a wide range of biological effects, for example, habitat destruction, reduced growth, disease, impaired reproduction, impaired physiological health, and mortality of fish, invertebrates, birds, and sea mammals (Beyer et al. 2016), so that beach tourism and ecological resources are adversely affected. Thus, such pollution is regarded as an essential environmental concern by marine scientists and relevant government agencies. Oil spills require days to years to clean up, and can stay in marine waters for decades, becoming a long-term pollutant. Due to its intensity, temporal and spatial scales, the damage caused by an oil spill may have a very long-term impact on coastal marine ecosystems.

9.5 Plastics Pollution

Plastics are synthetic organic polymers made by polymerization of monomers extracted from petroleum or natural gas (Derraik 2002).

9.5.1 Global Patterns

Plastics were invented more than 100 years ago and are widely used in daily life and industrial production. In the past half century, the global total plastic production increased by nearly 250 times, from 1.5 million tons in 1950 to 368 million tons in 2019 (PlasticsEurope 2020). Due to special physical and chemical properties of plastics, plastic fragments can disperse in the natural water environment and be transported long distances by ocean currents. Now plastics are the main component of marine litter (Galgani et al. 2021). It may take hundreds of years before they are finally deposited in seafloor sediments (Ryan 1987; Hansen 1990; Goldberg 1995, 1997).

Riverine input is the main source of plastics to the ocean, transporting 1.15 million to 2.41 million tons of plastic wastes each year (Lebreton et al. 2017), although some plastics originate from various marine activities, for example, commerce, recreation, fisheries and aquaculture (Haward 2018). It is estimated that 640,000 tons of fishing gear is discarded in the ocean every year, accounting for about 10% of the total marine debris (Li et al. 2016). Plastics, like other organic materials, eventually degrade, but at a very slow rate (Andrady 2015). Some natural processes accelerate the degradation process, such as UV-induced photodegradation, thermal reactions, polymer hydrolysis, and microbial degradation.

Plastic fragments found in the marine environment vary in size, with a continuous distribution of particle sizes from nanometers to meters. According to their sizes and forms, plastic particles (fragments, fibers or plastic beads) with a diameter of less than 5 mm are usually defined as microplastics. These small plastic particles come from the decomposition of large plastic fragments, fabrics and polymer materials on clothes, and small plastic beads used in cosmetics and other consumer products (Browne et al. 2011; Ladewig et al. 2015; Napper and Thompson 2016; Cesa et al. 2017). Microplastics are mainly distributed by ocean currents, wind and river outflows (Ng and Obbard 2006; Barnes et al. 2009; Martinez et al. 2009) and are transported to remote locations, including islands in the middle of the ocean (Ivar do Sul et al. 2009), polar regions (Barnes et al. 2010), and the deep ocean (Lozano and Mouat 2009; Reineccius et al. 2020). Deep ocean troughs and trenches may be one of the largest microplastic sinks on the planet.

9.5.2 *Patterns in Developing Countries*

The rivers from the Asian continent are one of the most important sources of plastics into the ocean; the 20 rivers from which most plastic pollution enters the ocean are mainly located in Asia (Lebreton et al. 2017). The top 20 countries for waste discharge of mismanaged plastic in 2010 include 13 Asian countries; China, Indonesia, and the Philippines are the top three, emitting 8.82, 3.22, and 1.88 million metric tons of plastics per year, respectively. Microplastic pollution has been widely detected in the natural aqueous environment of developing countries, for example, China, India and South Africa (Chae and An 2017; Dahms et al. 2020; Singh et al. 2021).

9.5.3 *Impacts of Plastics Pollution*

The hazards of microplastics to aquatic organisms can be divided into three types: physical, chemical, and biological hazards. Microplastics can be ingested and accumulated by low-trophic level plankton, causing physical internal wear and blockage, which can lead to reduced feeding efficiency, energy deficiency, and injury or death (Browne et al. 2008; Murray and Cowie 2011; Wright et al. 2013). Components leached from microplastics can be toxic, such as some persistent organic pollutants, carcinogenic and endocrine-disrupting compounds (Mato et al. 2001; Oehlmann et al. 2009; Talsness et al. 2009). Microplastics can cause diseases in organisms that ingest them through pathogens adsorbed to the surface of the microplastics (Zettler et al. 2013; Kiessling et al. 2015). Because of their potential to compromise food security, food safety, and consequently human health, microplastic pollution is of growing concern as the presence of microplastics in marine animals used for human food is an emergent global phenomenon (Galgani et al. 2021). Due to their special physical and chemical properties, microplastics can also be a carrier of other environmental pollutants, and have a significant impact on environmental behaviors of heavy metals and some hydrophobic organic compounds (Ashton et al. 2010; Law and Thompson 2014; Alimi et al. 2018).

9.6 Radionuclide Pollution

Radionuclide pollution refers to the introduction of radioactive materials into the ocean by human activities, leading to elevated radioactivity relative to natural baselines, causing harm to organisms.

9.6.1 Global Patterns

Much of the radioactivity in the waters, biota and sediments of the ocean is from natural sources. Significant inputs from human activities since the 1940s, however, have resulted in additional radioactivity in the ocean above natural background levels (Ebinghaus et al. 2021). Anthropogenic radionuclides in the coastal ocean mainly originate from three sources: (a) products from nuclear explosions (e.g., ^{90}Sr , ^{131}I , and ^{35}S), transported into the ocean via atmospheric deposition; (b) discharges from nuclear power plants and nuclear submersibles (e.g., ^{137}Cs , ^{90}Sr , ^{66}Mn , and ^{60}Co), in cooling water and wastes; and (c) radionuclides generated from medical radiation applications and nuclear research, including ^{131}I , ^{32}P , ^3H , ^{14}C , etc., and discharged in aqueous form. In recent years, nuclear leakage due to nuclear accidents has become another source of radionuclide pollution. For example, after the Fukushima Dai-ichi Nuclear Power Plant incident, the activities of ^{134}Cs and ^{137}Cs measured three months later in seawaters off Japan increased 10–1,000 times over prior levels off Japan (Buesseler et al. 2017). Radioactive discharges from nuclear power reactors to the ocean were orders of magnitude less than those from weapons testing, reprocessing plants and major accidents and most of such discharges tend to decrease over time with improved technology, even though the number and scale of nuclear power plants have increased (Ebinghaus et al. 2021).

The level of radionuclide pollution of the ocean is higher in the Northern Hemisphere than in the Southern Hemisphere due to nuclear tests mostly carried out in the Northern Hemisphere, for example, $2.9 \pm 0.8 \text{ Bq m}^{-3}$ of ^{137}Cs in 45–50°N, while $1.5 \pm 0.2 \text{ Bq m}^{-3}$ in 45–50°S (Duran et al. 2004). For the same reason, the Pacific Ocean is more contaminated than the Atlantic Ocean and radionuclide pollution is much less seen in developing countries than in developed countries. Enclosed and semi-enclosed seas, as well as coastal areas, have higher radionuclide concentrations than the open ocean. Radioactivity in surface waters is usually greater than in the intermediate and bottom layers of the ocean (Ma 1981). Due to its persistence caused by radionuclide pollutants being relatively long-lived (e.g., the half-life of ^{239}Pu is 2.4×10^4 years), radionuclide pollution usually lasts relatively long in the marine environment (Yang et al. 2015).

9.6.2 Patterns in Developing Countries

Along the entire coast of China in regions where nuclear power plants are located, one or more of the three anthropogenic radionuclides, ^3H , ^{90}Sr , and ^{137}Cs , are detectable at environmental baseline levels of $0.2\text{--}11 \text{ Bq L}^{-1}$, $0.3\text{--}2.4 \text{ mBq L}^{-1}$, and $0.5\text{--}3.5 \text{ mBq L}^{-1}$, respectively in the seawater and sediments. ^{54}Mn , ^{58}Co , ^{60}Co , ^{65}Zn , ^{95}Zr , $^{110\text{m}}\text{Ag}$, ^{124}Sb , ^{134}Cs , and ^{144}Ce are not detected in the seawater and ^{54}Mn , ^{58}Co , ^{60}Co , ^{95}Zr ,

^{110m}Ag , ^{134}Cs , and ^{144}Ce are not detected in the sediments.³ The activities of these radionuclides indicate little radionuclide pollution due to nuclear power plants in Chinese coastal zones. The overall level of anthropogenic radionuclides in marine organisms in Chinese seas decreased from late 1970s to the late 1990s (Tang and Shang 2005). For example, the activity of ^{137}Cs in fish flesh was in the range of 128–1340 Bq kg⁻¹ in 1976–1981 and decreased to 0.03–0.08 Bq kg⁻¹ in 1997–1998 in Chinese coastal waters. In 2015, the activity of ^{137}Cs was almost identical before and after the Fukushima incident, indicating that the impact of the incident on Chinese seas was minor (Wu et al. 2012). Most of $^{239,240}\text{Pu}$ in the East China Sea and Yellow Sea are retained in the continental shelf sediments, and 50–80% of ^{137}Cs is contained in sediments (Nagaya and Nakanura 1992). The activity of ^{137}Cs in the surface seawater decreases in the order: the South China Sea, the Sulu and Indonesian Seas, and the Bay of Bengal and the Andaman Sea, while the Sulu and Indonesian Seas have the highest $^{239,240}\text{Pu}$ activity in these regions (Yamada et al. 2006).

9.6.3 Impacts of Radionuclide Pollution

Exposure to large amounts of radioactivity is life threatening to humans and other organisms. According to the World Health Organization, the dose threshold for acute radiation syndrome for humans is about 1000 millisieverts. Marine organisms can take up and accumulate radionuclides through seawater, sediments, feeding, and uptake by the body surface, serving as carriers and transporters of marine nuclear pollutants (Benitez-Nelson et al. 2018). Accumulation of radioisotopes inside organisms via the food chain results in much higher radioactivity levels than in the ambient environments, which severely damages the health of organisms.

9.7 Mitigations Against Coastal Pollution

After the impacts of coastal pollution on humans became better known, strategies for mitigating these pollutants have been adopted, based on ever-growing scientific understanding of their sources to coastal waters and the fates of these pollutants. For example, based on the scientific knowledge of the role of nutrient inputs on coastal eutrophication, many European and North American countries began to limit the use of chemical fertilizers and initiated steps to reduce nutrient loadings to the coastal ocean in the 1970s. Consequently, nutrient discharges in these areas peaked in the 1980s and 1990s (Reusch et al. 2018). Most of the nutrient reductions have come from improvements in wastewater treatment plants, for example, for the Baltic

³ Available from National Nuclear Safety Administration of China at <http://nnsa.mee.gov.cn/ztlz/haqnb>.

Sea (Boesch 2019). Management of nutrients, both N and P, and carbon inputs has reduced coastal hypoxia in a few systems, such as the Hudson River and Chesapeake Bay in the United States and the Mersey Estuary in England (Parker and O'Reilly 1991; Jones 2006; Boesch 2019). However, in most cases these practices fail to reduce eutrophication. Associated eutrophication, hypoxia, and other environmental problems such as algal blooms and coastal acidification have persisted both at regional and global scales.

As for heavy metal pollution, after the hazardous effects of heavy metals became well recognized, particularly on human well-being, the use of heavy metals has been constrained and their emission is monitored worldwide. Bans on leaded fuels and antifouling paints, and mercury regulations, have been implemented in European countries and the United States (Lu et al. 2018). In addition, wastewater has been treated to remove heavy metals before being discharged, using strategies based on the scientific knowledge of these metals. Following these mitigations, levels of metals have significantly decreased in coastal waters and surface sediments in most areas, although the decrease in surface sediments is relatively slow. However, there are observed increases in concentrations of metals in higher trophic-level fish species in spite of some decreases in emissions (Ebinghaus et al. 2021).

In terms of oil spills, improved safety measures regarding the phaseout of single-hull tankers came into effect in 2003 and at the same time maritime inspections started as a measure for cargo owners to demand higher safety standards for oil tankers, which likely has resulted in a decreasing global trend in terms of shipping accidents leading to oil spills (Ebinghaus et al. 2021). Moreover, significant improvements have been achieved in oil spill forecasting and response, and understanding of oil spill impacts has been aided by advances in modeling, the use of satellites, and other techniques such as ultrasound and artificial intelligence (NOAA 2020).

The remediation of the microplastic waste has been proposed as part of both upstream (e.g., wastewater treatment plant, waste management and bioplastics) and downstream (e.g., physico-chemical and biological remediation) solutions (Wong et al. 2020). More than 60 countries have introduced bans and levies to curb single-use plastic waste (UNEP 2018). A variety of measures have been implemented including, but not limited to, gear marking, onshore collection, disposal and recycling, and alternatives to single-use plastics (Food and Agriculture Organization of the United Nations 2016).

9.8 Cases of Coastal Pollution in Developing Countries

Typical cases of pollution in the Pearl River Delta in China and the iSimangaliso Marine Protected Area in South Africa, and along the coasts of India and Thailand, are presented below (Fig. 9.3a). These regions experience pollution with different substances and levels, and with different degrees of scientific understanding, which makes them good models to show how science can help us understand and tackle pollution problems.

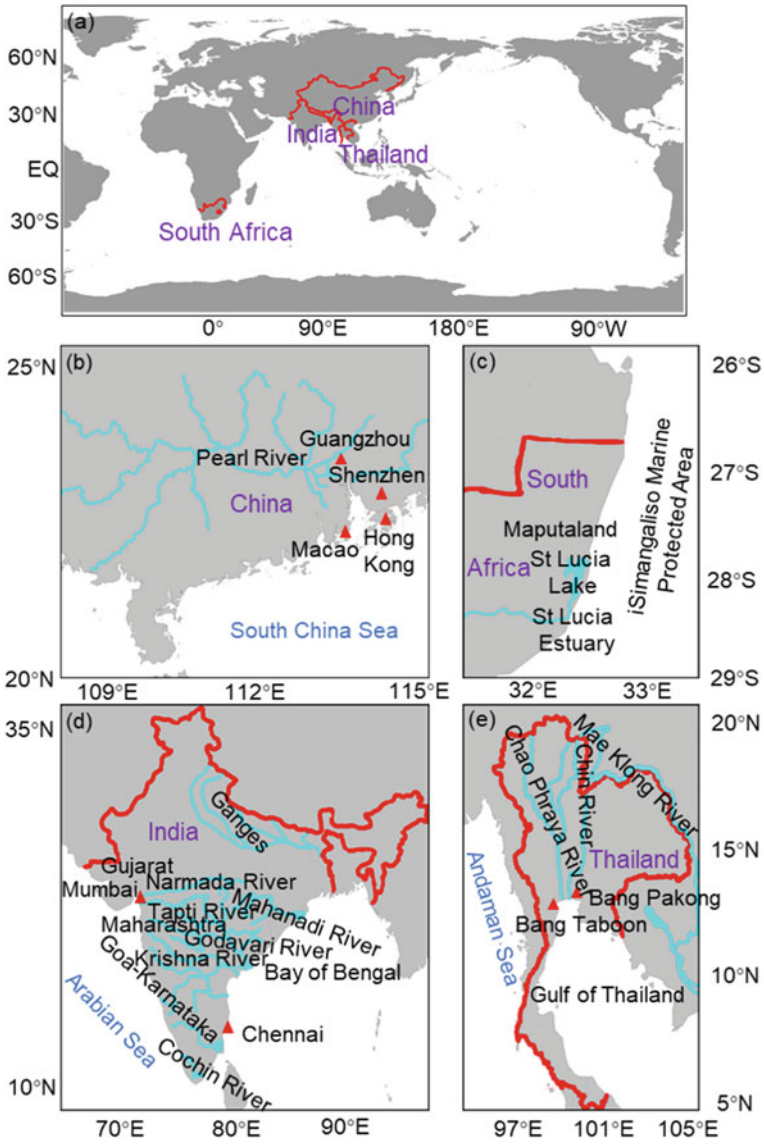


Fig. 9.3 Sites of cases of coastal pollution. **a** locations of the developing countries where these sites are located, **b** the Pearl River Delta in China, **c** the iSimangaliso Marine Protected Area in South Africa, **d** India, and **e** Thailand

9.8.1 The Pearl River Delta in China

The Pearl River Delta (PRD) is located on the northern shelf of the South China Sea and covers about 4,000 km² marine area and 56,000 km² land area, including the large cities of Hong Kong, Macao, Shenzhen, and Guangzhou (Fig. 9.3b). The Pearl River, with an annual water discharge of $\sim 3.26 \times 10^{11}$ m³ and a drainage area of 4.5×10^5 km², is the 17th largest river in the world in terms of freshwater discharge (Dai et al. 2014). The ocean and humans are inextricably linked in the PRD via various key social and economic activities.

Coastal eutrophication and associated issues: Since the 1980s, rapid industrial and agricultural development and urbanization have input large amounts of anthropogenic nutrients into the Pearl River Estuary and onto the adjacent continental shelf (Huang et al. 2003; Callahan et al. 2004; Harrison et al. 2008). Sewage discharge in the PRD increased more than seven fold from 2100 Mt in the 1980s to 15,100 Mt in the 2000s (Ma et al. 2009). As a result, the coastal waters in the PRD, especially around Hong Kong, are affected by persistent and increasing eutrophication. This deteriorating situation may increase the frequency of HABs, expand the area of hypoxic zones and lead to other ecosystem disruptions such as loss of habitat for bottom-dwelling fish.

In the last decade, summer hypoxia was frequently observed off the Pearl River Estuary, with an increasing area and intensity (e.g., Su et al. 2017; Zhao et al. 2020). In 2014, the area of bottom hypoxia was about 3,000 km² southwest of Hong Kong (Su et al. 2017). A decreasing trend of $\sim 2 \pm 0.9$ $\mu\text{mol kg}^{-1} \text{yr}^{-1}$ was shown in the annual minimum DO concentration in the bottom water adjacent to Hong Kong over the period 1990–2014 (Qian et al. 2018). Associated with the decrease in DO was an increase in the annual maximum surface concentration of DIN at a rate of $\sim 1.4 \pm 0.3$ $\mu\text{mol kg}^{-1} \text{yr}^{-1}$ under almost constant bottom temperatures, suggesting that eutrophication is the most plausible driver of oxygen deficiency in this region.

In contrast, before the 1990s only small-scale and short-lived hypoxia events were recorded in this area (Yin et al. 2004), but since then, these events have been increasing in intensity, frequency, and geographic extent. Hypoxia has been growing and has reached an alarming level in the Pearl River Estuary. If the current trend continues, large-scale hypoxia could spread and may eventually offset the progress made by the costly sewage treatment and cause severe ecological and environmental damage.

Eutrophication/hypoxia in the PRD is primarily caused by the ecosystem's responses to the increasing nutrient discharge from the Pearl River and local sewage effluents. As direct waste products from human activities and the most reactive nitrogen species, ammonium discharge resulted from domestic sewage (67%), agricultural wastes (25%), and industrial wastes (8%) in 2017 (National Bureau of Statistics and Ministry of Ecology and Environment 2018). Meanwhile, increasing discharge of organic pollutants also modulates biogeochemical pathways and ecological consequences, and further increases the severity of eutrophication/hypoxia in the PRD. Cyclonic vortices and centers of convergence in the coastal transition zone

between the Pearl River Estuary and the adjacent continental shelf create a stable water column with weak mixing and long residence time, and accumulate nutrients and organic matter that result in eutrophication and hypoxia development (Li et al. 2020). In addition, passages of typhoons can cause stirring up of bottom waters so that hypoxia is disrupted, while nutrients stirred up from the bottom foster primary production and subsequent hypoxia reinstatement in 6–12 days (Kuss et al. 2021; Zhao et al. 2021). Ocean acidification in coastal waters is further greatly aggravated with the development of bottom water hypoxia due to a reduction in the acid–base buffering capacity of seawater.

Heavy metal pollution: Besides eutrophication, hypoxia and coastal acidification, other factors also contribute to the deterioration of the coastal ecosystem in the PRD. Coastal sediments in the offshore waters of Hong Kong are the most polluted by heavy metals in southern China, with high levels of copper, lead, zinc, cadmium, and mercury. There were significantly high heavy metal concentrations, especially zinc (200 mg kg^{-1}) and chromium (130 mg kg^{-1}), in sediments deposited in 1975–1985, consistent with the rapid development in coastal areas in China, particularly the PRD, and increasing discharges of contaminants from local industrial, agriculture and urban activities due to China's reform and opening-up policy (Ye et al. 2020). Over the period 1986–1992, heavy metal concentrations displayed a downward trend, likely related to economic adjustment. The high heavy metal concentrations after 1992 were related to a new economic reform driven by economic transition in 1992 with the concentrations in surface sediments of 91 mg kg^{-1} for chromium and 145 mg kg^{-1} for zinc. Heavy metals in waters of the Pearl River Estuary mainly come from wastewater of the metallurgical industry, electroplate industry and corrosion of metal equipment in ports, boats and ships, and overland runoff of mining areas upstream (Huang and Onyx 2004).

Ecological and economic impacts and science and technology applied to deal with the environmental issues: Eutrophication/hypoxia and metal pollution affect local fisheries in the PRD. In terms of food resources, fish and crustaceans are less tolerant to reduced oxygen levels than gastropods and bivalves, so that for resource use sectors and communities reliant on fish and crustaceans, greater impacts are expected from hypoxia on productivity and size of stocks. Metal contamination may render water and sediments unsuitable for marine aquaculture, which potentially reduces seafood stocks in the PRD, and subsequently may reduce the benefits of marine aquaculture to the blue economy of the region.

To deal with deteriorating water quality in the PRD, regular monitoring of water quality has been carried out by the Hong Kong Environmental Protection Department and by local environmental agencies on the mainland China since the 1990s. Environmental measures such as wastewater treatment in the large cities of the PRD before wastewater is discharged have been implemented. These measures have been effective in reducing nutrient point-source inputs to the Pearl River Estuary; consequently the upper Estuary has become relatively clean since the beginning of the Twenty-first Century. However, large amounts of anthropogenic nutrient inputs and resultant eutrophication have tipped the lower Estuary and adjacent shelf areas into

seasonal hypoxia, despite intermittent summertime mixing of coastal waters by tropical cyclones (Qian et al. 2018). The risk of eutrophication and hypoxia is rapidly increasing around Hong Kong despite the massive sewage treatment project (Qian et al. 2018).

Due to strengthening of pollution controls by local government and relocation of industries to mainland China, heavy metals in coastal sediments of Hong Kong increased before the early 1990s and dropped afterward (Wang et al. 2013). The strengthening of environmental controls imposed by local governments, such as the construction of sewage interception pipe networks at the upstream and establishment of wastewater treatment plant in the PRD and industrial transformation and upgrading, likely explain the lower concentrations of chromium, nickel, copper, and zinc in the top sediment layers in this region (Gao et al. 2017). However, the average chromium, nickel, copper, and lead concentrations in surface sediments still exceed the threshold effect level values of 52.3, 15.9, 18.7, and 30.2 mg kg⁻¹, respectively, but lower than the probable effect level values of 160.4, 42.8, 108.2, and 112.2, indicating some degree of potential adverse ecological effects.

9.8.2 *The iSimangaliso Marine Protected Area in South Africa*

The iSimangaliso Wetland Park (10,700 km²) located in Maputaland on the east coast of South Africa (Fig. 9.3c), encompasses a diverse variety of terrestrial, coastal and marine environments. Declared a UNESCO World Heritage Site in 1999, iSimangaliso is the single largest formally protected area along the South African coastline. Limited sediment exchange with the ocean occurs and the absence of any major riverine inputs north of St. Lucia Estuary results in remarkably clear offshore waters.

Pesticide pollution: Despite their protected status, seemingly pristine coastal and marine habitats are threatened by pollution, originating largely from activities occurring within catchment areas external to the Wetland Park. Maputaland has a long history of pesticide use and pesticide pollution is probably the single most serious contamination threat to the region. Beginning in the mid-1940s, organochlorine pesticides (OCPs) were widely used on agricultural crops and to control the spread of insect-borne diseases. Large quantities of insecticides—including hexachlorocyclohexanes (HCHs), aldrin, heptachlor, and endosulfan—were used on commercial sugarcane and citrus fruit farmlands, while aerial spraying with DDT was employed to combat tsetse fly that spread African trypanosomiasis and mosquitos that spread malaria. As in many other developing countries impacted by malaria, use of DDT in South Africa is permitted for indoor residual spraying (IRS) purposes and DDT is typically applied annually during the late summer months to the inside of dwellings as the primary method of malaria control (Maharaj et al. 2019).

Due to their environmental persistence and susceptibility to long-range transport, the intensive use of OCPs in Maputaland led not only to widespread contamination

in the areas where they were applied, but also in the neighboring ecosystems of iSimangaliso. Transport of sediment from contaminated catchment areas remain an importance source of legacy OCPs, particularly for large fluvially dominated systems such as Lake St. Lucia (Buah-Kwofie and Humphries 2021). While the majority of this contamination is attributable to past use, the illegal and continued use of obsolete OCP stocks on farmlands surrounding iSimangaliso has been suspected (Buah-Kwofie and Humphries 2017, 2021). Furthermore, while malaria control operations permit the limited use of DDT, thousands of homesteads across large areas of Maputaland that border conservation areas are routinely sprayed. Today, iSimangaliso's lake and wetland systems represent vast contaminated sinks in the landscape, harboring substantial quantities of sediment-bound pesticides that originated from catchment areas outside of the park boundary (Humphries 2013; Buah-Kwofie and Humphries 2017). The continued presence of significant DDT concentrations detected within sediments ($74\text{--}510\text{ ng g}^{-1}$) and biological tissues ($390\text{--}5,000\text{ ng g}^{-1}$) (Buah-Kwofie and Humphries 2021) suggest that ongoing IRS practices remain an important source of environmental contamination in the region, indicating a conflict between the need to protect human health against malaria and protection of coastal ecosystems from DDT pollution.

Ecological impacts and science and technology applied to deal with the environmental issues: While offering a highly effective and low-cost approach to pest control, the release of OCPs into the environment is accompanied by significant ecological and human health concerns. Because of their high toxicity and tendency to bioaccumulate through the food web, many OCPs have been linked with several adverse toxicological responses in both humans (Bornman and Bouwman 2012; Ferguson et al. 2013) and wildlife populations (Delong et al. 1973; De Guise et al. 1995; Tubbs and McDonough 2017). The accumulation of OCPs in local fish species is prevalent, with tissue analyses revealing the presence of particularly high concentrations of HCHs, DDTs, endrin, and methoxychlor (Buah-Kwofie et al. 2018). While a variety of teratogenic, reproductive, and neurotoxic effects have been reported in fish exposed to environmentally significant levels of OCPs (Martyniuk et al. 2020), such effects remain largely understudied in local fish species.

Pesticides also impact adjacent coral reef systems, diminishing their value as blue economy resources. The proximity of coral reef communities found along the Maputaland coastline exposes a diverse variety of marine organisms to the long-term effects of pesticide pollution. Remarkably high OCP concentrations ($450\text{--}3000\text{ ng g}^{-1}$ wet weight) have been detected in soft corals and sponges from several shallow reefs along the coastline (Porter et al. 2018), rivalling some of the highest pesticide levels reported in marine organisms globally. Although the toxicological impacts of OCP pollution on Maputaland reefs are yet to be studied, monitoring studies have indicated a steady decline in soft coral cover of almost 1% per year over the past 25 years (Porter and Schleyer 2017). It is speculated that the observed decline in cover of soft coral (54% in 1993 to 36% in 2014) may be associated with prolonged exposure to OCPs (Porter and Schleyer 2017; Porter et al. 2018). Moreover, it is likely that OCPs bioaccumulate in other reef-associated fauna (e.g.,

crustaceans, fish and turtles), potentially affecting coral reef ecosystems in the region more broadly.

To deal with the pesticide pollution, use of most OCPs in South Africa was banned in the early 2000s, with the exception of DDT, which continues to be used for disease vector control in the northeastern malaria-endemic regions of the country. Despite the widespread occurrence of pesticide pollution in Maputaland, little is known about the specific long-term toxicological impacts of these contaminants on ecosystems and biological communities. So far, there have been no meaningful attempts from management authorities to assess or mitigate the effects of pesticide contamination. Of particular relevance is the continued use of DDT in areas surrounding iSimangaliso. While promoted by the World Health Organization and South African Department of Health, evaluating the trade-off between disease control and related adverse effects on human and ecosystem health is severely constrained by inadequate data.

9.8.3 India

India is the 7th largest country by area and second largest by population (~1.3 billion) in the world, with over 25% of its population residing in the coastal areas (Fig. 9.3d). The coastal zone of India is the location of many cities (such as Mumbai, Chennai, Kolkata, Visakhapatnam, Kochi, Mangalore etc.). In addition, 14 major rivers drain into the Bay of Bengal and the Arabian Sea from India's east and west coasts, respectively (Rao 1979). Due to urbanization, coastal areas have become hotspots for pollution. Apart from industrial and agricultural effluents, there have been growing concerns over pollution associated with heavy metals, microplastics, and oil pollution in recent years.

Microplastic pollution: India is one of the leading consumers of plastics in the world, with an annual consumption of nearly 5.6 million tons (Toxics link 2014), which is a significant portion of global consumption. The River Ganges is the second largest plastic polluter to the global ocean (Lebreton et al. 2017). The highest concentrations of microplastics are found in metropolitan cities such as Mumbai (west coast of India; Maharana et al. 2020), Chennai (east coast of India; Sathish et al. 2019), and the River Ganges (Goswami et al. 2020). However, sediments found along the east coast of India are relatively less polluted with microplastics than sediments of the west coast of India (Ranjani et al. 2021).

Eighty percent of the plastic debris in India is derived from land-based sources such as rivers and by the human population, mainly at coastal places (Lebreton et al. 2017). The most frequently identified polymer types of microplastic materials in sediments along the east coast and west coast of India are polyethylene (47%) and polypropylene (18.8%); other polymer types are polystyrene, polyethylene terephthalate, and polyamide (Ranjani et al. 2021). India produces nearly 2.5 MTPA (million tons per annum) of polypropylene, where demand is 2.1 MTPA; the rest is exported to other southeast Asian countries (Veerasingam et al. 2017).

Oil spills and tarballs: In India, oil pollution is another concern due to the existence of several oil rigs and significant transport of oil by ship, as international shipping routes traverse the Arabian Sea and Bay of Bengal. Oil spills were more frequent in the offshore waters off Gujarat (41.6%), Maharashtra (34.8%), and Goa-Karnataka (23.5%) based on data in 2017 (Suneel et al. 2019). Oil residues in the form of tarballs are observed along the west coast of India, especially along the coasts of Goa and Gujarat (Suneel et al. 2016). Tarballs were first reported in the peer-reviewed literature on Indian beaches by Nair et al. (1972). The main sources of tarballs are emergent oil spills from ships and oil platforms along international ship transport routes and in areas of offshore production. Due to the monsoon circulation patterns in the northern Indian Ocean, these floating tarballs reach the coasts of India.

Ecological and economic impacts and science and technology applied to deal with the environmental issues: Plastics and oil pollution affect fisheries and beach tourism in India, negatively impacting the country's blue economy. Ingestion of plastic materials has been reported in lower trophic levels of the food chain, such as fish, mollusk, crab, and shrimp, which eventually may affect humans (Kumar et al. 2018; Naidu 2019; Piarulli et al. 2019; Daniel et al. 2020). In addition, due to the existence of a long coastline around India, beaches are another hotspot for microplastic accumulation introduced due to tourism and recreational activities. Oil spills cannot dissolve in water and form a thick sludge that can suffocate marine life such as fish, mammals, and seabirds, and can hamper photosynthetic activity by blocking sunlight (Dicks 1998) so as to damage marine ecosystems such as coral reefs. The science on oil spills is limited in terms of their fate, origin, and transport along the east and west coasts of India.

The Indian government is committed to reduce plastic usage by encouraging reducing, recycling, and reuse of plastics. As a result, 10 beaches in India have won blue flags by 2021 (<https://www.blueflag.global/all-bf-sites>), an eco-label certificate awarded by the Foundation for Environmental Education to beaches and sustainable beach tourism operators that meet a comprehensive set of requirements.

9.8.4 Thailand

Thailand is located between the Gulf of Thailand and the Andaman Sea (Fig. 9.3e), with a coastline of 3,219 km (DMCR 2015) and a population of about 69 million in 2020 (UN Data 2020).

Water pollution: The first major water pollution event in Thailand occurred in 1970, named the "molasses incident", caused by a spill of molasses into the Mae Klong River, which resulted in elimination of fish in the river and massive cockle mortality, covering several thousand acres in the coastal zone (Ludwig 1976). Water pollution has increased due to deterioration of watersheds caused by agricultural development, industrialization, and rapidly growing population since 1965 and sharply since 1985 (World Bank 2020). Eutrophication is increasing in frequency as well. Between 2007 and 2020, 86 algal blooms were reported along the Thai

coastal zone. DO concentrations below $122 \mu\text{mol kg}^{-1}$ have occurred in the upper Gulf of Thailand, predominantly caused by domestic wastes, with ammonia the main contributor from agriculture and aquaculture sources (PCD 2000).

Water pollution in the Gulf of Thailand has two sources: (a) primary untreated metropolitan, urban and industrial wastewater; and (b) water contamination by agricultural nutrients, which contributes to coastal eutrophication and oxygen depletion events, killing organisms in the upper Gulf of Thailand. Domestic sewage, industrial effluents, and agricultural runoff each year are estimated to be 9.6, 9.9, and $178 \times 10^6 \text{ m}^3 \text{ d}^{-1}$, respectively (Dumrongthai 2019; ONREPP 2020).

Additionally, oil pollution has degraded water resources in the estuarine and coastal environments since the 1950s due to oil spill accidents, industrial activities, and shipping along the coast (Boonyatumanond et al. 2007). Moreover, emerging organic pollutants such as cosmetics, pharmaceutical drugs (including acetylsalicylic acid, caffeine, and ibuprofen), and skincare products (such as synthetic musk and UV filters) in wastewaters may pose a high risk to aquatic organisms in Thailand's estuaries and coastal zones (Juksu et al. 2020). Heavy metals have high concentrations in the sediments of the Chao Phraya estuary and the Gulf of Thailand, e.g., 1.04 mg kg^{-1} for cadmium, 213 mg kg^{-1} for copper, 50.7 mg kg^{-1} for chromium, 98.1 mg kg^{-1} for lead, and 643 mg kg^{-1} for zinc (Wijaya et al. 2013).

Ecological and economic impacts and science and technology applied to deal with the environmental issues: Water pollution affects fisheries and tourism in Thailand. Contaminated waters have resulted in habitat degradation, human health vulnerability, and marine ecosystem damage in the Gulf of Thailand and Andaman Sea (Wattayakorn 2006). Mass shellfish death occurred more frequently after 2006 in shellfish farms in the upper Gulf of Thailand (DMCR 2020). Microplastic fibers were found in 82.76% of demersal fish and 57.14% of pelagic fish in Thai waters (Klangnarak and Chunniyom 2020). The decline of *Rastrelliger brachysoma*, a commercially exploited fish species, due to poor reproduction, may be caused by pollutants such as heavy metals and oil (Senarat et al. 2017). Increasing plastic waste accumulation in Thai marine ecosystems has become an additional acute stress to an already overstressed fisheries (overfishing) and marine wildlife, and impacts tourist destination images.

To address the water pollution problem in Thailand, untreated metropolitan, urban and industrial wastewater is the top priority concern of government management that intends to support the master plan of SDG 14 in Thailand (ONREPP 2020). Currently, the industrial sector is reducing pollutant loads due to the wastewater outflow control, required by the Pollution Control Department in Thailand (PCD). The master plan for water quality management in Thailand (2018–2037) is as follows: (a) improve and maintain surface water quality, and (b) improve and maintain coastal marine quality (NESDC 2018). The PCD has taken actions on marine debris on beaches and in coastal seas to limit the ever-growing consumption and disposal of plastics under the government and private sectors, and to increase society's engagement (PCD 2020).

9.9 Knowledge and Capacity-Building Gaps

In terms of scientific understanding, given the vast diversity of coastal contaminants, coupled with climate change and associated processes, it is extremely challenging to have a complete understanding of the distribution of contaminants in coastal water, sediments, and biota, their interactions, and synergistic short- and long-term effects on coastal ecosystems on regional and global scales. Further studies are needed at the community and population levels to improve knowledge of the ecotoxicity of coastal pollutants. Socio-economic impacts of coastal pollution are rarely quantitatively assessed. Research needs to be advanced in how to transfer the best available science acquired into actionable strategies and schemes.

In terms of observations, insufficient or non-existent monitoring of coastal pollutants, especially in developing countries, results in a significant gap in understanding of the impacts of anthropogenic pollutants on coastal waters. There is a need for more coordinated spatial and temporal sampling of pollutants, within a global strategy. A long-term monitoring of essential indicators and processes is required (see Chap. 14).

In terms of capacity building, standardized measurement techniques and protocols need to be applied at an optimized resolution to detect temporal trends and for ease of comparisons between researchers and geographic regions. There is a need to develop laboratory and in-situ facilities that can improve knowledge and monitoring of pollutants. There are major gaps in the capacities of most developing countries to monitor concentrations of pollutants in coastal areas. There are inadequate infrastructures for effective waste collection and managements. A database of pollutants in coastal areas as well as a scientist network would be desirable. An integrated modelling and forecasting framework is proposed to serve cross-scale and interdisciplinary synthesis, diagnosis and simulations of key processes, allowing prediction of future changes. Improving awareness, information and education and communicating scientific findings to management and policy makers are crucial steps in helping advance monitoring strategies and measures to effectively preserve the marine environment and to sustainably utilize coastal resources. Joint efforts are sought from academia, industry, and government agencies to understand physical, chemical, and biological factors, socio-economic drivers, and governance affecting coastal pollution in order to identify the sources and mediate existing coastal pollution around the globe and adapt to climate change for future healthy developments of coastal systems.

9.10 Implications for Blue Economy

Several sectors of blue economy are affected or have the potential to be affected by the wide variety of organic and inorganic pollutants reaching coastal seas. They disrupt coastal water quality, and the biogeochemical and ecological functions of such

interconnected ecosystems as mangroves, seagrasses, and corals reefs (see Chaps. 2–3). As a consequence, such pollution has an impact on ecosystem health, products and services, and the aesthetic value of coastal habitats. Our cases of pollution from selected developing countries show examples of the blue economic sectors that can be impacted: human health, fisheries, and tourism. The multiplicity of pollutants, their complex interactions, as well as their impact and potential exacerbation due to climate change pose challenges that can be confronted by blue economic policies based on a better scientific understanding of the issues involved.

Acknowledgements We are thankful to Weizhen Jiang, Guiyuan Dai, Yafei Sun, and Fei Zhang for their help in literature searching. We appreciate the thorough editing and constructive comments from Ed Urban, Venu Ittekkot, and an anonymous reviewer. Guiyuan Dai plotted Fig. 9.1 and Weizhen Jiang drafted Fig. 9.3. The work by Guizhi Wang was supported by Natural Science Foundation of Fujian Province (#2019J01020).

References

- Akagha SC, Nwankwo DI, Yin K (2020) Dynamics of nutrient and phytoplankton in Epe Lagoon, Nigeria: possible causes and consequences of reoccurring cyanobacterial blooms. *Appl Water Sci* 10(5):109
- Al-Amri AA, Qari HA, El-Sherbiny MM (2020) Distribution and community structure of micro-phytoplankton in relation to increasing anthropogenic impact along coastal waters of Jeddah, the central Red Sea. *Oceanol Hydrobiol St* 49(2):193–205
- Alimi OS, Budarz JF, Hernandez LM et al (2018) Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. *Environ Sci Technol* 52(4):1704–1724
- Altieri AH, Harrison SB, Seemann J et al (2017) Tropical dead zones and mass mortalities on coral reefs. *Proc Natl Acad Sci USA* 114(14):3660–3665
- Andrady AL (2015) Persistence of plastic litter in the oceans. In: Gutow L, Klages M (eds) Bergmann M. Marine anthropogenic litter. Springer, pp 57–72
- Ashton K, Holmes L, Turner A (2010) Association of metals with plastic production pellets in the marine environment. *Mar Pollut Bull* 60(11):2050–2055
- Baohong C, Muchtar M, Tingting F et al (2016) A baseline study of coastal water quality in the Lembeh Strait of North Sulawesi, Indonesia, in 2013. *Mar Pollut Bull* 104:364–370
- Barnes D, Galgani F, Thompson RC et al (2009) Accumulation and fragmentation of plastic debris in global environments. *Philos T R Soc B Biol Sci* 364(1526):1985–1998
- Barnes DKA, Walters A, Goncalves L (2010) Macroplastics at sea around Antarctica. *Mar Environ Res* 70(2):250–252
- Basatnia N, Hossein SA, Rodrigo-Comino J et al (2018) Assessment of temporal and spatial water quality in international Gomishan Lagoon, Iran, using multivariate analysis. *Environ Monit Assess* 190(5):314
- Benitez-Nelson CR, Charmasson S, Buesseler K et al (2018) Radioactivity in the marine environment: understanding the basics of radioecology. *Limnol Oceanogr e-Lectures*, 8(1):170–228. <https://aslopubs.onlinelibrary.wiley.com/doi/abs/10.1002/loe2.10007>
- Beyer J, Trannum HC, Bakke T et al (2016) Environmental effects of the Deepwater Horizon oil spill: A review. *Mar Pollut Bull* 110(1):28–51
- Boesch DF (2019) Barriers and bridges in abating coastal eutrophication. *Front Mar Sci* 6:25

- Boonyatumanond R, Wattayakorn G, Amano A et al (2007) Reconstruction of pollution history of organic contaminants in the upper Gulf of Thailand by using sediment cores: first report from Tropical Asia Core (TACO) project. *Mar Pollut Bull* 54(5):554–565
- Bornman MS, Bouwman H (2012) Environmental pollutants and diseases of sexual development in humans and wildlife in South Africa: harbingers of impact on overall health? *Reprod Domest Anim* 47:327–332
- Bouwman L, Goldewijk K K, Van Der Hoek KW et al (2013) Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *Proc Natl Acad Sci USA* 110:20882–20887.
- Boyle EA, Lee JM, Echevoyen Y et al (2014) Anthropogenic lead emission in the ocean the evolving global experiment. *Oceanography* 27(1):69–75
- Breitbart D, Levin LA, Oschlies A et al (2018) Declining oxygen in the global ocean and coastal waters. *Science* 359(6371). <https://doi.org/10.1126/science.aam7240>
- Browne MA, Crump P, Niven SJ et al (2011) Accumulation of microplastic on shorelines worldwide: sources and sinks. *Environ Sci Technol* 45(21):9175–9179
- Browne MA, Dissanayake A, Galloway TS et al (2008) Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L). *Environ Sci Technol* 42(13):5026–5031
- Buah-Kwofie A, Humphries MS (2017) The distribution of organochlorine pesticides in sediments from iSimangaliso Wetland Park: ecological risks and implications for conservation in a biodiversity hotspot. *Environ Pollut* 229:715–723
- Buah-Kwofie A, Humphries MS (2021) Organochlorine pesticide accumulation in fish and catchment sediments of Lake St. Lucia: risks for Africa's largest estuary. *Chemosphere* 274:129712
- Buah-Kwofie A, Humphries MS, Pillay L (2018) Bioaccumulation and risk assessment of organochlorine pesticides in fish from a global biodiversity hotspot: iSimangaliso Wetland Park, South Africa. *Sci Total Environ* 621:273–281
- Buesseler K, Dai MH, Aoyama M et al (2017) Fukushima Daiichi-derived radionuclides in the ocean: transport, fate, and impacts. *Ann Rev Mar Sci* 9:173–203
- Cabral H, Fonseca V, Sousa T et al (2019) Synergistic effects of climate change and marine pollution: an overlooked interaction in coastal and estuarine areas. *Intern J Environ Res Pub Health* 16(15):17
- Callahan J, Dai MH, Chen RF et al (2004) Distribution of dissolved organic matter in the Pearl River estuary, China. *Mar Chem* 89(1–4):211–224
- Carstensen J, Conley DJ (2019) Baltic Sea hypoxia takes many shapes and sizes. *Limnol Oceanogr* Bull 28(4):125–129
- Cesa FS, Turra A, Baruque-Ramos J (2017) Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. *Sci Total Environ* 598(15):1116–1129
- Chae Y, An YJ (2017) Effects of micro- and nanoplastics on aquatic ecosystems: current research trends and perspectives. *Mar Pollut Bull* 124(2):624–632
- Chauhan OS, Raghavan BR, Singh K et al (2011) Influence of orographically enhanced SW monsoon flux on coastal processes along the SE Arabian Sea. *J Geophys Res-Oceans* 116:C12037. <https://doi.org/10.1029/2011JC007454>
- Ciotti AM, Ferreira A, Giannini MFC (2018) Seasonal and event-driven changes in the phytoplankton communities in the Araçá Bay and adjacent waters. *Ocean Coast Manage* 164:14–31
- Cunningham PA, Sullivan EE, Everett KH et al (2019) Assessment of metal contamination in Arabian/Persian Gulf fish: a review. *Mar Pollut Bull* 143:264–283
- Dahms H, Rensburg G, Greenfield R (2020) The microplastic profile of an urban African stream. *Sci Total Environ* 731:138893
- Dai M, Gan JP, Han A et al (2014) Physical dynamics and biogeochemistry of the Pearl River plume. In: Bianchi T, Allison M, Cai WJ (eds.) *Biogeochemical dynamics at major river-coastal interfaces: linkages with global change*. Cambridge University Press, pp 321–352
- Damar A, Colijn F, Hesse KJ et al (2020) Phytoplankton biomass dynamics in tropical coastal waters of Jakarta Bay, Indonesia in the period between 2001 and 2019. *J Mar Sci Eng* 8

- Daniel DB, Ashraf PM, Thomas SN (2020) Abundance, characteristics and seasonal variation of microplastics in Indian white shrimps (*Fenneropenaeus indicus*) from coastal waters off Cochin, Kerala, India. *Sci Total Environ* 737:139839
- Danish EY (2010) Ecological impact from chemicals in the Arabian Gulf due to Gulf oil spill. *Water Environ J* 24(1):65–73
- de Carvalho Aguiar VM, Abuchacra PFF, Neto JAB (2013) Biogeochemistry of Jurujuba sound concerning phosphorus dynamics, Rio de Janeiro, Brazil. *J Coast Res* 65:1–6
- De Guise S, Martineau D, Beland P et al (1995) Possible mechanisms of action of environmental contaminants on St. Lawrence beluga whales (*Delphinapterus leucas*). *Environ Health Perspect* 103:73–77
- DeLong R, Gilmartin WG, Simpson JG (1973) Premature births in California sea-lions: association with high organochlorine pollutant levels. *Sci* 181:1168–1170
- Department of Marine and Coastal Resources (DMCR) (2020) Plankton bloom. https://km.dmcr.go.th/th/c_261/d_2419. Accessed 20 Dec 2020
- Derraik J (2002) The pollution of the marine environment by plastic debris: a review. *Mar Pollut Bull* 44(9):842–852
- Devlin M, Smith A, Graves CA et al (2020) Baseline assessment of coastal water quality, in Vanuatu, South Pacific: insights gained from in-situ sampling. *Mar Pollut Bull* 160:111651
- Diaz RJ, Rosenberg R (2008) Spreading dead zones and consequences for marine ecosystems. *Science* 321(5891):926–929
- Diaz RJ, Selman M, Chique C (2011) Global eutrophic and hypoxic coastal systems. World Resources Institute. Eutrophication and hypoxia: nutrient pollution in coastal waters. http://docs.wri.org/wri_eutrophic_hypoxic_dataset_2011-03.xls
- Dicks B (1998) The environmental impact of marine oil spills—effects, recovery and compensation. International seminar on tanker safety, pollution prevention, spill response and compensation, Rio de Janeiro, Brazil
- DMCR (2015) Marine and Coastal Resources of Thailand. Ministry of Natural Resources and Environment, Bangkok. p. 246 (in Thai)
- Duffus JH (2002) “Heavy metals” a meaningless term? (IUPAC technical report). *Pure Appl Chem* 74(5):793–807
- Dumrongthai P (2019) Progress of water environment governance in Thailand. Paper presented at the 14th WEPA Annual Meeting, Tokyo, 22 Feb 2019
- Duran EB, Povinec PP, Fowler SW et al (2004) Cs-137 and Pu239+240 levels in the Asia-Pacific regional seas. *J Environ Radioact* 76(1–2):139–160
- Durga Rao G, Kanuri VV, Kumaraswami M et al (2017) Dissolved nutrient dynamics along the southwest coastal waters of India during northeast monsoon: a case study. *Chem Ecol* 33:229–246
- Ebinghaus R, Grøsvik BE, Hassellöv I-M et al (2021) Changes in liquid and atmospheric inputs to the marine environment from land (including through groundwater), ships and offshore installations. In *The Second World Ocean Assessment, vol II*. United Nations, New York
- El Sayed MA, Al Farawati RK, El Maradny AA et al (2013) Environmental status and nutrients and dissolved organic carbon budget of two Saudi Arabian Red Sea coastal inlets: a snapshot statement. *Environ Earth Sci* 74(12):7755–7767
- El-Sorogy AS, Youssef M, Al-Kahtany K et al (2020) Distribution, source, contamination, and ecological risk status of heavy metals in the Red Sea-Gulf of Aqaba coastal sediments. Saudi Arabia. *Mar Pollut Bull* 158:111411
- Er HH, Lee LK, Lim ZF et al (2018) Responses of phytoplankton community to eutrophication in Semerak Lagoon (Malaysia). *Environ Sci Pollut Res Int* 25(23):22944–22962
- Ferguson KK, O’Neill MS, Meeker JD (2013) Environmental contaminant exposures and preterm birth: a comprehensive review. *J Toxicol Environ Health B Crit Rev* 16:69–113
- Ferrera CM, Watanabe A, Miyajima T et al (2016) Phosphorus as a driver of nitrogen limitation and sustained eutrophic conditions in Bolinao and Anda, Philippines, a mariculture-impacted tropical coastal area. *Mar Pollut Bull* 105(1):237–248

- Food and Agriculture Organization of the United Nations (2016) *The State of World Fisheries and Aquaculture 2016: contributing to Food Security and Nutrition for All*. Rome
- Galgani F, Stöfen-O'Brien A, Ambulkar A et al (2021) Changes in inputs and distribution of solid waste, other than dredged material, in the marine environment. In *the Second World Ocean Assessment*, vol II. United Nations, New York
- Gao L, Wang Z, Shan J et al (2017) Aquatic environmental changes and anthropogenic activities reflected by the sedimentary records of the Shima River, Southern China. *Environ Pollut* 224:70–81
- Gao X, Chen CJWR (2012) Heavy metal pollution status in surface sediments of the coastal Bohai Bay. *Water Res* 46:1901–1911
- George R, Muraleedharan KR, Martin GD et al (2012) Nutrient biogeochemistry of the eastern Arabian Sea during the southwest monsoon retreat. *Environ Earth Sci* 68:703–718
- Goldberg ED (1995) The health of the oceans—a 1994 update. *Chem Ecol* 10(1–2):3–8
- Goldberg ED (1997) Plasticizing the seafloor: an overview. *Environ Technol* 18(2):195–201
- González-De Zayas R, Rossi S, Hernández-Fernández L et al (2020) Stable isotopes used to assess pollution impacts on coastal and marine ecosystems of Cuba and México. *Reg Stud Mar Sci* 39:101413
- Goswami P, Vinithkumar NV, Dharani G (2020) First evidence of microplastics bioaccumulation by marine organisms in the Port Blair Bay, Andaman Islands. *Mar Pollut Bull* 155:111163
- Guo Z (2004) The prevention and control of oil pollution off Chinese coastal waters. *J Zhejiang Ocean Uni* 23(3):269–273
- Halpern BS, Walbridge S, Selkoe KA et al (2008) A global map of human impact on marine ecosystems. *Science* 319(5865):948–952
- Hamuna B, Tanjung R, Alianto A (2019) Assessment of water quality and pollution index in coastal waters of Mimika, Indonesia. *J Ecol Eng* 20:87–94
- Hansen J (1990) Draft position statement on plastic debris in marine environments. *Fish* 15(3):16–17
- Harrison PJ, Yin KD, Lee JHW et al (2008) Physical-biological coupling in the Pearl River estuary. *Cont Shelf Res* 28(12):1405–1415
- Haward M (2018) Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. *Nat Commun* 9(1):667
- He BY, Dai MH, Zhai WD et al (2014) Hypoxia in the upper reaches of the Pearl River Estuary and its maintenance mechanisms: a synthesis based on multiple year observations during 2000–2008. *Mar Chem* 167:13–24
- Herrera-Silveira JA, Comin FA, Aranda-Cirerol N et al (2004) Coastal water quality assessment in the Yucatan Peninsula: management implications. *Ocean Coast Manage* 47(11–12):625–639
- Howarth RW (2008) Coastal nitrogen pollution: a review of sources and trends globally and regionally. *Harmful Algae* 8(1):14–20
- Howarth R, Paerl HW (2008) Coastal marine eutrophication: control of both nitrogen and phosphorus is necessary. *Proc Natl Acad Sci USA* 105(49):E103–E103
- Huang SL, Onyx WHW (2004) A review of heavy metal pollution in the pearl river estuary. *J Hydrodyn* 16(4):367–378
- Huang XP, Huang LM, Yue WZ (2003) The characteristics of nutrients and eutrophication in the Pearl River estuary. South China. *Mar Pollut Bull* 47(1–6):30–36
- Humphries MS (2013) DDT residue contamination in sediments from Lake Sibaya in northern KwaZulu-Natal, South Africa: Implications for conservation in a World Heritage Site. *Chemosphere* 93:1494–1499
- Ivar do Sul JA, Spengler A, Costa M (2009) Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). *Mar Pollut Bull* 58(8):1236–1238
- Jickells TD, Buitenhuis E, Altieri K et al (2017) A reevaluation of the magnitude and impacts of anthropogenic atmospheric nitrogen inputs on the ocean. *Glob Biogeochem Cycles* 31(2):289–305

- Jilani S (2015) Assessment of heavy metal pollution in Lyari river and adjoining coastal areas of Karachi. *J Biodivers Environ Sci* 6(2):208–214
- Johnson A, Harrison M (2015) The increasing problem of nutrient runoff on the coast. *Am Sci* 1003:98
- Jones PD (2006) Water quality and fisheries in the Mersey estuary, England: a historical perspective. *Mar Pollut Bull* 53(1–4):144–154
- Juksu K, Liu YS, Zhao JL et al (2020) Emerging contaminants in aquatic environments and coastal waters affected by urban wastewater discharge in Thailand: an ecological risk perspective. *Ecotoxicol Environ Saf* 204:110952
- Kadafa AA (2012) Oil exploration and spillage in the Niger Delta of Nigeria. *Civil Environ Res* 22(1):45–50
- Kibria G, Hossain MM, Mallick D et al (2016) Trace/heavy metal pollution monitoring in estuary and coastal area of Bay of Bengal, Bangladesh and implicated impacts. *Mar Pollut Bull* 105(1):393–402
- Kiessling T, Gutow L, Thiel M (2015) Marine litter as habitat and dispersal vector. In: Bergmann M, Gutow L, Klages M (eds) *Marine anthropogenic litter*. Springer, pp 141–181
- Klangnarak W, Chunninyom S (2020) Screening for microplastics in marine fish of Thailand: the accumulation of microplastics in the gastrointestinal tract of different foraging preferences. *Environ Sci Pollut Res* 27:27161–27168. <https://doi.org/10.1007/s11356-020-09147-8>
- Kumar VE, Ravikumar G, Jeyasanta KI (2018) Occurrence of microplastics in fishes from two landing sites in Tuticorin, South east coast of India. *Mar Pollut Bull* 135:889–894
- Kuss J, Frazão HC, Schulz-Bull, DE et al (2021) The impact of typhoon “Mangkhut” on surface water nutrient and chlorophyll inventories of the South China Sea in September 2018. *J Geophys Res: Biogeosci* 126:e2021JG006546
- Ladewig SM, Bao S, Chow AT (2015) Natural fibers: a missing link to chemical pollution dispersion in aquatic environments. *Environ Sci Technol* 49(21):12609–12610
- Laffoley D, Baxter JM (2019) *Ocean deoxygenation: everyone’s problem: causes, impacts, consequences and solutions*. IUCN, Gland, Switzerland
- Lamsal LN, Martin RV, Padmanabhan A et al (2011) Application of satellite observations for timely updates to global anthropogenic NO_x emission inventories. *Geophys Res Lett* 38:L05810
- Law KL, Thompson RC (2014) Microplastics in the seas. *Science* 345(6193):144–145
- Lebreton LC, Van Der Zwet J, Damsteeg JW et al (2017) River plastic emissions to the world’s oceans. *Nat Commun* 8(1):1–10
- Lee CW, Lim JH, Heng PL et al (2020) Influence of elevated river flow on hypoxia occurrence, nutrient concentration and microbial dynamics in a tropical estuary. *Environ Monitor Assess* 192(10):1–12
- Lemley DA, Adams JB, Bornman TG et al (2019) Land-derived inorganic nutrient loading to coastal waters and potential implications for nearshore plankton dynamics. *Cont Shelf Res* 174:1–11
- Li D, Gan J, Hui R et al (2020) Vortex and biogeochemical dynamics for the hypoxia formation within the coastal transition zone off the Pearl River Estuary. *J Geophys Res* 125(8) e2020JC016178. <https://doi.org/10.1029/2020jc016178>
- Li WC, Tse HF, Fok L (2016) Plastic waste in the marine environment: a review of sources, occurrence and effects. *Sci Total Environ* 566–567:333–349
- Liu R, Jiang W, Li F et al (2021) Occurrence, partition, and risk of seven heavy metals in sediments, seawater, and organisms from the eastern sea area of Shandong Peninsula, Yellow Sea. *China. J Environ Manage* 279:111771
- Lozano RL, Mouat J (2009) *Marine litter in the North-East Atlantic Region: assessment and priorities for response*. KIMO International
- Lu C, Tian H (2017) Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. *Earth Syst Sci Data* 9:181–192
- Lu Y, Yuan J, Lu X et al (2018) Major threats of pollution and climate change to global coastal ecosystems and enhanced management for sustainability. *Environ Pollut* 239:670–680

- Ludwig HF (1976) Environmental guidelines for coastal zone management in Thailand: inner Gulf Zone. Environmental Impact Evaluation Division National Environmental Board, Office of the National Environment Board
- Ma S (1981) Introduction to marine radionuclide pollution. *Mar Sci Bull* 2:78–88
- Ma Y, Wei W, Xia HY et al (2009) History change and influence factor of nutrient in Lingdingyang Sea area of Zhujiang River Estuary. *Acta Oceanol Sin* 31(2):69–77
- Maharaj R, Seocharan I, Qwabe B et al (2019) Decadal epidemiology of malaria in KwaZulu-Natal, a province in South Africa targeting elimination. *Malar J* 18:368
- Maharana D, Saha M, Dar JY et al (2020) Assessment of micro and macroplastics along the west coast of India: abundance, distribution, polymer type and toxicity. *Chemosphere* 246:125708
- Malone TC, Newton A (2020) The globalization of cultural eutrophication in the coastal ocean: causes and consequences. *Front Mar Sci* 7:30
- Malone TC, Ambulker A, Bebianno MJ et al (2021) Changes in nutrient inputs to the marine environment. In the Second World Ocean Assessment, vol II. United Nations, New York
- Martinez E, Maamaatuaiahutapu K, Taillandier V (2009) Floating marine debris surface drift: convergence and accumulation toward the South Pacific subtropical gyre. *Mar Pollut Bull* 58(9):1347–1355
- Martyniuk CJ, Mehinto AC, Denslow ND (2020) Organochlorine pesticides: agrochemicals with potent endocrine-disrupting properties in fish. *Mol Cell Endocrinol* 507:110764
- Mato Y, Isobe T, Takada H et al (2001) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environ Sci Technol* 35(2):318–324
- Mourão FV, de Sousa ACSR, da Luz Mendes RM et al (2020) Water quality and eutrophication in the Curuçá estuary in northern Brazil. *Reg St Mar Sci* 39
- Murray F, Cowie PR (2011) Plastic contamination in the decapod crustacean *Nephrops norvegicus* (Linnaeus, 1758). *Mar Pollut Bull* 62(6):1207–1217
- Nagaya Y, Nakamura K (1992) ^{239,240}Pu and ¹³⁷Cs in the East China and the Yellow Seas. *J Oceanogr* 48(1):23–35
- Naidu SA (2019) Preliminary study and first evidence of presence of microplastics and colorants in green mussel, *Perna viridis* (Linnaeus, 1758), from southeast coast of India. *Mar Pollut Bull* 140:416–422
- Nair A, Devassy VP, Dwivedi SN et al (1972) Tar ball pollution in Central west coast of India. *Curr Sci* 41:766–767
- Napper IE, Thompson RC (2016) Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. *Mar Pollut Bull* 112(1–2):39–45
- Naser HA (2013) Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: a review. *Mar Pollut Bull* 72(1):6–13
- National Bureau of Statistics and Ministry of Ecology and Environment (ed) (2018) China Statistical Yearbook on Environment. China Statistical Press. <https://www.yearbookchina.com/navibooklist-n3019041927-1.html>
- National Oceanic and Atmospheric Administration (NOAA) (2020) Advances in oil spill science in the decade since *Deepwater Horizon*. Office of Response and Restoration. <https://blog.response.restoration.noaa.gov/8-advances-oil-spill-science-decade-deepwater-horizon>
- National Strategy Secretariat Office (NESDC) (2018) National Strategy 2018–2037 (Royal Thai Government Gazette). National Strategy Secretariat Office, Office of the National Economic and Social Development Council (NESDC), Bangkok
- Naz S, Iqbal MF, Mahmood I et al (2021) Marine oil spill detection using synthetic aperture radar over Indian Ocean. *Mar Pollut Bull* 162:111921
- Ng KL, Obbard JP (2006) Prevalence of microplastics in Singapore's coastal marine environment. *Mar Pollut Bull* 52(7):761–767
- Nguyen TT, Némery J, Gratiot N et al (2019) Nutrient dynamics and eutrophication assessment in the tropical river system of Saigon-Dongnai (southern Vietnam). *Sci Total Environ* 653:370–383
- Nwilo PC, Badejo OT (2006) Impacts and management of oil spill pollution along the Nigerian Coastal Areas. *Administering Marine Spaces: International Issues* 119

- Oehlmann J, Schulte-Oehlmann U, Kloas W et al (2009) A critical analysis of the biological impacts of plasticizers on wildlife. *Philos Trans R Soc B* 364(1526):2047–2062
- Olaifa FE (2005) Hydrocarbon and heavy metal pollution of water and sediments of cross river and Akwa Ibom coastal waters, Nigeria. *J Environ Syst* 32(1, SI)27–36
- ONREPP (2020) State of the Environment 2019. Office of Natural Resources and Environmental Policy and Planning (ONREPP), Ministry of Natural Resources and Environment, Bangkok, Thailand
- Pan Q, Zhu X, Wan L et al (2021) Operational forecasting for Sanchi oil spill. *Appl Ocean Res* 108
- Parker CA, Oreilly JE (1991) Oxygen depletion in Long Island sound—a historical perspective. *Estuaries* 14(3):248–264
- Pekey H (2006) Heavy metal pollution assessment in sediments of the Izmit Bay, Turkey. *Environ Monitor Assess* 123(1–3):219–231
- Pérez-Gómez JA, García-Mendoza E, Olivos-Ortiz A et al (2020) Indicators of nutrient enrichment in coastal ecosystems of the northern Mexican Caribbean. *Ecol Indic* 118:106756
- Piarulli S, Scapinello S, Comandini P et al (2019) Microplastic in wild populations of the omnivorous crab *Carcinus aestuarii*: a review and a regional-scale test of extraction methods, including microfibres. *Environ Pollut* 251:117–127
- PlasticsEurope (2020) Plastics—the facts 2020: an analysis of European plastic production, demand and waste data
- Pollution Control Department (PCD) (2000) Thailand State of Environment: the decade of 1990s. Pollution Control Department, Ministry of Natural Resources and Environment
- Pollution Control Department (PCD) (2020) State of the Environment 2019. Office of Natural Resources and Environmental Policy and Planning, Ministry of Natural Resources and Environment
- Porter SN, Schleyer MH (2017) Long-term dynamics of a high-latitude coral reef community at Sodwana Bay, South Africa. *Coral Reefs* 36:369–382
- Porter SN, Humphries MS, Buah-Kwofie A et al (2018) Accumulation of organochlorine pesticides in reef organisms from marginal coral reefs in South Africa and links with coastal groundwater. *Mar Pollut Bull* 137:295–305
- Prayitno HB, Afdal (2019) Spatial distributions of nutrients and chlorophyll-a: a possible occurrence of phosphorus as a eutrophication determinant of the Jakarta Bay. *J Ilmu dan Teknologi Kelautan Tropis* 11:1–12
- Qian W, Gan J, Liu J et al (2018) Current status of emerging hypoxia in a eutrophic estuary: the lower reach of the Pearl River Estuary, China. *Estuar Coast Shelf Sci* 205:58–67
- Ra K, Kim J.-K, Hong SH et al (2014) Assessment of pollution and ecological risk of heavy metals in the surface sediments of Ulsan Bay, Korea. *Ocean Sci J* 49(3):279–289
- Rabalais NN, Cai WJ, Carstensen J et al (2014) Eutrophication-driven deoxygenation in the coastal ocean. *Oceanography* 27(1):172–183
- Rabalais NN, Turner RE, Diaz RJ et al (2009) Global change and eutrophication of coastal waters. *ICES J Mar Sci* 66(7):1528–1537
- Rahman MM, Noor NM, Saad S et al (2015) Coastal water quality of Tioman Island: effects of human activity and the distance from shoreline. *Desalin Water Treat* 1–5
- Rajan A, Al Raisi A, Thankamony R et al (2020) Eutrophication sources, impacts and management: a case study from Abu Dhabi. *Aquat Ecosyst Health* 23(2):175–186
- Ram A, Jaiswar JRM, Rokade MA et al (2014) Nutrients, hypoxia and mass fishkill events in Tapi Estuary, India. *Estuar. Coast Shelf Sci* 148:48–58
- Ramseur JL (2017) Oil spills: background and governance. Congressional Research Service
- Ranjani M, Veerasingam S, Venkatachalapathy R et al (2021) Assessment of potential ecological risk of microplastics in the coastal sediments of India: a meta-analysis. *Mar Pollut Bull* 163:111969
- Rao KL (1979) India's water wealth. Orient Blackswan
- Reineccius J, Appelt J-S, Hinrichs T et al (2020) Abundance and characteristics of microfibers detected in sediment trap material from the deep subtropical North Atlantic Ocean. *Sci Tot Environ* 738:140354. <https://doi.org/10.1016/j.scitotenv.2020.140354>

- Reusch TBH, Dierking J, Andersson HC et al (2018) The Baltic Sea as a time machine for the future coastal ocean. *Sci Adv* 4(5):eaar8195
- Ridgway J, Shimmield G (2002) Estuaries as repositories of historical contamination and their impact on shelf seas. *Estuar Coast Shelf Sci* 55(6):903–928
- Rodríguez-Figueroa GM, Shumilin E, Sánchez-Rodríguez I (2009) Heavy metal pollution monitoring using the brown seaweed *Padina durvillaei* in the coastal zone of the Santa Rosalía mining region, Baja California Peninsula, Mexico. *J Appl Phycol* 21(1):19–26
- Rui Z, Li Z, Fan Z et al (2013) Heavy metal pollution and assessment in the tidal flat sediments of Haizhou Bay, China. *Mar Pollut Bull* 74(1):403–412
- Ryan PG (1987) The origin and fate of artefacts stranded on islands in the African sector of the Southern Ocean. *Environ Conserv* 14(4):341–346
- Saher NU, Siddiqui AS (2016) Comparison of heavy metal contamination during the last decade along the coastal sediment of Pakistan: multiple pollution indices approach. *Mar Pollut Bull* 105(1):403–410
- Sam K, Coulon F, Prpich G (2016) Working towards an integrated land contamination management framework for Nigeria. *Sci Total Environ* 571:916–925
- Santos IR, Chen X, Lecher AL et al (2021) Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. *Nat Rev Earth Environ Environment* 2(5):307–323
- Saravi HN, Pourang N, Foong SY et al (2019) Eutrophication and trophic status using different indices: a study in the Iranian coastal waters of the Caspian Sea. *Iranian J Fish Sci* 18(3):531–546
- Sathish N, Jeyasanta KI, Patterson J (2019) Abundance, characteristics and surface degradation features of microplastics in beach sediments of five coastal areas in Tamil Nadu, India. *Mar Pollut Bull* 142:112–118
- Senarat S, Jiraungkoorskul W, Kettratad J (2017) Ovarian histology and reproductive health of short mackerel, *Rastrelliger brachysoma* (Bleeker, 1851), as threatened marine fish in Thailand. *Songklanakarinn J Sci Technol* 39(2):225–235
- Singh N, Mondal A, Bagri A et al (2021) Characteristics and spatial distribution of microplastics in the lower Ganga River water and sediment. *Mar Pollut Bull* 163:111960
- Singh S, Aalbersberg WGL, Morrison RJ (2009) Nutrient pollution in Laucala Bay, Fiji Islands. *Water Air Soil Poll* 204(1–4):363–372
- Sivasankar R, Ezhilarasan P, Sathish Kumar P et al (2018) Loriccate ciliates as an indicator of eutrophication status in the estuarine and coastal waters. *Mar Pollut Bull* 129:207–211
- Sotto LPA, Jacinto GS, Villanoy CL (2014) Spatiotemporal variability of hypoxia and eutrophication in Manila Bay, Philippines during the northeast and southwest monsoons. *Mar Pollut Bull* 85(2):446–454
- Steffen W, Richardson K, Rockstrom J et al (2015) Planetary boundaries: guiding human development on a changing planet. *Science* 347(6223):11
- Su J, Dai MH, He BY et al (2017) Tracing the origin of the oxygen-consuming organic matter in the hypoxic zone in a large eutrophic estuary: the lower reach of the Pearl River Estuary, China. *Biogeosciences* 14:4085–4099
- Suneel V, Ciappa A, Vethamony P (2016) Backtrack modeling to locate the origin of tar balls depositing along the west coast of India. *Sci Total Environ* 569:31–39
- Suneel V, Rao VT, Suresh G et al (2019) Oil pollution in the Eastern Arabian Sea from invisible sources: a multi-technique approach. *Mar Pollut Bull* 146:683–695
- Syakti AD, Idris F, Koenawan CJ et al (2019) Biological pollution potential in the water of Bintan-Riau Islands Province, Indonesia: first appearance of harmful algal bloom species. *Egypt J Aquat Res* 45:117–122
- Talsness CE, Andrade A, Kuriyama SN et al (2009) Components of plastic: experimental studies in animals and relevance for human health. *Philos Trans R Soc* 364:2079–2096
- Tang S, Shang Z (2005) Investigating environmental radioactivity in the coastal zone of China. *Nucl Saf* 2:25–34
- Tian R (2020) Factors controlling hypoxia occurrence in estuaries, Chester River, Chesapeake Bay. *Water* 12(7):1961

- Toxics link (2014) Plastics and the environment assessing the impact of the complete ban on plastic carry bag. Central Pollution Control Board (CPCB New Delhi India)
- Tubbs CW, McDonough CE (2017) Reproductive impacts of endocrine-disrupting chemicals on wildlife species: implications for conservation of endangered species. *Annu Rev Anim Biosci* 6:287–304
- United Nations Environment Programme (UNEP) (2018) Single-Use Plastics: a roadmap for sustainability. Nairobi
- UN Data (2020) Thailand, UN Data: A world of information, accessed 10 Jan 2021, <http://data.un.org/en/iso/th.html>
- Valdes J, Vargas G, Sifeddine A et al (2005) Distribution and enrichment evaluation of heavy metals in Mejillones Bay (23 degrees S), Northern Chile: geochemical and statistical approach. *Mar Pollut Bull* 50(12):1558–1568
- Vareda JP, Valente AJM, Durães L (2019) Assessment of heavy metal pollution from anthropogenic activities and remediation strategies: a review. *J Environ Manage* 246:101–118
- Veerasingam S, Saha M, Suneel V et al (2017) Microplastic pollution: a serious threat to the marine ecosystem. *Blue Waters: Newsletter on Marine Environment Protection* 18:6–9
- Wallace RB, Baumann H, Grear JS et al (2014) Coastal ocean acidification: the other eutrophication problem. *Estuar Coast Shelf Sci* 148:1–13
- Wang G (2022) Why coastal zones become eutrophic. *Front Sci* 15(4):62–66
- Wang SL, Xu XR, Sun YX et al (2013) Heavy metal pollution in coastal areas of South China: a review. *Mar Pollut Bull* 76:7–15
- Wang Y, Liu D, Xiao W et al (2021) Coastal eutrophication in China: trend, sources, and ecological effects. *Harmful Algae* 107:102058
- Wattayakorn G (2006) Environmental issues in the Gulf of Thailand. In: Wolanski E (ed) *The environmental in Asia Pacific harbours*. Springer, pp 249–259
- Wijaya AR, Ouchi AK, Tanaka K et al (2013) Evaluation of heavy metal contents and Pb isotopic compositions in the Chao Phraya River sediments: implication for anthropogenic inputs from urbanized areas, Bangkok. *J Geochem Explor* 126–127:45–54
- Winther JG, Dai M, Douvrou F et al (2020) Integrated ocean management. World Resources Institute, Washington, DC. Available online at www.oceanpanel.org/blue-papers/integrated-ocean-management
- Wisha UJ, Ondara K, Ilham (2018) The influence of nutrient (N and P) enrichment and ratios on phytoplankton abundance in Keunekai Waters, Weh Island, Indonesia. *Makara J Sci* 22:187–197
- Wong J, Lee K, Tang K et al (2020) Microplastics in the freshwater and terrestrial environments: prevalence, fates, impacts and sustainable solutions. *Sci Total Environ* 719:137512
- World Bank (2020) Thailand Population. <https://datacommons.org/place/country/THA>. Accessed 27 Dec 2020
- Wright SL, Thompson RC, Galloway TS (2013) The physical impacts of microplastics on marine organisms: a review. *Environ Pollut* 178:483–492
- Wu JW, Zhou KB, Dai MH (2012) Impacts of the Fukushima nuclear accident on the China Seas: evaluation based on anthropogenic radionuclide ^{137}Cs . *Chin Sci Bull* 58(4–5):552–558
- Xiong S, Long H, Tang G et al (2015) The management in response to marine oil spill from ships in China: a systematic review. *Mar Pollut Bull* 96(1–2):7–17
- Yamada M, Zheng J, Wang ZL (2006) Cs-137, Pu239+240 and Pu-240/Pu-239 atom ratios in the surface waters of the western North Pacific Ocean, eastern Indian Ocean and their adjacent seas. *Sci Total Environ* 366(1):242–252
- Yan T, Zhou M, Zou J (2002) A national report on harmful algal blooms in China. *Harmful Algal Blooms in the PICES Region of the North Pacific*, vol. 21. F.J.R. “Max” Taylor and Vera L. Trainer, (eds.) PICES Scientific Report, No. 23. Sidney, British Columbia, Canada: North Pacific Marine Science Organization (PICES)
- Yang X, Li S, Wei P et al (2015) Radionuclide pollution in the environment and its harmfulness. *Front Sci* 1(9):4–15

- Ye ZP, Chen JY, Gao L et al (2020) Pb-210 dating to investigate the historical variations and identification of different sources of heavy metal pollution in sediments of the Pearl River Estuary, Southern China. *Mar Pollut Bull* 150:110670
- Yin K, Lin Z, Ke Z (2004) Temporal and spatial distribution of dissolved oxygen in the Pearl River Estuary and adjacent coastal waters. *Cont Shelf Res* 24(16):1935–1948
- Yin K, Harrison PJ (2008) Nitrogen over enrichment in subtropical Pearl River estuarine coastal waters: possible causes and consequences. *Cont Shelf Res* 28(12):1435–1442
- Yoshikawa T, Tomizawa K, Okamoto Y et al (2017) Nutrients, light and phytoplankton production in the shallow, tropical coastal waters of Bandon Bay, Southern Thailand. *Mar Ecol* 38(6):e12475
- Yu CQ, Huang X, Chen H et al (2019) Managing nitrogen to restore water quality in China. *Nature* 567:516–520
- Zettler ER, Mincer TJ, Amaral-Zettler LA (2013) Life in the “Plastisphere”: microbial communities on plastic marine debris. *Environ Sci Technol* 47(13):7137–7146
- Zhang B, Tian H, Lu C et al (2017) Global manure nitrogen production and application in cropland during 1860–2014: A 5 arcmin gridded global dataset for Earth system modeling. *Earth Syst Sci Data* 9:667–678
- Zhao Y, Liu J, Uthaiapan K et al (2020) Dynamics of inorganic carbon and pH in a large subtropical continental shelf system: interaction between eutrophication, hypoxia, and ocean acidification. *Limnol Oceanogr* 65(6):1359–1379
- Zhao Y, Uthaiapan K, Lu Z et al (2021) Destruction and reinstatement of coastal hypoxia in the South China Sea off the Pearl River estuary. *Biogeosciences* 18:2755–2775
- Zhuang W, Gao X (2014) Integrated assessment of heavy metal pollution in the surface sediments of the Laizhou Bay and the coastal waters of the Zhangzi Island, China: comparison among typical marine sediment quality indices. *PLoS ONE* 9(4):e94145