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Review

Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis

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Abstract

The history of aquatic environmental pollution goes back to the very beginning of the history of human civilization. However, aquatic pollution did not receive much attention until a threshold level was reached with adverse consequences on the ecosystems and organisms. Aquatic pollution has become a global concern, but even so, most developing nations are still producing huge pollution loads and the trends are expected to increase. Knowledge of the pollution sources and impacts on ecosystems is important not only for a better understanding on the ecosystem responses to pollutants but also to formulate prevention measures. Many of the sources of aquatic pollutions are generally well known and huge effort has been devoted to the issue. However, new concepts and ideas on environmental pollution are emerging (e.g., biological pollution) with a corresponding need for an update of the knowledge. The present paper attempts to provide an easy-to-follow depiction on the various forms of aquatic pollutions and their impacts on the ecosystem and organisms.

1. Introduction

The United Nations Convention on the Law of the Sea defined pollution as ‘the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of the sea water and reduction of amenities’. Williams (1996) criticized the division of pollution into categories (e.g., air, water, land etc.) and commented that there is only ‘one pollution’ because every pollutant, whether in the air, or on land tends to end up in the ocean. Production and emissions of pollutants are usually derived from human settlements, resource uses and interventions, such as infrastructural development and construction, agricultural activities, industrial developments, urbanization, tourism etc. Contaminants of major concerns include persistent organic pollutants, nutrients, oils, radionuclides, heavy metals, pathogens, sediments, litters and debris etc. (Williams, 1996). Categorization of pollution only facilitates discussion; most contaminants are interrelated and jeopardize the environment and organisms, at a same way and scale, regardless of the source of contamination.

Most of the coastal areas of the world have been reported to be damaged from pollution, significantly affecting commercial coastal and marine fisheries. Therefore, control of aquatic pollution has been identified as an immediate need for sustained management and conservation of the existing fisheries and aquatic resources. Unfortunately, the pollution problem, as described by Williams (1996), is characterized by interconnectedness, complicated interactions, uncertainty, conflicts and constraints, making it difficult to control the problem. Moreover, because scientific knowledge on marine pollution is patchy, knowledge gaps have been identified as one of the major problems in introducing effective management strategies for its control. The present paper focuses on three objectives: (1) to provide

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a review on the major areas of coastal and marine pollution with respect to their impacts on the ecosystem and living resources in general; (2) to synthesize information on the present status of the coastal and marine fisheries affected by pollution; and (3) to synthesize a conceptual model for better management of pollution for sustainable utilization of these resources.

2. Major pollutants and potential impacts

2.1. Fertilizers, pesticides and agrochemicals

Agricultural activities are reported to contribute about 50% of the total pollution source of surface water by means of the higher nutrient enrichment, mainly ammonium ion (NH_4) and NO_3 derived from agricultural inputs. Ammonia constitutes a major contributor to the acidification of the environment, especially in areas with considerable intensive livestock farming. Wastes, manures and sludges, through biological concentration processes, can supply soils with 100 times more hazardous products than do fertilizers for the equivalent plant nutrient content (Joly, 1993). The huge increases in fertilizer use worldwide over the past several decades are well documented. Manure produced by cattle, pigs and poultry are used as organic fertilizer worldwide. To this is added human excreta, especially in some Asian countries where animal and human excreta are traditionally used in fish culture as well as on soils.

In areas where intensive monoculture is practiced, pesticides are used as a standard method for pest control. Although the list of pesticides in use (Table 1) is big enough, the largest usage tends to be associated with a small number of pesticide products. The underlying fact of the pesticides usage in relation to pollution is that only a very small fraction of all applied pesticides becomes directly involved in pesticide mechanisms, i.e., unless the compounds are rapidly degradable, most of the pesticides find their way as residues in the environment (Duursma and Marchand, 1974). In fact, most of the pesticides are not rapidly degradable because of technical reasons, i.e., rapid degradation might reduce their applicability. Therefore, it is likely that a large volume of pesticide residues accumulate into the environment and the process is continuous. Duursma and Marchand (1974) reported an estimated world production of DDT about 2.8×10^6 tons of which 25% (7×10^5 tons) is assumed to be released into the world ocean. Significant contributions to aquatic pollution from agricultural sources are made by a few Asian countries with higher agricultural crop productions. It has been reported that about 9000 metric tons of different pesticides and more than 2 million metric tons of fertilizers are used annually in Bangladesh and at present about 1800 tons year^{-1} of pesticide residues are added to the coastal waters through runoff. Similar figures can be expected from India, Myanmar, Indonesia and China.

Pesticides and their residues are reported to be among the most devastating agents for aquatic ecosystems and organisms affecting all levels of the food chain from the lowest to the top level (Duursma and Marchand, 1974). The two principal mechanisms associated with the effects of agricultural wastes are bioconcentration (accumulation of chemical from the surrounding medium into an organism by virtue of the lipophilicity of many chemicals) and biomagnification (increasing concentration of a chemical as food energy is transformed within the food chain). As smaller organisms are eaten by larger organisms, the concentration of pesticides and other chemicals are increasingly magnified in tissue and other organs. Very high concentrations can be observed in top predators, including man. The occurrence of pesticide residues in different organisms of the food chain starts with the first link of marine phytoplankton in which relatively high levels of DDT and analogues can occur.

The ecological effects of pesticides are varied and are often complex. Effects at the organism or ecological level are usually considered to be an early warning indicator of potential human health impacts. The important point is that many of these effects are chronic, are often not noticed by casual observers, yet have consequences for the entire food chain. Major effects include death of the organism, cancers, tumors and lesions on fish and animals, reproductive inhibition or failure, suppression of immune system, disruption of endocrine system, cellular and molecular damage, teratogenic effects, poor fish health marked by low red to white blood cell ratio, excessive slime on fish scales and gills, etc., intergenerational effects, other physiological effects such as egg shell thinning. These effects are not necessarily caused solely by exposure to pesticides or other organic contaminants, but may be associated with a combination of environmental stresses such as eutrophication and pathogens.

The European Environment Agency (EEG, 1994) reported links with the toxicity of river water caused by runoff of agricultural pesticides to the Zooplankton *Daphnia magna*. In the Great Lakes of North America bioaccumulation and magnification of chlorinated caused the disappearance of top predators such as eagle and mink and deformities in several species of aquatic birds. The World Wide Fund for Nature (WWF, 1993) reported that a significant amount of an estimated 190,000 tons of agricultural pesticides plus additional loadings of non-agricultural pesticides that are released by riparian countries bordering the North Sea, eventually are transported into the North Sea by a combination of riverine, groundwater, and atmospheric processes. WWF further reported that the increased rate of disease, deformities and tumors in commercial fish species in highly polluted areas of the North Sea and

Table 1
Pesticides and agrochemicals that are in use worldwide and are of major environmental concerns

Pesticide	Trade name	Type
Acifluorfen	Blazer, Carbofluorfen	Herbicide
Alachlor	Lasso	Herbicide
Aldicarb	Temik	Insecticide
Aldrin	HHDN, Octalene	Insecticide
Ametryn	Gesapax	Herbicide
Atraton	Gesatamin	Herbicide
Atrazine	AAtrex	Herbicide
Barban	Carbyne	Herbicide
Baygon	Propoxur, Unden, Blattanex	Insecticide
Bentazon	Basagran	Herbicide
Bromacil	Borea, Hyvar, Uragan	Herbicide
Butachlor	Machete	Herbicide
Butylate	Sutan	Herbicide
Carbaryl	Sevin	Insecticide
Carbofuran	Furadan, Caraterr	Insecticide
Carboxin	D-735, DCMO, Vitavax	Fungicide
Chloramben	Amiben, Vegiben	Herbicide
Chlordane	Gold Crest C-100	Insecticide
Chlorobenzilate	Akar, Benzilian	Acaricide
Chloroneb	Terraneb	Fungicide
Chlorothalonil	Bravo, Daconil	Fungicide
Chlorpropham	Chloro IPC, CIPC, Furloe, Sprout NP	Herbicide
Cyanazine	Bladex, Fortrol	Herbicide
Cycloate	Ro-Neet	Herbicide
2,4 Dichloro-phenoxyacetic acid	Aqua Kleen	Herbicide
Dalapon	Dowpon, Ded-Weed	Herbicide
2,4-DB	Butyrac, Embutox	Herbicide
DCPA	Chlorthal-dimethyl Dachtal	Herbicide
4,4-DDD and DDT	TDE, Rothane	Insecticide
Diazinon	Spectracide, Basudin, AG-500	Insecticide
3,5-Dichlorobenzoic acid	Dalapon	Herbicide
1,2-Dichloropropane	Propylene, Dichloride, 1,2-DCP	Soil fumigant
cis-1,3 Dichloropropene	Telone II	Nematocide
Dichlorprop	Maizeox RK	Herbicide
Dichlorvos	Herkol, Nogos, Phosvit	Insecticide
Dieldrin	Heod, Dielorex, Octalox	Insecticide
Dinoseb	DNBP, Dinitro, Premerge	Herbicide
Diphenamid	Dymid, Enide	Herbicide
Disulfoton	Dysyston, Dithiodemeton, Ditio-systox	Insecticide
Diuron	DCMU, Karmex	Herbicide
Endosulfan I	Thiodan, Cyclodan, Malix	Insecticide
Endrin	Nendrin	Insecticide
EPTC	EPTAM	Herbicide
Ethoprop	Prophos, Ethoprophos	Insecticide
Ethylene dibromide (EDB)	Bromofume, Nephis	Insecticide
Ethylene thiourea (ETU)	ETU	Fungicides
Etridiazole	Koban, Terrazole	Fungicide
Fenamiphos	Nemacur Inemacury	Insecticide
Fenarimol	Bloc, Rimidin, Rubigan	Fungicide
Fluometuron	Cotoron	Herbicide
Fluridone	Sonar	Herbicide
Glyphosate (4)	Roundup	Herbicide
Alpha-, beta-, delta-, and gamma-HCH (Lindane)	gamma BHC, Lindane	Insecticide
Heptachlor (2)	Velsicol 3-chlorochlorene	Insecticide
Hexachlorobenzene	Anti-Carie, HCB	Fungicide
Hexazinone	Velpar	Herbicide
Linuron	Afalon	Herbicide
Merphos	Folex	Defoliant
Methiocarb	Mesurol, Draza	Insecticide
Methomyl	Lannate, Nudrin	Insecticide
Methoxychlor	Malate	Insecticide
Methyl paraoxon	E-600, Mintacol	Insecticide

Table 1 (*continued*)

Pesticide	Trade name	Type
Metolachlor	Dual, Primext	Herbicide
Metribuzin	Sencor, Sencorex, Lexone	Herbicide
Mevinphos	Phosdrin	Insecticide
MDK 264	Van Dyke-264	Synergist
Molinate	Ordram	Herbicide
Napropamide	Devrinol	Herbicide
Neburon	Kloben	Herbicide
4-Nitrophenol	–	Fungicide/insecticides
Norflurazon	Zorial, Evital, Solicam	Herbicide
Oxamyl	Vydate, DPX-1410	Insecticide
Pentachlorophenol (PCP)	Dowicide	Insecticide/herbicide
Pebulate	Tillam	Herbicide
Permethrin	Ambush, Perthrine	Insecticide
Picloram	Tordon	Herbicide
Prometon	Gesagram	Herbicide
Prometryn	Gesagard, Caparol	Herbicide
Pronamide	Kerb	Herbicide
Propachlor	Bexton, Ramrod	Herbicide
Propanil	Rogue	Herbicide
Propazine	Gesomil, Milogard, Primatol	Herbicide
Propham	IPC, Beet-Kleen	Herbicide
Simazine	Princep, Aquazine, Gesatop, Weedex	Herbicide
Simetryn	Gy-bon	Herbicide
Stirofos	Gardona, Tetrachlorvinphos	Insecticide
Swep	SWEP	Herbicide
Tebuthiuron	Graslan, Spike	Herbicide
Terbacil	Sinbar	Herbicide
Terbufos	Counter	Insecticide
Terbutryn	Igram, Preban	Herbicide
2,4,5-TP (trichlorophenol)	Silvex	Herbicide
Triademefon	Bayleton	Fungicide
Tricyclazole	Beam, Bim, Blascide	Fungicide
Trifluralin	Treflan	Herbicide
Vernolate	Vernam	Herbicide

coastal waters of the United Kingdom since the 1970s is consistent with effects known to be caused by exposure to pesticides.

2.2. Domestic and municipal wastes and sewage sludge

By far the greatest volume of waste discharged to the marine environment is sewage. Sewage effluent contains industrial waste, municipal wastes, animal remains and slaughterhouse wastes, water and wastes from domestic baths, utensils and washing machines, kitchen wastes, faecal matter and many others. Huge loads of such wastes are generated daily from highly populated cities and are finally washed out by the drainage systems which generally open into nearby rivers or aquatic systems. The industrial areas are generally highly populated or the industries are usually established near highly populated areas. Therefore, higher pollution load from industrial sources is generally accompanied by a higher risk of domestic and sewage pollution. Robson and Neal (1997) studied the water quality in term of pollution from industrial and domestic sources and reported higher pollution loads from domestic sources where the industrial pollution loads are also higher. Cheevaporn and Menasveta (2003) reported BOD loads of 659–34,376 tons year^{-1}, resulting from municipal and industrial wastes in the Gulf of Thailand. It is reported that the annual production of sewage is as high as 1.8×10^8 m^3 for a population of 800,000. Taking the organic matter load to be 20 mg l^{-1} in the sewage (Duursma and Marchand, 1974), this gives an annual release of 3.6×10^3 tons of organic matter. The approximate amount of sewage produced by the total world population and the organic loads released from that sewage can now be easily calculated.

Sewage contains in itself a diverse array of polluting agents including pathogens (Table 2), organic substances, heavy metals and trace elements (Table 3) and so on, which pose direct and indirect effects on ecosystems and organisms. Sewage is primarily organic in nature and, therefore, subject to bacterial decay. As a result of this bacterial activity, the oxygen concentration in the water is reduced, thus sewage is said to have a high BOD. This can starve aquatic life of the oxygen it needs and also leads to the breakdown of proteins and other nitrogenous compounds, releasing hydrogen

Table 2
Major sewage-related bacterial species recorded from marine mammals (Grillo et al., 2001)

Bacteria species	Host species
Aeromonas hydrophila	Cetaceans
Vibrio cholerae	Cetaceans
Staphylococcus aureus	Cetaceans
Salmonella spp.	Cetaceans/pinnipeds
Pseudomonas aeringinosa	Cetaceans
Proteus mirabilis	Cetaceans
Mycobacterium tuberculosis	Pinnipeds
Leptospira spp.	Pinnipeds
Klebsiella spp.	Cetaceans/pinnipeds
Escherichia coli	Cetaceans/pinnipeds
Enterobacter spp.	Cetaceans
Clostridium spp.	Cetaceans
Citrobacter freundii	Cetaceans
Alcaligens spp.	Cetaceans

Table 3
Concentrations of major heavy metals and trace elements in sewage (Grillo et al., 2001)

Trace metals in sewage	Concentrations ($\mathrm{mg\,l^{-1}}$)
Arsenic	<0.1
Cadmium	<0.02
Chromium	0.1–0.5
Copper	0.2–0.5
Lead	0.08–0.4
Mercury	–
Nickel	<0.02
Silver	<0.02
Zinc	0.4–0.7

sulphide and ammonia, both of which are potentially toxic to marine organisms in low concentrations. Solids suspended in sewage may also blanket river and sea beds preventing respiration of the benthic flora and fauna. Decaying organic matter and nutrients in sewage enhance plant growth. Excessive plant growth and oxygen depletion can lead to alterations in ecosystem structure and these are both features of eutrophication. The dumping of sewage sludge at sea is another cause of ecological damage. Dependent on hydrography, sludge can smother the benthos, increase biomass, decrease species biodiversity and increase heavy metal concentrations.

Sewage effluent entering coastal waters contains a variety of harmful substances including viral, bacterial and protozoan pathogens, toxic chemicals such as organochlorines, organotins and heavy metals, and a variety of other organic and inorganic wastes (HMSO, 1990). Domestic sewage discharged into the coastal waters contains a particularly unhealthy mix of both harmless and infectious microorganisms. Pathogens found in sewage include *Salmonella* spp., *Escherichia coli, Streptococcus* sp., *Staphylococcus aureus, Pseudomonas aeruginosa*, the fungi *Candida*, and viruses such as enterovirus, hepatitis, poliomyelitis, influenza and herpes. Bacteria and viruses are present in large concentrations in raw sewage: up to 4×10^9 bacteria 1–1000×10^4 virus per liter of raw sewage (HMSO, 1990). Numerous studies have indicated that the greater the sewage contamination and exposure of people, the higher the risk of contracting ear, nose and throat infections and stomach upsets such as gastroenteritis. Faecal streptococci bacteria are more closely associated with human sewage and their presence in a sample is believed to be a better indicator of sewage contamination than Coliforms. Faecal streptococci can cause illness, especially gastroenteritis. Other disease-causing agents which may be present in sewage include enteric viruses, *Salmonella* and the Hepatitis A virus.

Bossart et al. (1990) suggested that some viruses are transferred to marine mammals by human sewage and are zoonotic in nature. Influenza, respiratory synctial virus, herpes, cytomegalovirus and measles are also zoonotic viruses capable of infecting marine mammals. Bacteria associated with sewage water contaminated with human pathogens (Olivieri, 1982), which have been documented in marine mammals, include: *Escherichia coli*, *Mycobacterium tuberculosis*, *Vibrio cholera* and *Salmonella* sp. (Table 2). Sewage-borne fungi could also, theoretically, infect marine mammals living in contaminated waters. *Candida* sp. is a common component of sewage wastes and has been isolated from both captive and wild cetaceans.

A common short-term response by fish to a sewage outfall is an initial increase in abundance around the point of discharge. There is a short-term increase in nutrients and, hence, prey items for the fish and, on occasions an increase in habitat complexity, which may cause an initial population rise in fish species. Yet, as nutrient levels increase so does the chance of algal bloom development, toxin production and a corresponding decrease in dissolved oxygen. Long-term effects include phytoplankton biomass increases and large scale decreases in species diversity with benthic and fish communities (Bonsdorff et al., 1997). Fish species feeding in water contaminated by algal toxins will absorb these toxins and are subject to mass mortality (Hernandez et al., 1998). One of the most crucial problems caused by the sewage wastes is the loss of amenity which, therefore, affects the recreational use of water. Debris associated with sewage probably has the highest monetary cost associated with its presence on beaches and loss of tourism.

2.3. Oils

Oil pollution has been receiving increasing attention since the middle of the 19th century with the increase in tanker operations and oil use and frequent marine tanker collisions and accidents resulting in oil spills. Millions of oils are being added into the coastal and marine

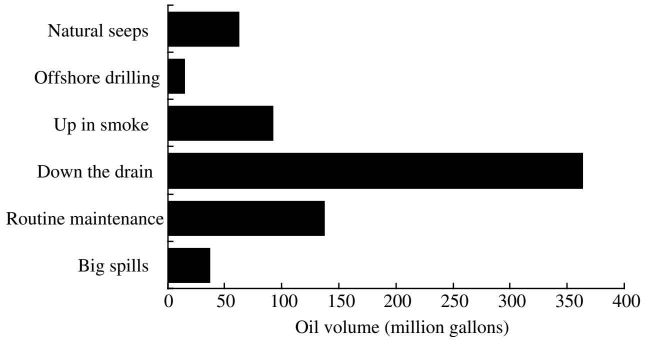

Fig. 1. Millions of gallons of oil put into the coastal and marine environment worldwide each year from different sources.

environments from variety of sources (Fig 1). Considerable tanker accidents were reported during the 1960s of which as many as 78 accidents were reported between 1964 and 1968 resulting in huge volume of oil spilled into the marine environment (Smith, 1970) in addition to the ballast water which is reported to amount 0.3–0.5% of the previous oil loads—about 200 tons in a 50,000-ton tanker (Smith, 1970). Smith (1970) reported that as many as half a million tons of persistent oils are discharged into the sea each year. Reed (1972) suggested a similar figure, and reported that the annual release of hydrocarbon is estimated to be 600,000–1,000,000 tons. Under still conditions, the oil traps silts and other suspended matters and sinks to the bottom where it is deposited. Coastal refineries are another obvious risk of continuous oil pollution because millions of gallons of crude oil and its fractions are processed and stored there. Crude oil is purified and processed in refineries to produce a variety of fuels, lubricants and solvents. During these operations, continuous small-scale pollution occurs through leakages, spills, breakages etc. Water is used in many processes and inevitably become contaminated with oil and derivatives and when discharged, carries appreciable oil loads.

Nelson (2000) described the sources and extent of oil pollution in Australian coasts (Fig. 2A) and reported that in addition to the spills resulting from tanker operations, an estimated volume of 16,000 tons of oil enters the marine environment as run-off and waste from land-based municipal and industrial sources each year. A similar scenario was reported also from the Baltic Sea (Fig. 2B). Continuous discharge and spills of oils pose potential risk of severe pollution in recently increasing but unregulated marine traffic in developing countries. Owing to a lack of waste-reception and treatment facilities in the ports, and a lack of effective legislation and surveillance, foreign and domestic ships and trawlers discharge their oily waste in the sea.

Although Shriadah (1998) reported that temporary elevation of contamination levels due to oil pollution was followed by a rapid reduction of contamination level and recovery of the ecosystem along the Gulf of Oman, Yamamoto et al. (2003) concluded that the recovery rate depends largely on the pollution sites and intensity. There are enough evidences that oil pollution poses serious adverse effects on aquatic ecosystem and the organisms extending from primary producers level through secondary, tertiary and up to the top levels. The sensitivity of echinoderms and molluscs can be understood from the use of oil slurries to form a barrier around oyster beds to protect them from predatory molluscs and sea-stars. Smith (1970) reported mortality and elimination of sea-stars (*Pisaster* spp.) and sea-urchins (*Strongylocentrotus* spp.) as a result of diesel oil pollution and reported that as little as 0.1% emulsion of the oil may inactivate the tube-feet of the urchins.

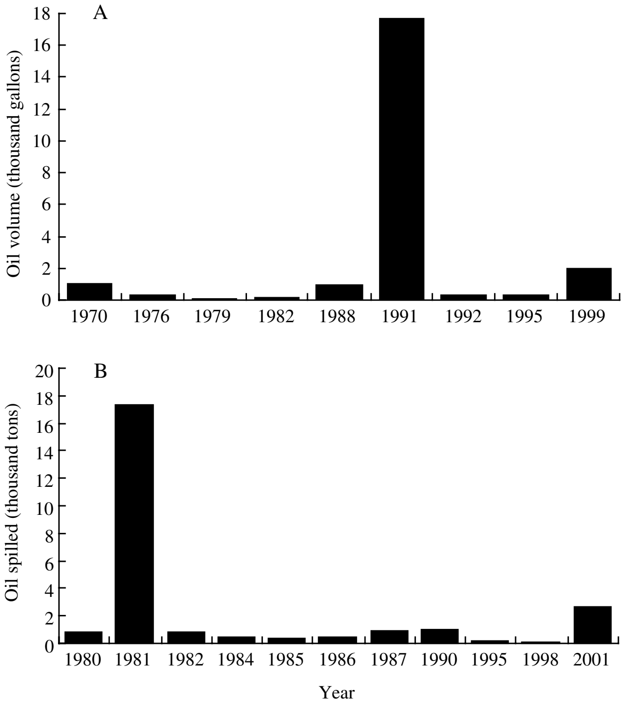

Fig. 2. Time series data of oil volumes released from spills in Australia (only those resulted >100 tons oil lost) (Nelson, 2000); and C: oil pollution and volume of oil spilled in the Baltic Sea.

Phenol occurring in oil refinery effluents irritates the gills and causes heavy secretion and erosion of the mucus membrane, and also affects the central nervous and endocrine systems. Russel and Kotin (1956) reported carcinomas and papillomas on the lips of bottom-feeding fish caught near an oil refinery and changes in the cell membrane caused by hydrocarbons which could lead to cellular changes and thus to cancer. Among marine mammals, damage to seals has been reported form the Antarctic and Cornwall (Smith, 1970) and during the Santa Barbara Channel spillage in California (California Department of Fish and Game, 1969). Oil damage in seals is frequently said to include severe eye irritation with subsequent blindness.

The aerial and flying birds, e.g., gulls, gannets and their relatives are at relatively lower risk of oil toxicity than those spending most of the time in contact with oil on the water surface, e.g., ducks, auks, divers, penguins etc. The primary effect of oil on sea birds is to penetrate to their plumage; water eventually replaces the air trapping with a resultant elimination of heat insulation and reducing buoyancy and a heavily oiled bird is physically over-weighed and becomes incapable of swimming and flying. Nervous abnormalities also occur which suggest inhibition of anti-cholinesterase activity, probably due to organic phosphate additives in diesel and cutting oils (Smith, 1970). The bird become sensitive and incapable of tolerating environmental fluctuations and little fluctuation induce physiological stress. The population level effects of oil toxicity on aquatic birds occur through the loss of egg viability.

2.4. Heavy metals and trace elements

Heavy metals and trace elements are by-products of many industrial processes, contributing varying amounts of different metals and trace elements (Fig. 3) and as such are discharged as waste into the marine environment (Robson and Neal, 1997). They enter the marine environment through atmospheric and land-based effluent sources. The metals considered toxic and which are of concern have been restricted largely, but not exclusively, to the ten which appear to be most poisonous to marine life. These include, in order of decreasing toxicity (Davies, 1978): mercury, cadmium, silver, nickel, selenium, lead, copper, chromium, arsenic and zinc. Goldberg (1995) reviewed different sources of heavy metal inputs into the sea and their possible role in ecosystems. Heavy metals are non-degradable elements naturally occurring in coastal seas. They are not particularly toxic as the condensed free elements but they are dangerous to living organisms in the form of cations with capacity to bind with short carbon chains. In this form, they bioaccumulate in marine organisms and concentrate year after year.

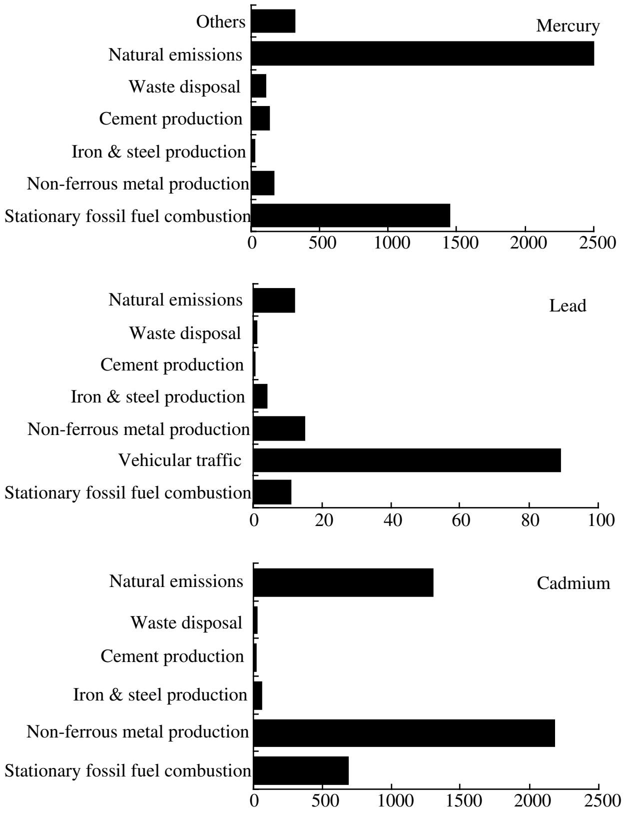

Fig. 3. Contribution of different sources in global emissions of major heavy metals (AMAP, 2002); mercury: tons/year^{-1}; lead and cadmium: thousand tons/year^{-1}.

The effects of metals on organisms is associated with interference in the metabolic processes involving sulphur containing constituents (Davies, 1978) because most of the widely distributed heavy metals (e.g., mercury, silver, copper) have high affinities for sulphur and tend to bind with sulphydryl groups of proteins and enzymes in living beings. Heavy metals interference are reported to cause an increase in the permeability of the cell membrane in phytoplankton and other marine algae, leading to the loss of intracellular constituents and, therefore, cellular integrity. Kayser (1976) reported change in cell shape of phytoplankton as a result of heavy metal incorporations and such changes in shape are much likely to be related to the loss of cellular integrity. Similarly, Davies (1978) reported production of very large cells of phytoplankton as an effect of copper and mercury and found that the size spectrum of cells was related to the mercury concentrations. They concluded that metals inhibit independent cell division in phytoplankton and, therefore, they grow big in size.

Once in the system, metals concentrate in protein-rich tissues such as liver and muscle. High trace element burdens in marine mammals have been associated with a variety of responses. These include lymphocytic infiltration, lesions and fatty degeneration in bottlenose dolphins, and decreasing nutritional state and lung pathology (Siebert et al., 1999). In addition, cadmium, lead and mercury are potential immuno-suppressants; of particular concern is the build-up of mercury, which marine mammals tend to accumulate in the liver to higher levels than other marine organisms (Law et al., 1999) and concentrations exceeding 100–400 $\mu g\,l^{-1}$ wet weight in the liver are a threat to marine mammals. Due to its long persistence and high mobility in the marine ecosystem, mercury shows an age-related accumulation and strong bio-magnification in the food web (Nigro and Leonzio, 1996). Correlations have also been reported between age and cadmium levels in the kidneys of harbor porpoises from the east coast of Scotland (Falconer et al., 1983).

2.5. Organic compounds

Many synthetic organic chemicals (e.g. organochlorines, organophosphates, PAHs and organometals) are of growing environmental concern, because of their high toxicity and high persistence in the environment and in biological systems. Furthermore, the high lipophilicity of many of these xenobiotics greatly enhances their bioconcentration/biomagnification, thereby posing potential health hazards on predators at higher trophic levels (including human beings). Nowadays, persistent xenobiotic compounds have been found in every part of the ocean: from arctic to Antarctic, and from intertidal to abyssal. For example, PCBs, HCH and DDT (and its derivatives) were found in rat-tail fish collected at 3000 m depth in the Atlantic and arctic seals long after the ban of DDT and PCBs in the early 1970s, indicating the persistence of these chemicals in the marine environment (GESAMP, 1990). Longwell et al. (1992) reported as high as 70 organic contaminants in fully ripe spawned eggs of winter flounder *Pseudopleuronected americanus*. Such contaminations result not only in egg mortality and defective embryos but also defects in other periods of fish ontogeny resulting high rate of larval mortality, lowering significantly the recruitment. This is particularly destructive for those populations that have been affected otherwise such as by overfishing.

Most xenobiotic compounds occur only at very low concentrations in the environment, and their threats to marine life and public health are still not well understood. However, sub-lethal effects of these compounds over long-term exposure may cause significant damage to marine populations, particularly considering that some of these compounds may impair reproduction functions of animals while others may be carcinogenic, mutagenic or teratogenic. Many of the environmental oestrogen compounds act as anti-oestrogens by interfering in the activity of the oestrogen receptors or by reducing the number of receptors in the organisms. One of the most serious of the chemicals is the DDT and its derivatives. Some of the effects of such chemicals have been listed among other by Goldberg (1995). These generally include the effects of DDT on the reproductive success of fish eating birds, tributyltin cause sexual changes (imposex) in gastropods and eventually damage of the population. Stone (1994) reported a 90% fall-off in the birthrate of alligators and reduced penis size in many of the young alligators exposed to high level of DDT introduced by an accident spill. The total amount of dissolved organic matter in the world ocean is about 2×10^{12} tons, calculated from the volume of the world ocean of 1.369×10^9 km^3 multiplied by the average concentration of dissolved organic matter of 1.5 mg l^{-1} (Duursma and Marchand, 1974).

Accumulation of complex organics in different steps of a food chain is well documented from all forms of aquatic ecosystems. Some examples of PCBs and HCHs accumulation in calanoid copepod in different islands and bays and in different species of fishes are given in Figs. 4 and 5. The major ecological concern of xenobiotics is their ability to impair reproductive functions and subsequently threaten survival of the species. For example, white croaker inhabiting contaminated areas near Los Angles have higher body burdens of chlorinated hydrocarbons, lower fecundity and lower fertilization rates (Cross and Hose, 1988). Likewise, endocrine dysfunction and reduced gonad size were reported for the yellow perch (*Perca flavescens*) exposed to sediments in the St. Lawrence River contaminated with PAHs and PCBs (Hontela et al., 1995). Reproductive failure and population decline of the common seal (*Phoca vitulina*) in the Wadden Sea were attributable to their PCB body burden (Reijnders, 1986a,b). High body burden of organochlorines found in seals and sea birds in the Baltics has been related to reduced egg hatching (HELCOM, 1996).

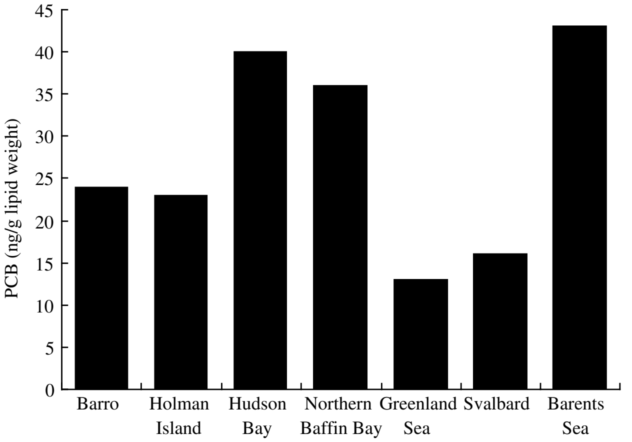

Fig. 4. Concentrations of PCBs (ng g^{-1} of lipid) in calanoid copepod in different bays and seas in the Arctic (AMAP, 2002).

There is growing evidence that exposure to very low levels of certain xenobiotic organic compounds (e.g. halogenated hydrocarbons, PCBs, DDT, TBT) may disrupt normal metabolism of sex hormones (including gonadotropins) in fish, birds and mammals. This in turn, may lead to reproductive dysfunction such as reduction in fertility, hatch rate, alternation of sex behavior and viability of offspring (Crews et al., 1995). Perhaps one of the most well-studied endocrine disrupters is organotin. Exposure to very low levels of TBT (0.5–3 ng l^{-1}) or a body burden of only 10–20 ng TBT/g wet tissue has been shown to cause a significant disruption in sex hormone metabolism/testosterone level, which subsequently leads to malformation of oviducts and suppression of oogenesis in female whelks, e.g. *Nucella lapillus*, *Thais claviger* and *T. bronni* (Gibbs, 1996). Secondary male characteristics, such as induction of spermatogenesis and development of a male penis

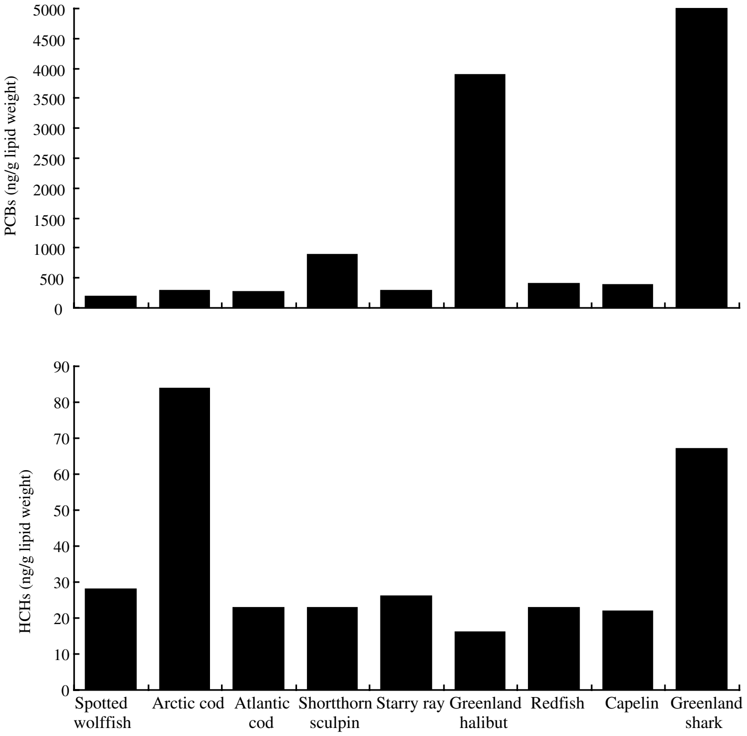

Fig. 5. Concentrations of PCBs and HCHs (ng g^{-1} of lipid in different fish species (AMAP, 2002).

and/or vas deferens, begins to develop in the females. This phenomenon, known as imposex, has been reported in some 50 species of gastropods all over the world in areas with high marine activities or where TBT has been used. The frequency of imposex in field populations shows a clear relation to environmental TBT levels, and sex imbalance causes a decline and species extinction in some natural populations (Cadee et al., 1995).

Increasing evidence from laboratory and field studies has shown that trace amounts of many chlorinated hydrocarbons (e.g. PCBs), organophosphates and diethylstilbestrol in the environment may cause significant endocrine disruption and reproductive failure in invertebrates, fish, birds, reptiles and mammals. Chronic exposure to low levels of diethylstilbestrol or pentachlorophenol alters steroid hormone metabolism of the water flea *Daphnia magna* and reduces their fecundity in the second generation (Parks and LeBlanc, 1996). Exposure to very low levels of certain organophosphate pesticides (e.g. elsan, carbaryl) has been shown to inhibit gonadotropin releasing hormones and reduce gonad development in the fish *Channa punctatus* (Bhattacharya, 1993). Likewise, the pesticide kepone has been shown to arrest sperm maturation in many fish, birds and mammals (Srivastava and Srivastava, 1994). Endocrine disruption found for the above freshwater species may well be applicable to marine species. A recent mesocosm study showed a significant elevation of testosterone and 17-*b*-oestradiol in the flounder *Platichthys flesus* exposed to polluted dredged soil (Janssen et al., 1997). Common seals (*Phoca vitulina*) fed with PCB contaminated fish and grey seals (*Halichoerus grypus*) with high body accumulations of PCBs and DDT had significantly lower levels of retinol and free thyroxin. The disturbance in hormonal systems was also related to an increase in microbial infections and reproductive disorders in natural seal populations in the Baltic and North Seas (Jenssen, 1996). Disruption of neuroendocrine functions after exposure to Aroclor 1254 has been demonstrated in Atlantic croaker *Micropogonias undulatus* (Khan and Thomas, 1996). In the Baltic Sea, high levels of DDT, PCBs and organochlorines markedly reduced the hatching rates of eggs (from 72% to 25%) and the nesting success of the fish eating White-tailed eagle (*Haliaeetus albicilla*) in 1960s and 1970s. Nesting and reproductive success showed a steady increase following the ban on DDT and PCBs, and in 1994, the values almost resumed those prior to the occurrence of organochlorines (HELCOM, 1996). Delayed sex maturity, smaller gonads, reduced fecundity and a depression in secondary sexual characteristics were reported in fish populations downstream of bleached pulp mills, and these changes were confirmed in fish exposed to treated effluents under laboratory conditions. The changes were closely related to alternations in endocrine systems controlling the production of sex steroid hormones. Improved reproductive performance was found in feral fish at five sites after the mills improved their waste treatment and pulping processes (Munkittrick et al., 1994).

Hydrocarbons interfere in the production and growth of phytoplankton in many ways. Hydrocarbon molecules disrupt the plasma membrane by displacing those of other lipid compounds, thus affecting its semi-permeability and inhibition of photosynthesis could result form hydrocarbons dissolving in the lipid phase of the chloroplasts and interfering the interactions of the chlorophyll molecules. A similar disruption could occur in mitochondrial membranes with inhibition of the tricarboxylic acid cycle and oxidative phosphorylation. Kerosene causes lipid distortion in the cell membrane with subsequent penetration of toxic agents in different marine red algae and naphthalene causes a reduction in the cellular protein level.

Organochlorin contamination has been well documented in many cetacean species. Levels of contamination are dependent largely upon the diet, sex, age and behavior of the cetacean species in question. Coastal species may accumulate higher levels due to closer proximity to discharge points. The long life span of cetaceans means that they tend to accumulate pollutants over a long period resulting in an accumulation of high contamination levels with age. Many organochlorine substances have been characterized as endocrine disrupters; some are also believed to reduce reproductive success, to interfere with developmental processes, and/or to suppress immune function. Organochlorines compounds are also known to induce vitamin A deficiency in mammals, which may be associated with impairment of immuno-competence, reproduction and growth (Borrell et al., 1999). DDT and PCBs affect steroid reproductive hormones, by prolonging oestrus and decreasing frequency of implantation. Organochlorine contamination can increase mammalian vulnerability to bacterial and viral diseases. It causes a disruption of T-lymphocyte cell growth and function (Vos and Luster, 1989) with, at higher concentrations, B-lymphocyte impairment. Significant relationships were reported between elevated PCB concentrations and mortality due to infectious disease in harbor porpoises which is suggestive of a causal relationship between chronic PCB exposure and infectious disease mortality (Jepson et al., 1999).

Butlyins (BTs) were primarily used as anti-fouling treatments on fish farm cages, ship hulls and marine structures. BTs are extremely toxic and can cause growth retardation and imposex in marine organisms in concentrations as low as 10–20 $\mathrm{ng\,l^{-1}}$ and disrupt the immune system of mammals (Gibbs and Bryan, 1986). Kannan and Tanabe (1997) furthermore cited toxicological studies that have unequivocally documented the immuno-suppressive capacity of butyltins. There is concern about the possible toxicological implications for BT pollution on marine cetaceans (Iwata et al., 1995). BTs have been identified in at least 14 species of cetacean from North Pacific and Asian waters, with elevated levels being seen in coastal species, indicating that, species such as harbor porpoise and bottlenose dolphin would be more at risk from BT contamination (Tanabe et al., 1998). BTs are thought to have played a role in mass mortality events of bottlenose dolphins in Florida through suppression of the immune system (Jones, 1997). Butyltins have been reported in harbor porpoises in the coastal waters of England and Wales (22–640 μg/kg wet weight) (Law et al., 1999). Data on organotin residues in sewage indicate a considerable organotin load in several sewage treatment plants, an additional source of organotins to the coastal waters.

2.6. Plastics

Plastics contribute the most significant part of marine litter deposits and solid wastes dumped into aquatic environments. Plastics are dumped in huge volumes in well-used beaches, lakes, navigation channels and other forms of water masses. In the north-western Mediterranean, plastics constituted most of the debris, at an average of about 77% (Goldberg, 1995). Wace (1995) reported that as many as 600,000 plastic containers worldwide were being dumped daily at sea by shipping. In a survey on the stranded and buried litter on beach in Japan and Russia along Japan Sea, Kusui and Noda (2003) reported that plastics contributed 72.9% by number and 53.8% by weight of the total litter deposits in the beaches of Japan and 55.1% by number 23.4% by weight in the beaches in Russia. Similar significant contributions of plastics were reported by Frost and Cullen (1997) form Northern New South Wales beaches, by Walker et al. (1997) from Bird Island, South Georgia, by Whiting (1998) from Fog Bay, Northern Australia, by Debrot et al. (1999) from South Caribbean. The bulk of plastic materials are even bigger in developing countries with poor waste disposal regulations. As well as an aesthetic problem, marine litter threatens wildlife through entanglement, ghost fishing, and ingestion (Gregory, 1999). The eventual fate of the plastic materials generally involves burial in adjacent sediments. The plastics are virtually indestructible and accumulate organic coatings which adsorb shells, sand and other debris and sink to the bottom where they create and act as partition inhibiting the transfer of nutrients and gases between water and sediments. Anoxia and hypoxia are the most common form of phenomena occurring at the sediment–water interface due to plastic partition. Such effects may seriously interfere in the normal functioning of the ecosystem and may alter the topographical and biological make-up of the sea floor. Information on the effects of plastic materials on aquatic organisms is scarce except some reports suggesting the occurrence of plastics in marine birds. Blight and Burger (1997) examined 58 species under three categories of marine birds and reported that 100% of surface-feeding procellriiforms, 75% of the shearwaters and 39% of the purcuit-diving alcids contained plastics in their guts. Similar reports were made by Furness (1985) and Robards et al. (1995).

2.7. Sediments

Global estimates of erosion and sediment transport in major rivers of the world vary widely, reflecting the difficulty in obtaining reliable values for sediment concentration and discharge in many countries. Milliman and Syvitski (1992) estimated global sediment load to oceans in the mid-20th century to be 20,000 million tons per year, of which about 30% comes from rivers of southern Asia. While erosion on mountainous islands and in upland areas of continental rivers reflects natural topographic influences, Milliman and Syvitski (1992) suggest that human influences in Oceania and southern Asia cause disproportionately high sediment loads in these regions. High levels of turbidity limit penetration of sunlight into the water column, thereby limiting or prohibiting growth of algae and rooted aquatic plants. In spawning rivers, gravel beds are blanketed with fine sediment which inhibits or prevents spawning of fish. In either case, the consequence is disruption of the aquatic ecosystem by destruction of habitat. Notwithstanding these undesirable effects, the hypertrophic status of many shallow lakes, especially in developing countries, would give rise to immense growth of algae and rooted plants were it not for the limiting effect of light extinction due to high turbidity.

The role of sediment in chemical pollution is tied both to the particle size of sediment, and to the amount of particulate organic carbon associated with the sediment. For phosphorus and metals, particle size is of primary importance due to the large surface area of very small particles. Phosphorus and metals tend to be highly attracted to ionic exchange sites that are associated with clay particles and with the iron and manganese coatings that commonly occur on these small particles. Many of the persistent, bioaccumulating and toxic organic contaminants, especially chlorinated compounds including many pesticides, are strongly associated with sediment and especially with the organic carbon that is transported as part of the sediment load in rivers. Measurement of phosphorus transport in North America and Europe indicate that as much as 90% of the total phosphorus flux in rivers can be associated with suspended sediment. The affinity for particulate matter by an organic chemical is described by its octanol–water partitioning coefficient (K_{OW}). This partitioning coefficient is well known for most organic chemicals and is the basis for predicting the environmental fate of organic chemicals. Chemicals with low values of K_{OW} are readily soluble, whereas those with high values of K_{OW} are described as "hydrophobic" and tend to be associated with particulates. Chlorinated compounds such as DDT and other chlorinated pesticides are very hydrophobic and are not, therefore, easily analyzed in water samples due to the very low solubility. For organic chemicals, the most important component of the sediment load appears to be the particulate organic carbon fraction which is transported as part of the sediment. Scientists have further refined the partitioning coefficient to describe the association with the organic carbon fraction (K_{OC}). Another important variable is the concentration of sediment, especially the <63 μm fraction, in the water column. Even those chemicals that are highly hydrophobic will be found in trace levels in soluble form. Where the suspended load is very small, the amount of water is so large relative to the amount of sediment that the bulk of the load of the chemical may be in the soluble fraction. This becomes an important issue in the monitoring of hydrophobic chemicals.

Unlike phosphorus and metals, the transport and fate of sediment-associated organic chemicals is complicated by microbial degradation that occurs during sediment transport in rivers and in deposited sediment. Organic chemicals associated with sediment enter into the food chain in a variety of ways. Toxic compounds bioaccumulate in fish and other top predators both directly though sediment ingestion and indirectly through the food web (associated with the particulate C fraction of the sediment). Deltas, mangrove forests, beaches and other coastal habitats are sustained by the supply of sediment, while other habitats, such as coral reefs and seagrass beds, may be smothered or deprived of light. Sedimentation is one of the major global threats to reefs, particularly in the Caribbean, Indian Ocean, and South and Southeast Asia.

2.8. Eutrophication and algal bloom

Cloern (2001) described two broad responses of nutrient loadings in coastal waters: direct responses such as changes in chlorophyll, primary production, macro- and microalgal biomass, sedimentation of organic matter, altered nutrient ratios, harmful algal blooms, and indirect responses such as changes in benthos biomass, benthos community structure, benthic macrophytes, habitat quality, water transparency, sediment organic matter, sediment biogeochemistry, dissolved oxygen, mortality of aquatic organisms, food web structure etc. Increase in phytoplankton biomass and the resultant decrease in transparency and light intensity can become an indirect response that limits growth of submerged vascular plants. Decadal trends of decreasing abundance of benthic macrophytes have been reported in Chesapeake Bay and Laguna Madre (Cloern, 2001). Blooming and finally collapse of algae may lead to hypoxia/anoxia and hence mass mortality of benthos and fish over large areas. Sensitive species may be eliminated and major changes in ecosystem may occur. Deteriorating environmental quality adversely affects the amenity, recreational values and the tourist industry in addition to the ecological and biological losses. Increases in nutrient concentration, phytoplankton biomass and productivity, alternation of nutrient ratios, change of species composition, and large scale hypoxia/anoxia affecting hundreds and thousands of km^2 have been reported in many areas all over the world (Sheppard, 2000a,b,c).

Eutrophication has been shown to cause major changes in species composition, structure and function of marine communities over large areas. The general response of phytoplankton communities to eutrophication involves an increase in biomass and productivity (Riegman, 1995). A general shift from diatoms to dinoflagellates, and also down shift in size in phytoplankton towards a dominance of small size nanoplankton (e.g. microflagellates and coccoids) is generally observed (Kimor, 1992). A similar response is observed in zooplankton communities, with herbivorous copepods being replaced by small-size and gelatinous zooplankton (Zaitsev, 1992). Eutrophication also promotes proliferation of macroalgae and filamentous algae. This often becomes a nuisance, and may affect benthic fauna, nursery and feeding of fish, amenity, recreational uses and tourism (Riegman, 1995; Rosenberg et al., 1996). Eutrophication-induced hypoxia alters the structure, diversity as well as trophic structure and food web of benthic and fish communities (Riegman, 1995). A decrease in dominance of predatory gastropods in the benthic community and a shift from demersal fish species to pelagic species in response to eutrophication have been reported. Changes in species composition of macrobenthos in response to eutrophication have also been reflected in the diet of demersal fish in Sweden waters (Phil, 1994).

Related to the chemical and physical factors that cause eutrophication, one of the most important ecological consequences of aquatic pollution is the occurrence of toxic algal bloom, often called red tides. These massive growths of phytoplankton, mostly dinoflagellates, may contain highly toxic chemicals that can cause illness and even death to aquatic organisms and humans. Large-scale algal blooms cause serious ecological damage and economic loss, while toxic blooms pose additional public health threats. More than 160 red tides have been reported in Chinese waters from 1980 to 1990, and the frequency, magnitude and geographic extent of red tides along the coast of China has increased in the last decade. The area covered ranged from 10 to 6100 km^2 and over 60 causative red tide species have been reported (Qi et al., 1993).

Potential toxins from red tide are able to cause extensive fish kills, contaminate shellfish and create severe respiratory irritation to humans along the shore. When the bloom is severe, fish die rapidly from the neurotoxic effects of the red tide which enter their bloodstream through the gills. Because the fish die immediately after intoxication, the toxins do not have time to build up in their tissue. Fish exposed to even lower concentrations may accumulate toxins in their body. Such bioaccumulation in fish eaten by mammals may have been a major factor in the deaths of marine mammals. People near the shore are likely to experience the characteristic burning sensation of the eyes and nose caused by gas choked in the air, and dry, choking cough. Another serious problem for public heath caused by red tide is through shellfish contamination. Bivalve shellfish, especially oysters, clams and coquinas can accumulate so many toxins that they become toxic to humans. Elevated growth and subsequent decay of phytoplankton has caused widespread areas of seasonally oxygen depleted water. The global distribution of frequently occurring oxygen depleted zones (Malakoff, 1998) dominates the highly developed industrial areas that include much of Europe, central and North America and some parts of the Asia–Pacific.

2.9. Aquaculture activities

Aquaculture as a form of agricultural pollution has received particular attention due to its potential for loading and discharging effluents rich in polluting agents. Effluent controls are possible on land-based systems; however, water-based systems are capable of causing potential problems. Aquaculture is rapidly expanding in most parts of the developed and developing world, both in freshwater and marine environments (Fig. 6). The environmental impact is primarily a function of feed composition and feed conversion, faecal waste generation, organic and inorganic fertilizers, liming materials, algicides and herbicides, disinfectants, antibiotics, inducing agents, osmoregulators, piscicides, probiotics etc. (Tacon et al., 1995). Wastage of feed is estimated to be 20% (Enell, 1995) even with high quality feed used for fish rearing European aquaculture. In Asia, Latin America and Africa, however, aquaculture usually suffers from a general lack of high quality fish feed resulting in poor feed conversion and higher feed loss which ranges as high as 75–80% depending on the culture systems and the degree of management applied. Waste feed and faecal production both add substantial nutrient loadings to aquatic systems and subsequent discharge into receiving waters.

Intense cultivation of fish and shellfish in coastal waters can be a source of environmental disturbance associated with unnaturally high concentrations and deposition of organic matter that alter sedimentary processes and oxygen concentrations. Shellfish culture has a strong influence on the nitrogen cycle by

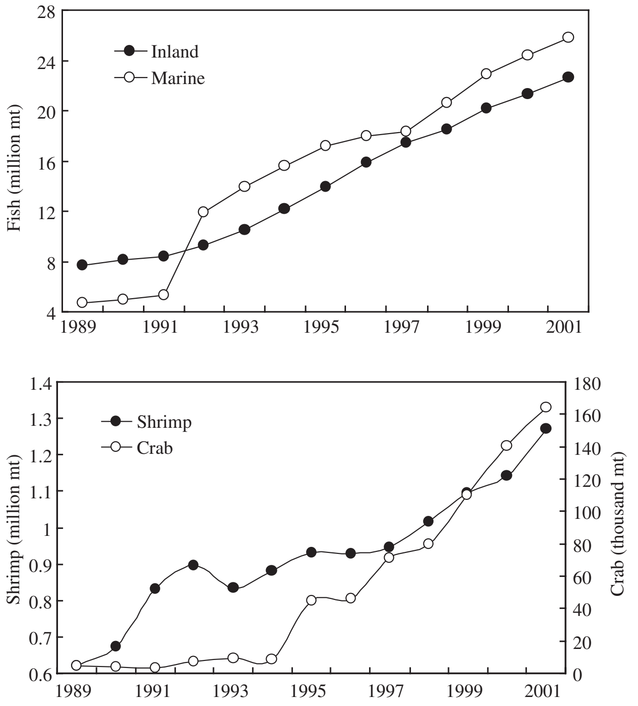

Fig. 6. Global production of fish from aquaculture in both inland and marine environment (upper) and shrimp and crab through coastal aquaculture (lower).

enhancing the deposition of organic matter to the sediments, reducing oxygen availability and promoting dissimilatory processes of N cycling. In the Thau Lagoon, France, used for intense oyster culture, these changes reduce the loss of nitrogen to denitrification and, therefore, retain N available to sustain primary production (Gilbert et al., 1997). Similar responses were measured in Upper South Cove, Nova Scotia, where sediments beneath cultured mussels release large quantities of ammonium and act as a net source of N, compared to reference sites which act as an N sink (Hatcher et al., 1994). Intense shellfish farming, therefore, increases the retention of nitrogen within coastal systems. Finfish culture is growing at an equally rapid rate with similar responses of organic enrichment and enhanced microbial activity of sediments, and also promotes development of toxic algal blooms. In the Aland archipelago, where harvest of farmed rainbow trout (*Oncorhyncus mykiss*) increased >10-fold from 1977 to 1991, fish farms now contribute more P (by 15×) and N (by 3.6×) than treated wastewater (Bonsdorff et al., 1997). This region of the northern Baltic exhibits multiple symptoms of change in response to nutrient enrichment, even during an era of improved wastewater treatment.

In oligotrophic environments such as the Mediterranean, aquaculture has been displacing fishing grounds, attracting dolphins and competing with traditional fisheries. Moreover, there are concerns that biotechnology and/or breeding techniques could have negative impacts on wild species in the event that genetically altered species escape and interbreed. In some cases, aquaculture is a resource intensive enterprise, e.g. salmon farming. Salmon farming in cages requires lots of resources collected by fishing vessels operating over vast marine ecosystems. The marine water surface area required to produce the food given to the salmon in the cages is about 1 km^2 per ton of salmon. The ecological footprint of the salmon farm is as much as 50,000 times larger than the areas of the cages (Folke, 1995). Figures published for 1996 estimate that the 80,000 tons of farmed salmon produced 35,000 tons of fecal waste, i.e. 0.44 tons of waste per ton of produced salmon (Taylor et al., 1998). Using SEPA data for 1999 (SEPA, 2000), 114,638 tons of salmon were produced, meaning that 50,440 tons of fecal waste would have been discharged into the marine environment. Elevated nutrient levels have been bound in many coastal areas and seas hosting fish farming operations (Gillibrand et al., 1996).

Additional environmental problems include risk of disease and its transfer to wild fish, introduction of exotic species, impacts on benthic communities and on the eutrophication of water, interbreeding of escaped cultured fish with wild fish with consequent genetic change in the wild population (the so-called 'biological pollution'; Elliott, 2003). Traditional integrated aquaculture systems, as in China, where sewage-fish culture is practiced, can be a stabilizing influence in the entire ecosystem (Rosenthal, 1992). The environmental impacts of aquaculture and associated activities have been discussed by many authors for different aquaculture systems and regions (Enell, 1995; Paez-Osuna et al., 1998; Selong and Helfrich, 1998; Boyd and Massaut, 1999, Karakassis et al., 2000; Tovar et al., 2000; Elliott, 2003).

2.10. Biological pollution

The terms 'biological pollution' and 'biological pollutants' have been emerging recently with a relatively recently identified impacts of introduction and invasion of species throughout the world; the terms have been used to discuss the problems caused by introduced and invasive species (Boudouresque and Verlaque, 2002). There is an increasing set of case studies regarding the presence and movement of invasive species in marine and estuarine waters as well as in aquaculture and the term biological invasions has become widely accepted (Elliott, 2003). The terms also appear reasonable to describe pollution emanating from organisms, such as nutrients or organic matter, and even pollution affecting biological organisms, i.e., contaminants and/or biological pollutants as agents of change in the marine environment. The central criterion of the definitions of pollutants is their ability to reduce the fitness for survival of some level of biological organization, from cell to ecosystem (Elliott, 2003).

Plants such as the green alga *Caulerpa taxifolia* are well known as an invasive species in the Mediterranean. Fishes such as the lionfish *Pterosis volitans* are also invaders, probably introduced with ballast water or by aquarists (Whitfield et al., 2002). There are numerous examples of fish species introduction around the world with varying degrees of consequences (Middleton, 1982; Amundsen et al., 1999; Shafland, 1999; Mills and Holeck, 2001). However, it is still a question whether these should be termed biological pollutants, i.e. whether they have reduced the fitness of the biological system for survival. In the estuarine and marine field, there are several good examples of introduced species and of the damage caused by them. For example, the Chinese mitten crab *E. sinensis* now extends to a large part of NW Europe from the Tagus Estuary in Portugal to northern Germany and eastern Scotland and it has started causing damage to flood defense walls by burrowing. The damage here is at an ecosystem level as well as affecting local community structure.

Most of the aquaculture industries in the world are biologically polluted in that almost all the suitable aquaculture species are now genetically modified. Deliberate genetic selection and breeding for long period has caused not only numerous consequences in the aquaculture unit itself but also the loss of the original stocks for many species in many parts of the world. In some instances, the modified populations are often released and mixed with the natural populations, breed with them and, therefore, cause biological pollution from molecular level to community and ecosystem level. The carp fishery in Indian subcontinent and China and salmonid fishery in Europe are two examples of large-scale biological pollution. As another example, introduced and in some cases genetically modified species such as non-native oysters, producing spat in South-west Britain and chromosome-modified salmonids escaping from fish farms in Scotland and Norway. It is notable that the recent flooding in central Europe has inadvertently caused the release of hybrid and modified fishes, such as sturgeon (*Acipenser* spp.) from aquaculture installations. In these cases, if the organisms survive and successfully breed then the biological pollutants can be regarded not only as conservative, but also accumulative (Elliott, 2003). Micro- and macroparasites and micropathogens have long been regarded as introduced and invasive. It is likely that the local populations of fish are not resistant to the pathogenic organisms carried by the introduced species and vice versa. Therefore, serious consequences occur for both the local and the introduced population in a deliberate species introduction. Most of the species introduction programs usually lack precautionary approach (FAO, 1995).

3. Global trends in coastal and marine pollution

Disposal into waterways is a very ancient practice of dealing with wastes and the open waterways have been used by people for dumping all kinds of waste produced. Consequently, most of the aquatic environments are now polluted to some extent; situations are even critical near intensive human settlements. Pollution of water-bodies from a large variety of sources and their various impacts has been reported from different ecosystems since long (Table 4). Progressive increases in nutrient concentration and altered nutrient ratio have been reported from the Baltic Sea, Waden Sea, North Sea, Black Sea, Adriatic Sea, Dutch Sea, Japan Sea, the Gulf of Thailand, the Indian Ocean and the bays and coasts of many countries (HELCOM, 1996; Sheppard, 2000a,b). As a result of human intervention and mobilization of nutrients, surface waters and ground waters throughout the developed world now have elevated concentrations of N and P compared to concentrations in the middle of 20th century (Cloern, 2001). For example, concentrations of nitrate have increased five times and phosphate 20 times in the Black Sea from 1960s to 1980s (Gomoiu, 1992). Cloern (2001) reported decadal scale of increasing N and P in the Northwest Black Sea, central Baltic Sea, Archipelago Sea and in the Irish Sea and in three rivers in North America and Europe including the Mississippi River; increasing phytoplankton productivity in Adriatic Sea, Belt Sea and Waden Sea, decreasing dissolved oxygen concentrations and secchi depths in different coastal seas from 1960s to 1990. Likewise, levels of N and P in Dutch Seas have increased four and two times respectively from 1930 to 1980 (GESAMP, 1990). Three to five times increases in N and P export have been reported in Queensland, Australia, in the last 65 years (Moss et al., 1992). Progressive increases in primary productivity and decreases in dissolved oxygen due to eutrophication have been reported in the Baltic Sea from 1958 to 1989 (HELCOM, 1996). A decrease in bottom oxygen was found in northern Adriatic Sea during the period 1911–1984 (Justic et al., 1995). The long-term increase in nutrient in the Baltic has caused an increase in phytoplankton biomass, a decrease in water transparency, proliferation of filamentous algae, and also large scale changes in species diversity of benthic and fish communities (Bonsdorff et al., 1997). Globally, increases in frequency and severity of hypoxia are evident, especially in coastal and estuarine areas; many ecosystems are now near the verge of hypoxia-induced catastrophe (Diaz and Rosenberg, 1995).

In the last two decades, there has been an increased frequency and scale of toxic algal blooms including red tides in coastal waters of Brunei, Malaysia, South Africa, Hong Kong, Japan and Thailand (three examples taken from Cloern, 2001 are given in Fig. 7) and an

Table 4
Effects of pollution on aquatic ecosystems and aquatic living resources in different parts of the world

Causes	Effects	Region	Reference
Pollution	Decrease in species diversity of fish and other aquatic organisms; there are 75 threatened species at present	Coastal Thailand	Chavalit and Siraprapha (2002)
Pollution	Changes in bivalve reef and bed structure	–	Richard et al. (2002)
Polycyclic aromatic hydrocarbons (PAH), chlorinated organic compounds	Decline on ocean and coastal fisheries particularly the Atlantic Salmon, *Salmo salar*; negative impacts on food chain	The Atlantic Ocean	Scott (2001)
Pollution	Loss of nesting sites and habitats of the green turtle, *Chelonia mydas*	Mediterranean	Max et al. (2001)
Pollution	Reduction or depletion of local and/or total population of the Atlantic White-eaked Dolphin	Northeastern and Northwestern Atlantic	Jon et al. (2001)
Pollution	Decline of stock of the Atlantic salmon, *Salmo salar* and brown trout, *Salmo trutta*	Norwegian river systems	Arne and Ove (2001)
Pollution	Degradation of coastal habitats, natural resources and biodiversity	The Indian Coast of Somalia	Federico and Giovanni (2000)
Nonpoint source pollution	Reduction in shellfish population	The west coast of the Pacific	William (2000)
Oil pollution	Decline in populations and colonies of seabirds	The Patagonian coast, Argentina	Pablo et al. (1999)
Pollution	Collapse of lake whitefish (*Coregonus clupeaformis*) population	The Great Lakes	Edsall (1999)
Pollution	Degradation of nursery areas of many fishes	Arabian Sea, Gulf of Oman and Arabian Gulf	Siddeek et al. (1999)
Pollution	Stock decimation of blue crab, *Callinectes sapidus*	South California	Whitaker et al. (1998)
Industrial pollution	Stock decimation of fishes	Bangladesh	Alam et al. (1998)
Pollution	Endangered and threatened (Ganges river dolphins, *Platanista gangetica*)	Bangladesh	Smith et al. (1998)
Pollution	Damage to mollusk producing beds in estuaries and bays	North and Central America and Europe	MacKenzie and Burrell (1997)
Pollution	Diminishing yields of American oysters (*Crassostrea virginica*)	Coastal lagoons of Mexico	Marin et al. (1997)
Pollution	Loss of nesting habitats and population decline of leatherback	Malaysia	–
Pollution	Habitat degradation and decline in salmon population	California	Olin (1996)
Pollution	Decline in the abundance of eggs and larvae of anchovy, *Engraulis encrasicolus*	Black Sea	Niermann et al. (1994)
Pollution due to the Gulf War 1991	Interruptions in the life cycles, morbidity, emigration, and recruitment collapse of penaeid shrimp, *Penaeus semisulcatus* and supporting fisheries	Arabian Gulf	Mathews et al. (1993)
Point sources of pollution	Changes in the water quality	Archipelago Sea and the Finnish part of the Gulf of Bothnia	Lappalainen and Hilden (1993)
Sewage and nonpoint pollution	Increased lake fertility, killing of yellow perch, cisco, white bass, and yellow bass	Yahara River lakes (Mendota, Monona, Waubesa and Kegonsa)	Lathrop et al. (1992)
Pollution	Mortality, malformation, and abnormal chromosome division of fish embryos (Atlantic mackerel, *Scomber scombrus*; windowpane flounder, *Scophthalmus acquosus*; winter flounder, *Pseudopleuronectes americanus*)	US Atlantic coast	Longwell et al. (1992)
Pollution	Poor reproductive success in hard clams (*Mercenaria mercenaria*)	Long Island Sound USA	Stiles et al. (1991)
Pollution by oil, chemicals and rubbish	Reduction in population of seabirds	North Sea	Dunnet et al. (1990)
Pollution from domestic and industrial wastes	Environmental changes; disappearance of endemic fishes in commercial catches particularly Schizothoracids and mahseers	Riverine systems of the north-western Himalaya, India	Sehgal (1985)
Pollution	Chronic shellfish toxicity; decline in anadromous fish stock	St. Lawrence Estuary, Quebec, Canada	Andersen and Gagnon (1980)
Pollution and eutrophication	Significant changes in the water chemistry (increase of BOD and total N content); changes in the structure and abundance of phytoplankton, zooplankton and bottom fauna	Lake Jamno, Poland	Zdanowski et al. (1979)

Table 4 (*continued*)

Causes	Effects	Region	Reference
Industrial, commercial, agricultural and domestic pollution	Massive fish kills and polluted water	Laguna de Bay, Philippines	Oledan (2001)
Pollution	Undefined impacts on the finless porpoise, *Neophocaena phocaenoides*		Reeves et al. (1997)
Pollution from industrial waste discharge, mining, pesticides, and oil residues and spills	Stock declines of fish and other commercially important aquatic organisms; changes in lake ecosystem and water quality	African Great Lakes	
Pollution from different sources	Alteration in population structure of the commercial fishes	USA	Grosse et al. (1997)
Pollution from intensive ship-scrapping activities, sewage disposal and antifouling paints	Bioaccumulation of butyltins and resulting butyltin pollution in fishes	India, Bangladesh, Thailand, Indonesia, Vietnam, Taiwan, Australia, Papua New Guinea and the Solomon Islands	Kannan et al. (1995)

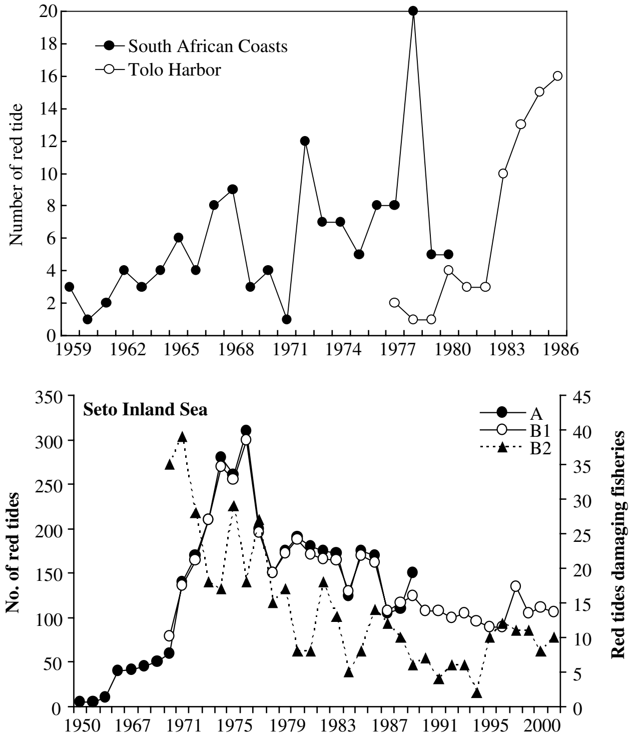

Fig. 7. Number of red tides occurrence in the South African Coast, the Tolo Harbor of Hong Kong and in the Seto Inland Sea of Japan.

increase in PSP frequency has been found in both temperate and tropical regions (Viviani, 1992). The Intergovernmental Oceanographic Commission of UNESCO has reported toxic blooms of *Pseudonitzschia australis* in California coastal waters; multiple species of dinoflagellates in Hong Kong and south China; brown tide species in Saldanha Bay and Langebaan Lagoon, South Africa; *Gymnodinium mikimotoi* in Wellington Harbor, New Zealand; *Alexandrium tamarensis* in Brazil, Uruguay, and Argentina; *Prorocentrum minimum* in Thermaikos Bay, Greece; red tides along the Salalah coast of Oman; *Pyrodinium* in Acapulco, Mexico; *Alexandrium* spp. in Alexandria Harbor, Egypt; *Gymnodinium breve* in south Florida; *Gymnodinium catenata* along the Atlantic coast of Morocco; *Dinophysis* in Loch Long, Scotland; *Pseudonitzschia pungens* in estuaries of Prince Edward Island, Canada; *Alexandrium minuta* in the Bay of Izmir, Turkey; *Dinophysis* along the northeast coast of Kamchatka, Russia; *Pyrodinium bahamens* in the Philippines; and *Gymnodinium nakasagiense* in southwestern India.

Long-term monitoring programs show a general decrease in environmental levels of DDT and PCB in many coastal waters. For example, the annual geometric means of DDT, PCBs and PAHs in mussels at 154 sites in coastal waters of the USA showed a general decrease from 1986 to 1993 (Beliaeff et al., 1997). Likewise, Blomkvist et al. (1992) showed a significant decrease in RDDT and PCB in the blubber of 109 specimens of ringed seals (*Phoca hispida botica*), grey seals (*Halichoerus grypus*) and harbor seals (*Phoca vitulina*) in Swedish waters since the early 1970s. Analysis of sediment core samples in Clyde estuary, UK showed a significant decrease in PAH deposition over time (Hursthouse et al., 1994). The decreased concentration of xenobiotics in the marine environment reflects the general reduction in the use and discharge of these compounds in the northern hemisphere. Unfortunately, very few long-term studies have been carried out in tropical and sub-tropical coastal waters. The decreasing trend observed in temperate regions may not be applicable to tropical and sub-tropical waters, since reduction in use and disposal of toxic organic chemicals in the latter regions may not be the same.

At present, some 65% of existing large cities (with more than 2.5 million people) are located along the coast. The world population has exceeded 6 billion, of whom 60% (3.6 billion) is living within 100 km of coast (UNEP, 1991). It is highly likely that a substantial proportion of wastewater generated from this population will be directly discharged into the coastal marine environment with little or no treatment, thereby adding to the already high nutrient input. Various studies have attempted to estimate the anthropogenic input of nutrients into the marine environment (Cornell et al., 1995; Sheppard, 2000a,b,c). The present anthropogenic emissions and deposition of nitrogen to the North Atlantic Ocean is about five times greater than pre-industrial time (Prospero et al., 1996). At present, atmospheric deposition of N contributes some 10–50% of the total anthropogenic N input ($2\text{–}10\times10^4$ μmol N m^{-2} $year^{-1}$), and further increase is expected in the coming years (Paerl, 1993).

There is a worldwide increase in irrigation in arid areas, large scale clearing of land vegetation, and deforestation, which contribute enormously to terrestrial runoff. Intensive farming results in overgrazing, ammonia emission, and farm waste disposal problems. Nutrient export from crop and pasture lands are typically an order of magnitude greater than those from pristine forest (Gabric and Bell, 1993). Mariculture activities have increased dramatically in many coastal areas in the last decade, and such a trend will continue (FAO, 1992). This will further augment the nutrient input into coastal environments, since some 80% of N input into a mariculture system will be lost into the marine environment (Wu, 1995). The volume of wastewater generated by human populations is typically large, and removal of nutrient from such huge amounts of wastewater is expensive. The cost of secondary treatment (which only removes some 30–40% of N and P) for example, is some 3–4 times more expensive that of primary treatment. Due to the high construction and recurrent costs, it is unlikely that building of sewage treatment facilities can match population growth and GNP in developing countries.

PCBs are frequently found in fish liver, seal blubber, bird eggs and human fat in the North Sea. Octachlorostyrenes (OCSs) were found in benthic organisms from the international North Sea (Dethlefsen et al., 1996). Concentrations of HCHs, PCBs, and triazines have been determined in the German Bight within the water column and rain water, and HCHs and PCBs in sediment samples (Huhnerfuss et al., 1997). Concentrations of insecticides and PCBs in sediment from the Thames estuary have been associated with sewage sludge dumping. Disposal of dredged material into the North Sea amounted to approximately 70 million tons per year in the 1990s. Litter and garbage disposal from ships overboard and from tourism is estimated at 600,000 m^3 per year. It is likely that organic inputs will continue, especially in those waters deemed to have sufficient carrying capacity to degrade, disperse and assimilate the materials (Elliott et al., 1998). Shipping in the North Sea is the most intense in the world and the area is a major navigation route for some of the world's most developed and highly populated economies. The effects of TBT, the active constituent of anti-foulant paints, on marine fauna have been extensively demonstrated with work done in this region and adjacent coasts.

Globally, sewage remains the largest source of contamination, by volume, of the marine and coastal environment (GESAMP, 2001), and coastal sewage discharges have increased dramatically in the past three decades. In addition, because of the high demand for water in urban neighborhoods, water supply tends to outstrip the provision of sewerage, increasing the volume of wastewater. Public health problems from the contamination of coastal waters with sewage-borne pathogens are well known, and in many developed countries improved sewage treatment and reduction of the disposal of industrial and some domestic contaminants into municipal systems have significantly improved water quality. In the developing world, however, the provision of basic sanitation, as well as urban sewer systems and sewage treatment, cannot keep pace. High capital costs, explosive pace of urbanization and in many cases, limited technical, administrative and financial capacities for urban planning and management and ongoing operation of sewage treatment systems are barriers to efficient sewage treatment (GESAMP, 2001). Recent evidence suggests that bathing in waters well within current microbiological standards still poses significant risk of gastrointestinal disease, and that sewage contamination of marine waters is a health problem of global proportions.

Human activities now account for more than half of global nitrogen fixation (Vitousek et al., 1997), and the supply of fixed nitrogen to the oceans has greatly increased. Sewage discharges are often the dominant local source near urban areas but global inputs are dominated by agricultural run-off and atmospheric deposition. The highest rates of riverine transport of dissolved inorganic nitrogen to estuaries from all sources occur in Europe and in South and East Asia (Seitzinger and Kroeze, 1998). Nitrogen levels are exacerbated by widespread loss of natural interceptors such as coastal wetlands, coral reefs and mangrove forests. Fertilizer use has stabilized in developed countries but is increasing in developing ones (Socolow, 1999), a trend expected to continue because of enhancement of fertilizer use through widespread subsidies, which reflect the high political priority of increasing food production and reducing food costs.

Another important feature of marine pollution is the existence of increased pollution levels in the enclosed seas and coastal waters as compared with the open ocean. Contamination levels also increase during the transition from the southern parts of all oceans to the north, where the main industrial centers and main pollution sources are concentrated. The existence of elevated levels of contaminants in the zones of high bioproductivity is extremely ecologically alarming. These zones include the water layer up to 100 m from the water surface (photic layer) and boundaries of natural environments (water-atmosphere and water-bottom sediment) as well as enclosed seas, estuaries, coastal and shelf waters. In particular, in shelf and coastal zones, which take only 10% of the World Ocean surface and less than 3% of its volume, the most intense processes of bio-production, including the self-reproduction of the main living resources of the sea, take place. The main press of anthropogenic impact is also concentrated here. In 1994, an estimated 37% of the global population lived within 60 km of the coast—more people than inhabited the planet in 1950 (Cohen et al., 1997). Progress in protecting the marine and coastal environment over the past 30 years has generally been confined to relatively few, mostly developed countries, and to relatively few environmental issues. Overall, coastal and marine environmental degradation not only continues but has intensified. There have, however, been significant changes in perspective, and new concerns have emerged. Marine and coastal degradation is caused by increasing pressure on both terrestrial and marine natural resources, and on the use of the oceans to deposit wastes. Population growth and increasing urbanization, industrialization and tourism in coastal areas are root causes of this increased pressure.

4. Fishery degradation

The previous sections discuss how pollution contributes to coastal and marine habitat degradation in general. Being one of the most important parts of the marine food chains, the ultimate effects of all sorts of coastal and marine pollution are seen in fish. Therefore, fishery degradation resulting from pollution deserves particular mention. Fig. 8 shows a generalized schematic diagram of how pollution directly and indirectly impacts on fish populations and fisheries and how these impacts are translated into reduced economic benefits for producers and consumers.

Pollution from different sources and subsequent impacts on commercial use of ecosystems have been reported from many parts of the world including the major fishing areas and have been summarized in Table 4. A comprehensive review of the existing status of the world's most significant fisheries in relation to pollution incidence can also be found in Sheppard (2000a,b). Most of the world's largest fishing industries are reported as either degraded or threatened. General degradation in the fishing industry and decline in catch was reported from the Baltic Coasts, the North Sea Coasts, the Atlantic Coasts and the Mediterranean Coasts. Fish catches have been in decline since the 1980s, and it is unlikely that there will be an increase in total catch in these regions. High seas trawlers have been forced to move closer to shore, competing with inshore artisanal trawling and other activities. As a result, the demand for fish products has exceeded the available catch. Decline in the catch of American Shad (*Alosa sapidissima*) in the Chesapeake Bay and in total US catch (Fig. 9) was reported over a long period; a similar decline in the catch of demersal fish was reported to be associated with water pollution and habitat degradation in the Gulf of Thailand and in the Aral Sea (Fig. 9).

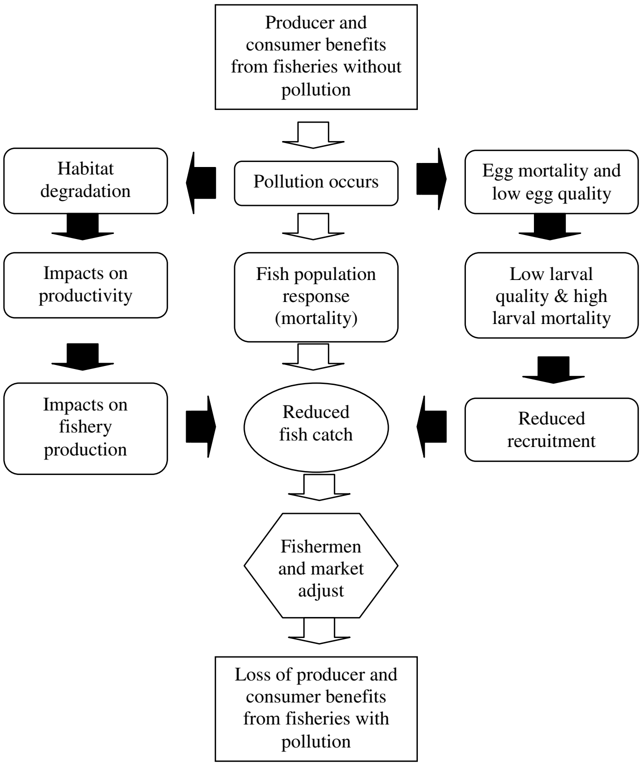

Fig. 8. Generalized scheme showing pollution effects of fish populations are translated into reduced economic benefits for producers and consumers (open and block arrows indicate direct and indirect effects respectively).

Around 30 species of fish are caught in the Baltic, but commercial fisheries are dominated by just three species: cod (*Gadus morhua*), herring (*Clupea harengus*) and sprat (*Clupea sprattus*), that make up about 93% of total catch in the Baltic Sea and about 75% of the catch in the Belt Sea and the Sound. However, fisheries of all three species are under steady decline over the last two decades. The spawning biomass of cod and herring declined sharply since the early 1970s (Fig. 10) with a corresponding decline in the catch quota in these fisheries until 2003 and the trend is expected to continue (Fig. 11).

Environmental degradation in the East Asian Seas (which include the Yellow Sea, East China Sea, the

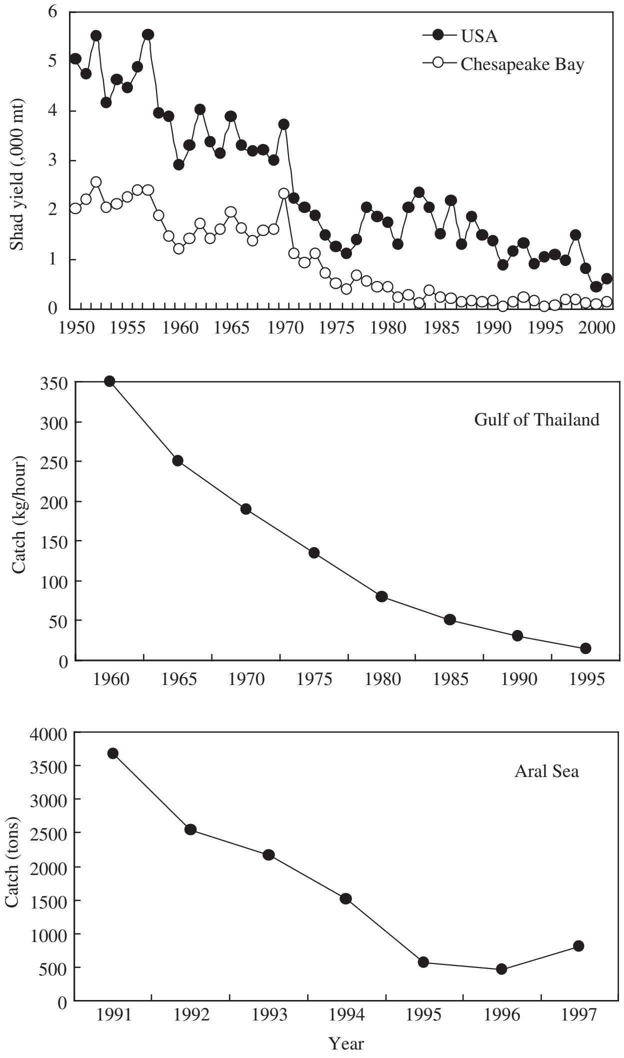

Fig. 9. Decline in the catch of American Shad (*Alosa sapidissima*) in the Chesapeake Bay and in total US catch (upper), catch per unit of fishing effort (kg$\,h^{-1}$) of demersal fish in the Gulf of Thailand (middle) and in the total catch (tons) of fish in the Aral Sea (lower).

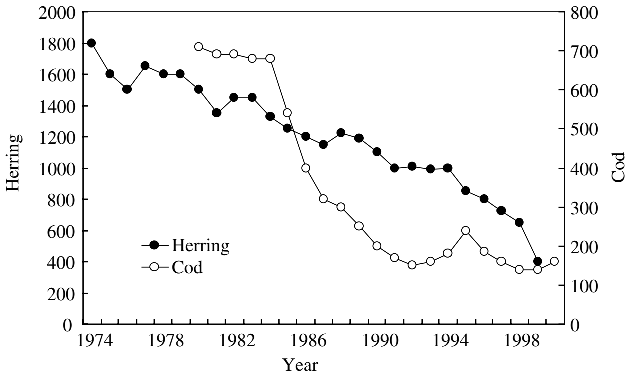

Fig. 10. Trends in the annual spawning stock biomass (thousand tons) of cod (*Gadus morhua*) and herring (*Clupea harengus membras*) in the Baltic Sea, taken from the homepage (www.helcom.fi) of the Baltic Marine Environment Protection Commission/Helsinki Commission.

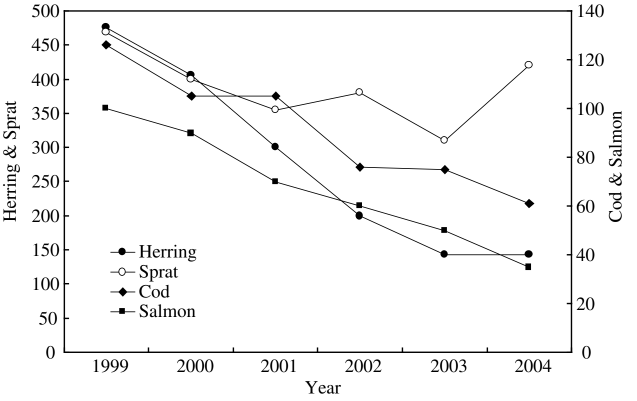

Fig. 11. Reduction in the catch quotas (thousand tons) of principal fish species in the Baltic Sea with a projection for year 2004.

South China Sea, the Sulu-Celebes Seas and the Indonesian Seas) is threatening the world's center for marine biodiversity, affecting the functional integrity of about a third of the world's coral reef, 30% of world's mangrove system and about 40% of the world's fish catch (Thia-Eng, 1999). Decline in fisheries of the Lake Victoria due to pollution was reported among other by Ntiba et al. (2001). Pollution of riverine fisheries both from industrial effluents and agricultural chemicals is a growing concern in developing areas of the world. Several reports are available on the extent of water pollutions and their consequences in South Asian developing countries. In Bangladesh, for example, most of the industries are situated on river banks and do not have waste disposal and treatment plants and thus discharge untreated wastes and effluents which find way directly or indirectly into water bodies. Kumar and Harada (2001) reported loss of biological and ecological sustenance and collapse of a river system near the capital of Bangladesh.

Smith (1970) reported mass killing of clams and abalone from oil toxicity and stated a probability of long-lasting ecological consequences. In the same review, Smith (1970) also reported massive killing of razor clam *Siliqua patula* followed by a serious event of oil pollution which was responsible for more than 90% reduction of the commercial catch of the clam in the north-west coast of US in 1963 resulting in collapse of the clam fishery.

Red tides occur throughout the world, drastically affecting Scandinavian and Japanese fisheries, Caribbean and South Pacific reef fishes, and shell fishing along US coasts. In 1989, a red tide affected large areas of shrimp farms in Bohai, and the total loss was estimated at US\$40 million (Xu et al., 1993). In Hong Kong, a red tide caused by a persistent bloom of *Gonyaulax polygramma* (>50 million cells/l) occurred continuously for three months in Tolo Harbour and Channel, covering an area of some 80 km^2, and all fish and benthos were killed in this incidence. In 1998, a

Table 5
Economic losses from red tides in fisheries and aquaculture (Worldwatch Institute, 1999)

Year	Region	Species	Loss in million US$
1972	Japan	Yellowtail	~47
1977	Japan	Yellowtail	~20
1978	Japan	Yellowtail	~22
1978	Republic of Korea	Oyster	4.6
1979	United States	Many	2.8
1980	United States	Many	7
1981	Republic of Korea	Oyster	>60
1985	United States	Scallops	2
1986	Chile	Red salmon	21
1987	Japan	Yellowtail	15
1988	Norway and Sweden	Salmon	5
1989	Norway	Salmon, rainbow trout	4.5
1990	United States	Salmon	4–5
1991	United States	Oyster	15–20
1992	Republic of Korea	Farmed fish	133
1996	United States	Oyster	24
1998	Hong Kong	Farmed fish	32

major and extensive red tide outbreak occurred along the coast of Hong Kong and south China, covering an area of more than 100 km^2. Over 80% (3400 ton) of mariculture fish were killed, and the total loss was over US$40 million. Red tides of *Chatonella antiqua* have caused massive killing of farmed fish, mostly yellowtail in Seto Inland Sea of Japan. A similar event was reported from Antifer, France where the entire stock of a fish farm perished after a red tide, dominated by *Exuvialelola* sp. producing a PSP toxin. Phytoplankton blooms can have major economic impacts on fisheries, aquaculture and tourism (Table 5).

5. Conceptual model for environmental management and restoration

Despite the obvious importance of the linkage between pollution and aquatic production of fish and other commercial species, the literature remains largely anecdotal. Enough baseline information is not available as to the extent of pollution as well as the specific effects in different regions of the world. Griswold (1997) defined the obstacles in identifying relationships between pollution and fish populations as (1) insufficient data, (2) insufficient use of existing data, (3) lack of analytical tools, (4) few direct examples of pollution effects, and (5) institutional constraints. The need for rehabilitation implies that the area under consideration has been altered or degraded in a way that conflicts with defined management or conservation objectives. Hence, rehabilitation is often the result of competition for resource use. It is essential that goals be defined as a first step in the rehabilitation process.

Protection of the aquatic environment from pollution is the most essential theme of environmental management. Based on, and guided by, ecological knowledge, environmental management comprise the judicious and responsible application of scientific and technological knowledge with the aim to achieve the maximum degree of ecosystem protection commensurate with the highest sustainable quality of living for mankind (Kinne, 1984). Problems in dealing with environmental pollution were identified as poor communication between scientists and managers, weak institutional structures and manpower capabilities, lack of sectoral integration and approach to environmental management, lack of cooperation between public and private sectors etc. (Williams, 1996). The management approach may be highly variable depending upon the ecosystem and the degree of deterioration and management problems and goals. However, environmental management approach should involve the following general points (Williams, 1996):

- identifying environmental and economic values of waterbodies;
- establishing objectives and goals for protecting of a particular waterbodies;
- establishing water quality management strategies and standards considering the qualities of all input waters and effluent waters as well as the catchment management;
- developing monitoring and surveillance program to ensure standard water quality for environmental safety;
- gathering scientific information on all aspects of pollution including effects at all levels;
- developing cooperation between all levels of involvement including general people and stakeholders;
- reviewing, amending and formulating local, national, regional and international plans and developing local, national, regional and international cooperation.

To the above points, Kinne (1984) added the following:

- long-term ecological research;
- worldwide international cooperation; and
- adequate interpretation and transposing of scientific knowledge into legislation and effective control measures.

The conceptual model (Fig. 12) should, therefore, have three essential components; the main component, the management body, supported by research, and monitoring and evaluation. Information on the environmental features is the primary to formulate subsequent research and management needs. Suggestions

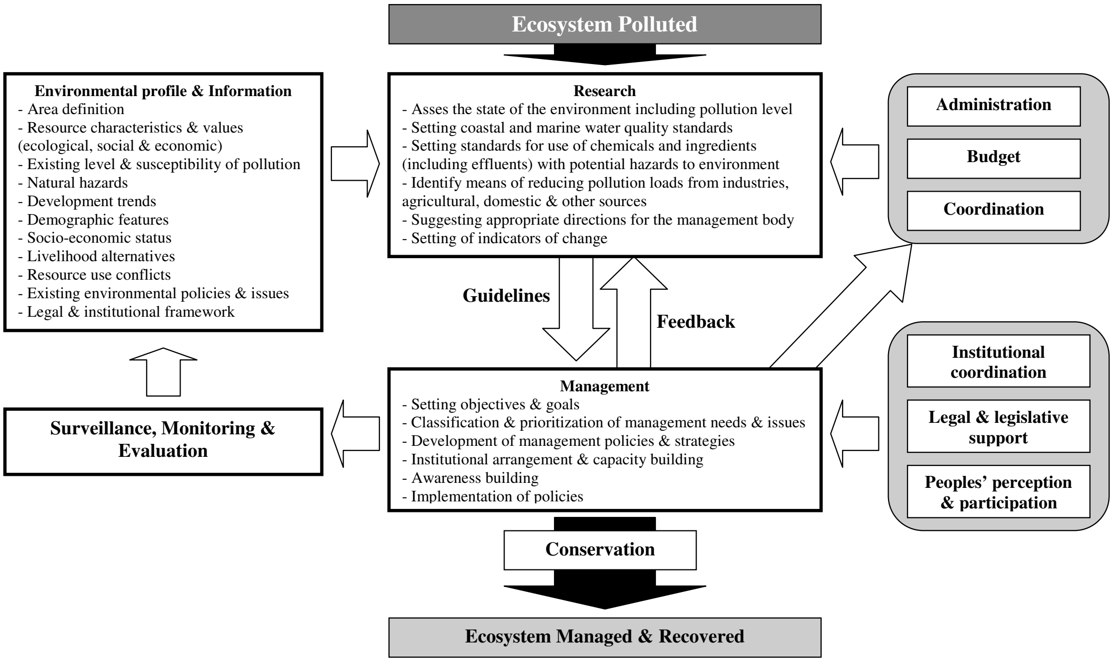

Fig. 12. Conceptual model for different components of management of coastal and marine pollution.

concerning the key points for managements as well the management strategies come from an extensive and effective research and baseline information. The management component must have the capacity to effectively identify objectives, classify the issues, prioritize management needs and formulate management plans. For a successful management, effective coordination with related departments/sectors and institutions (e.g., department of industry, agriculture, forest, social affairs, law etc.) is necessary to overcome management related problems such as land use conflicts and to have legal and legislative supports. The research and management components should be closely related, i.e., the information obtained through research will be used by the managers to formulate management directions and research component will use feedback information from the management component to formulate further research plans.

Environmental pollution cannot be limited by national territorial boundaries. However, effective environmental management on an international scale was considered rarely. Prior to 1972, the crash of some seabird populations caused by DDT, outbreaks of Minamata disease in Japan from mercury-contaminated seafood, and the *Torrey Canyon* and other oil spills focused particular attention on pollution issues. Policy responses included bans on production and use of some substances, regulations to reduce discharges, and the prohibition of ocean dumping, as well as a significant scientific effort to improve the status of knowledge about these pollutants. These responses are enshrined in a number of international agreements, including the 1972 London Dumping Convention and its 1996 Protocol, the 1989 Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and their Disposal, and the 1995 Global Program of Action for the Protection of the Marine Environment from Land-based Activities.

The reasons for restoration, the goals as well as the success to be gained are case-specific, and are, therefore, depends on particular fishery and the degree to which damage has been caused. One of the major problems in fishery restoration is to quantify the damage caused and to distinguish the role of pollution in the damage both of which are important for the fishery biologists as well as managers to select effective tools for restoration. Another important question in fishery restoration is to what extent the fishery managers can play role to protect their fishery from pollution? The institutional and legal settings in most nations are such that the fishery managers can, in fact, do little even if pollution is identified as the major cause for fishery decline. They can only manipulate their fishery, e.g., gear management, stock enhancement etc. However, as the pollution continues, degradation of fishery also continues. Collins et al. (1998) proposed that although the damage caused by acute pollution to fish stock is followed by a rapid recovery of the stock, the effects of chronic pollution is long-lasting. Although withdrawal of fishing can result in partial recovery of the stock, this may bring about changes in the stock structure by increasing the proportion of smaller size groups in the stock. Therefore, the need for multidisciplinary approach into the effects of pollution on fish stocks becomes evident for best

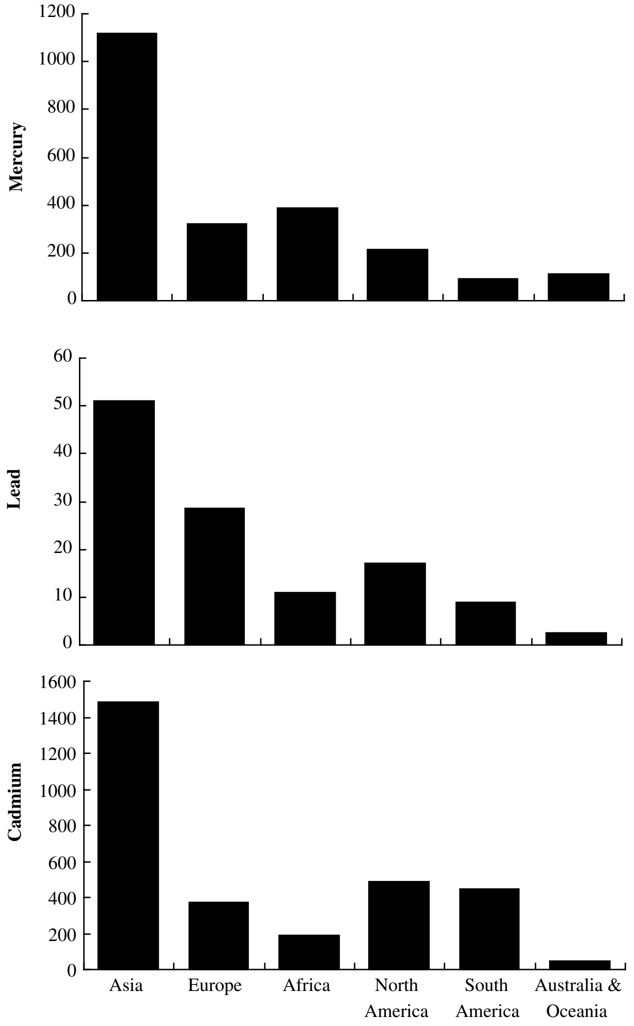

Fig. 13. Regional contribution of anthropogenic heavy metal emissions into the coastal and marine environment (AMAP, 2002).

management and economic gain. At the same time, the polluting bodies should be equally responsible for control and management of pollution.

It was believed that the industrially developed nations produce most of the pollution loads in coastal and marine environments—a scenario of the middle of 19th century when maximum development took place. However, the industrially developed countries are those which are usually characterized by most waste treatment and safest disposal facilities and also by environmental management systems. Therefore, these countries are less likely to produce critical pollution loads. Recent trends suggest that the least developed and the developing nations are more likely to produce threshold levels of environmental pollution due to their poor capacity to treat or recycle waste, poor legislation and regulation and poor management and protective measures. For example, anthropogenic emission of major heavy metals in coastal and marine environment in Asia (mainly dominated by developing nations) is, by several orders of magnitude, higher than Europe, North America and Australia (Fig. 13). This issue is very important because least developed and developing nations comprise the major part of the world (majority of the Asia, Africa and Latin America) and much of the world's future development is likely to take place in these nations. Unfortunately, neither the issues of the developing nations have been considered critically nor they have effective representation in global environmental protection and management programs.

6. Conclusion

The problems of aquatic pollution are likely to exacerbate and pose significant ecological risk/public health risk in the coming years, especially in developing countries. Coastal and marine pollution has already caused major changes in the structure and function of phytoplankton, zooplankton, benthic and fish communities over large areas including impacts on public health. Of particular interest is the impact of pollution caused to fisheries and other commercial use of coastal and marine habitats. Most of the world's important fisheries have now been damaged to varying extent; situations are even more critical in those fisheries that are already overexploited or otherwise vulnerable and, therefore, deserve immediate attention. Effective and sustainable management of coastal and marine environment should be initiated from local to international and global scale to ensure a sustained and best possible utilization of the resources for broader interest of mankind.

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