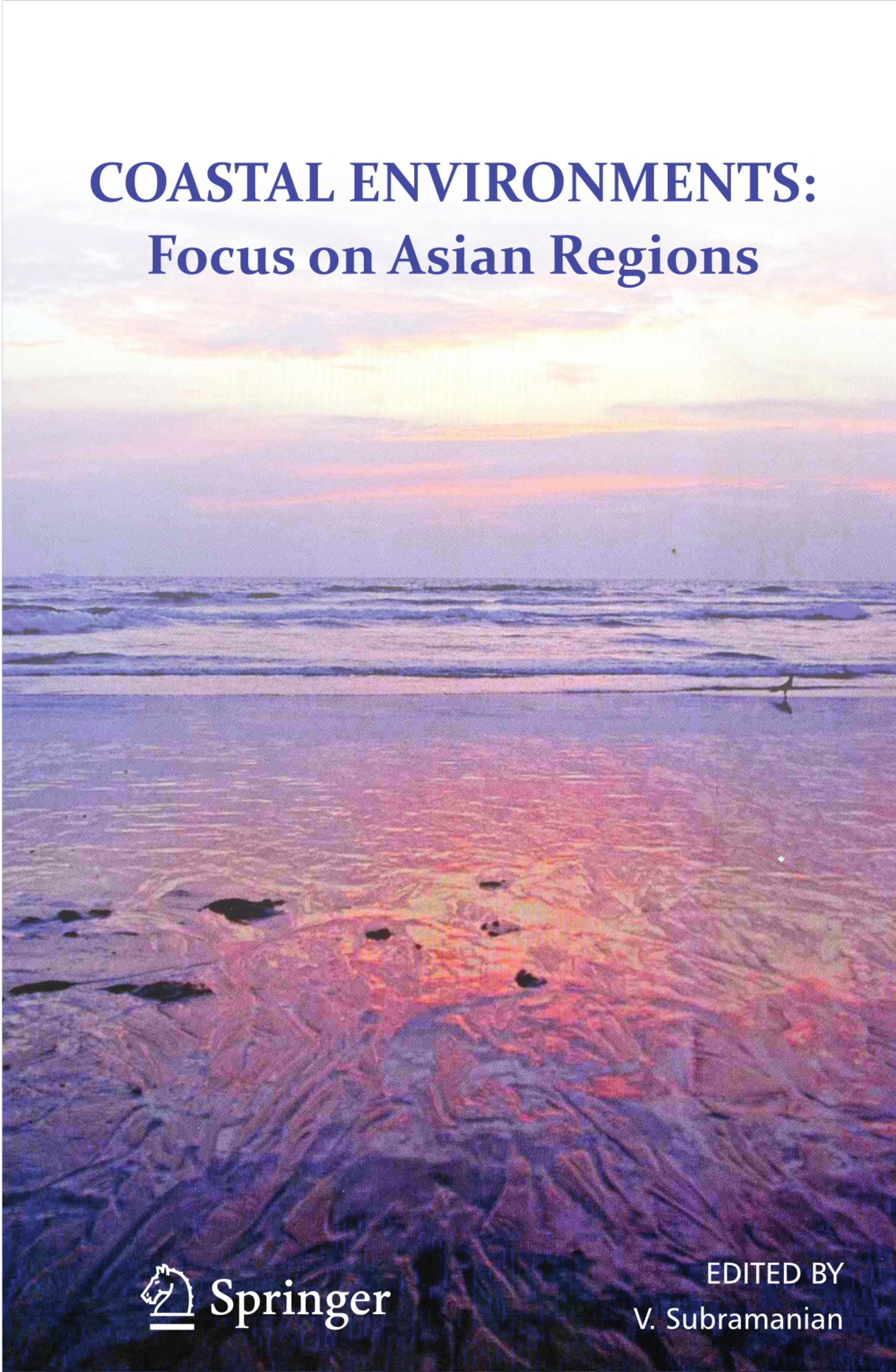
COASTAL ENVIRONMENTS:
Focus on Asian Regions



EDITED BY
V. Subramanian

Springer

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Preface

Today, globally approximately three billion people live within 200 kilometres of a coastline. By 2025, this figure is likely to double. Much of Asia's rapid population and economic growth is occurring in large coastal cities that are at high risk from sea level rise and climate change. The coastline of the Asian continent is about one fourth of the coastlines of the world. In general, with the exception of India, the bulk of Asia's population is coastal or near-coastal. Of the region's collective population of over 3.5 billion, (60%) 2.1 billion live within 400 kilometres of Asian coast. Indonesia and Vietnam are two typical examples of Asia's population shift from the hinterlands to coastal areas. Vietnam's and Japan's population is almost all coastal.

The average population density in Asian coastal areas is about 80 persons per square kilometre, that is twice the world's average population density. Thus Asian coastal areas are under threat. In a growing number of countries, coastal zone managers are adopting integrated, multidisciplinary approaches to resource management that incorporate the perspectives of all stakeholders, including governments, the private sector, non-governmental organizations (NGOs), and individuals. On the academic front, several institutions and individuals in Asia are working on practically all aspects of coastal science.

This book makes an endeavour to project some of the latest academic activities being carried out by individual experts in Asia. Topics chosen are very relevant in the context of pressures on Asian coastal population as well as those that are scientifically important for understanding the impact of climate change.

Experts who have authored individual chapters in this book are well known in their own sphere of expertise and care has been taken to project the diverse nature of academic research in Asia with a focus on Asian coasts. All manuscripts have been peer reviewed and revised before acceptance for the book. In fact one of the authors for chapter 2 (RR) is the current chairperson of SSC (Scientific Steering Committee) of LOICZ (Land Ocean Interaction in Coastal Zone) as a part of IGBP activities. The editor of this book is also the Chief Editor of the *Asian Journal of Water, Environment and Pollution* (AJWEP).

The editor has taken care to include topics that are scientifically as well as socially relevant to sustainable coastal management in the context of their vulnerability to several natural and man-made hazards. High pressure regions such as the south Asian and southeast Asian coasts have been adequately covered in this book. Diversity of topics covered is the hallmark of this book.

February 29, 2012

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Contents

1

Coastal Environment of Asia

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Abstract: Asian coast is under threat from two opposing directions – nature as well as man-made. Natural disasters along coastal regions affect a very large number of countries in Asia; at the same time, due to population pressure, several types of human impact on water, soil and sediments can be seen in many countries. The coastal marine life is also endangered, of course at different levels in different regions of Asia. Researchers have evolved a system of hazard zones along coasts to delineate the regions in terms of degree of vulnerability at any given time. Due to chemical pollution, both in south and southeast Asia, the biological system is in danger of severe domino effect almost mimicking the Minamata mercury episode more than half a century ago.

Key words: Pesticides, metals, hazards, erosion, carbon.

INTRODUCTION

A coastal zone has been variously described. One possible definition from the US Commission on Marine Science, Engineering & Resource is "the coastal zone represents that part of the land affected by its proximity to the sea, and that part of the ocean affected by its proximity to the land".

The definition by the Land Ocean Interaction in the Coastal Zone (LOICZ) Science plan: "the coastal zone as extending from the coastal plains to the outer edge of the continental shelves, approximately matching the region that has been alternately flooded and exposed during the sea-level fluctuations of the late Quaternary period". This second definition is of the coastal domain from 200 m above to 200 m below sea levels which occupies 18% of the surface of the globe; it is the area where around a quarter of global primary

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productivity occurs and supplies approximately 90% of world fish catch. It is also a highly vulnerable region since where around 60% of the human population lives and two thirds of the world cities with population of over 1.6 million people are located.

On the other hand, the coastal ocean accounts for 8% of the ocean surface but contributes to less than 0.5% of the ocean volume. Around 14% of global ocean production takes place in this ocean with up to 50% of global oceanic denitrification and 80% of the global organic matter burial along with 90% of the global sedimentary mineralization and 75-90% of the global sink of suspended river load and its associated elements/pollutant and most important being the fact that in excess of 50% of present-day global carbonate deposition takes place in this region.

The coastal seas on the other hand undergo cumulative changes which, though localised, have global impact. An example is the eutrophication of coastal waters leading to changes in carbon flow and its sequestration and the effect on the global carbon cycle. The other major problem is the complexity of biological systems. Even in a localised environment, the species are numerous, the numbers are large, and there are different metabolic rates, life styles and life expectancies. Environmental changes will affect species differently and thus their effect on the biogeochemical cycles will alter. Biological systems have a slowness of response to chronic low levels of external forcing, and this buffering capacity delays or, in some cases, masks the eco-system response. There are urgent needs to be addressed at the regional and local scale. The decline in fisheries, the increasing pollution by heavy metals, PCBs and pesticides are local effects produced by anthropogenic influence. However, not enough data exist to relate these to changes in the earth system. Such effects are however keenly felt and must be dealt with scientifically to ameliorate local fallout.

PHYSICAL PROCESSES OPERATING ALONG THE COAST OF SOUTH ASIA

Coastal zones are very important for Asia because rapid industrialisation and urbanization take place along the coasts, and protein from marine fisheries makes up a significant percentage of the region’s total protein consumption. Changes in the hydrological and nutrient cycles will manifest their effects in the coastal zones, and with the enclosed nature of regional seas, the impacts to the continental shelves are likely to be very significant. Also, the seas of Southeast Asia are parts of the Pacific warm pool which affects the trade winds and monsoons, and generates typhoons and hot towers which are very efficient transport mechanisms for greenhouse gases and aerosols which significantly affect global atmospheric chemistry. The role of extreme events (tropical storms, droughts and floods, earthquakes, tsunamis, volcanic eruptions, etc.) is also very important here considering their relatively high frequency of occurrence and the area's high population density.

Only in the last decade has there been a general understanding of the large-scale dynamics of the coastal circulation in the Arabian Sea and the Bay of Bengal. Large-scale currents along the outer shelf and beyond, around India, reverse seasonally with the monsoon winds. The currents form a continuum from the northern Bay of Bengal to the northern Arabian Sea.

What influences currents on the inner shelf? It is expected that large scale currents, tides, winds and river run off play important roles. Tides, winds in season (and sea-breezes), and river run-off would be the major influences nearest the coast. In the few instances of direct current measurements, the cross-shore components are tidal (towards shore on flow and away on ebb). The along-shore component would vary with season and location and could be due to the seasonal coastal currents.

Indian coastal waters are clean and well oxygenated with no detectable spread of "hot-spot" influence. The large rivers on the east coast also play a role in confining along shore pollutant transport. Their large run-offs acting as barriers to close to coast transport of pollutants and sediments. It is important to understand shelf and estuarine (of which there are a very large number of varying sizes) circulation, so that through effective modelling pertinent information is available to decision makers on movement of pollutants, sediments and offshore hazards (oil spills).

South Asian coasts have a large variety of sensitive eco-systems. Sand dunes, coral reefs, mangroves, seagrass beds and wet lands are some that deserve special mention. Some of these are the spawning grounds and nurseries of a number of commercially important fishes, gastropods and crustaceans. A critical feature of these ecosystems are the variety of bioactive molecules that they host. Recent mining of organisms from the tidal and inter-tidal zone have revealed large numbers of molecules with obvious application for human health and industrial applications. This could be the most commercially important aspect of the Coastal Zone. Molecules that show bioactivity from one ecosystem may not show the same activity, or level of activity, when mined from a different locale or different season. This feature alone should be reason enough for the protection of all such ecosystems, and not only representative isolated units in protected areas/parks.

Considering that Indian waters are of a good quality and that pollutant sources remain relatively confined, the protection of sensitive environments, with adjacent buffer zones should be promptly notified and enforced. Losses of such areas are losses to the common good and future generations.

Sand dunes seem to be ecosystems that are most often destroyed, probably because their place in the scheme of dynamic coastal morphology, is not obvious. Suffice to say that dunes are the reserves that nature stores, dissipates energy and moves on.

Coastal Erosion is a natural process rather than a natural hazard; erosion problems occur when people build structures in the coastal zone. Any shoreline construction causes change. Stabilization of the coastal zone through engineering structures protects the property of relatively few people at a larger general expense to the public. Engineering structures designed to protect a beach may eventually destroy it. Once constructed, shoreline engineering structures produce a trend in coastal development that is difficult if not impossible to reverse. In Asia, due to the population pressure, construction and other activities take place along their vast coastal network often without suitable safety net in place so that the safety of coastal border become vulnerable from time to time. This fact is compounded by the fact that all countries now are seriously exploiting coastal regions for important energy resource namely oil and gas.

Petroleum resources are not easy to find, nor are they often located in convenient places for oil or gas to be extracted, processed and sent to be used by the community. Exploring for oil and gas under the sea bed, and the production activities which follow a successful exploration programme, all involve some risks and potential impacts on the marine environment. Clearly identifying these risks and impacts and developing detailed management plans to avoid, prevent or minimise them is a vital and integral part of planning these exploration and production activities for safe coastal health.

The coastal areas are also the place where natural disasters are also experienced. The entire Asian coast has from time to time experienced different types of natural and man-made disasters. To name a few, the Japan Tsunami and earth quake followed by nuclear plant explosion, the 2004 Tsunami of Indonesia, Thailand, India and Sri Lanka, volcanic activity in Indonesia from time to time are some of the major disasters in recent times. The recent floods in Bangkok and inland movement of sea water is a case in point where damages could be serious. The entire east coast of India, the Gujarat coast along the west coast and the islands of Lakshadweep and Andaman and Nicobar face frequent cyclonic conditions which sometimes cause large scale destruction of life and property. While it is agreed that no human interference is possible to control such an event but precautionary measures such as coastal area planning for locating coastal communities in safer areas, protecting and propagating the natural systems such as mangroves, coral reefs, shelter belt plantations, along with installation of early warning systems, timely evacuation and relief measures can minimize loss of life and property to a large extent. Most sensitive to coastal pollution is the coral reefs in many regions of the Asian coastal land mass. It is well known that coral reefs around the world are facing serious problems, as can be seen in Figs 1a and 1b.

The reef—an indicator of the health of the ocean—is facing more than 50% serious survival problems in south and southeast Asian region.

Major observed threats to the world's coral reefs include extreme climate events, unsustainable tourism practices, poison fishing for ornamental fish,

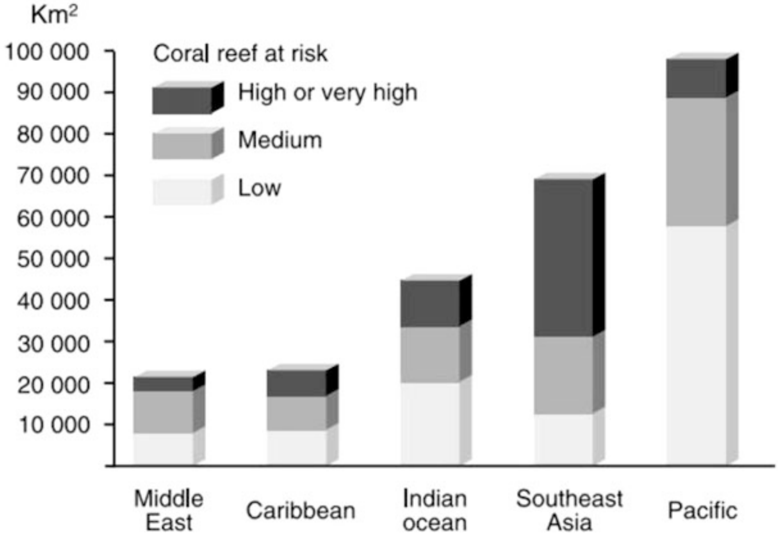

Fig. 1a: Coral reefs at risk from human activities.

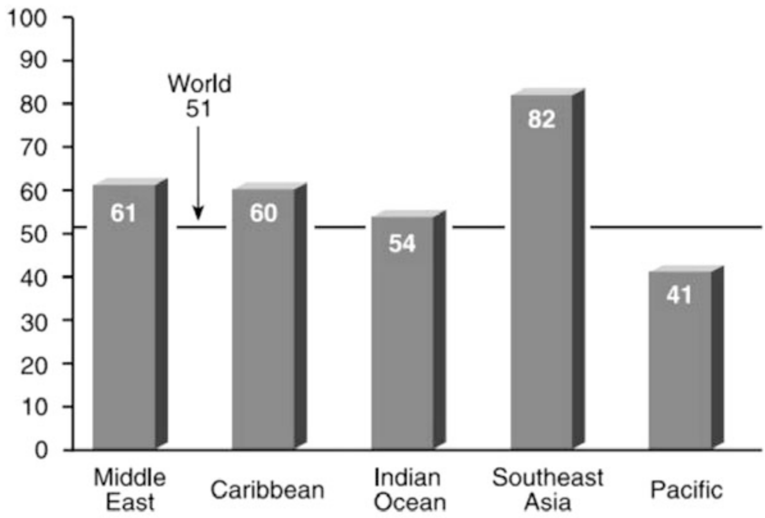

Fig. 1b: Percent of the region at risk.

Note: Reefs classified as low risk are not considered in imminent danger.
Source: Lauretta Burke et al. (1998), Reefs at Risk: A map-based indicator of threats to the world's coral reefs, World Resources Institute, Washington D.C.

overexploitation by fisheries, sedimentation, coral harvesting, dynamite fishing and pollution (not in order of priority). Figure 2 explains which activities or conditions are affecting various coral reefs throughout the world. Figure 2 also shows the percentage of reefs that are threatened by over-exploitation, coastal

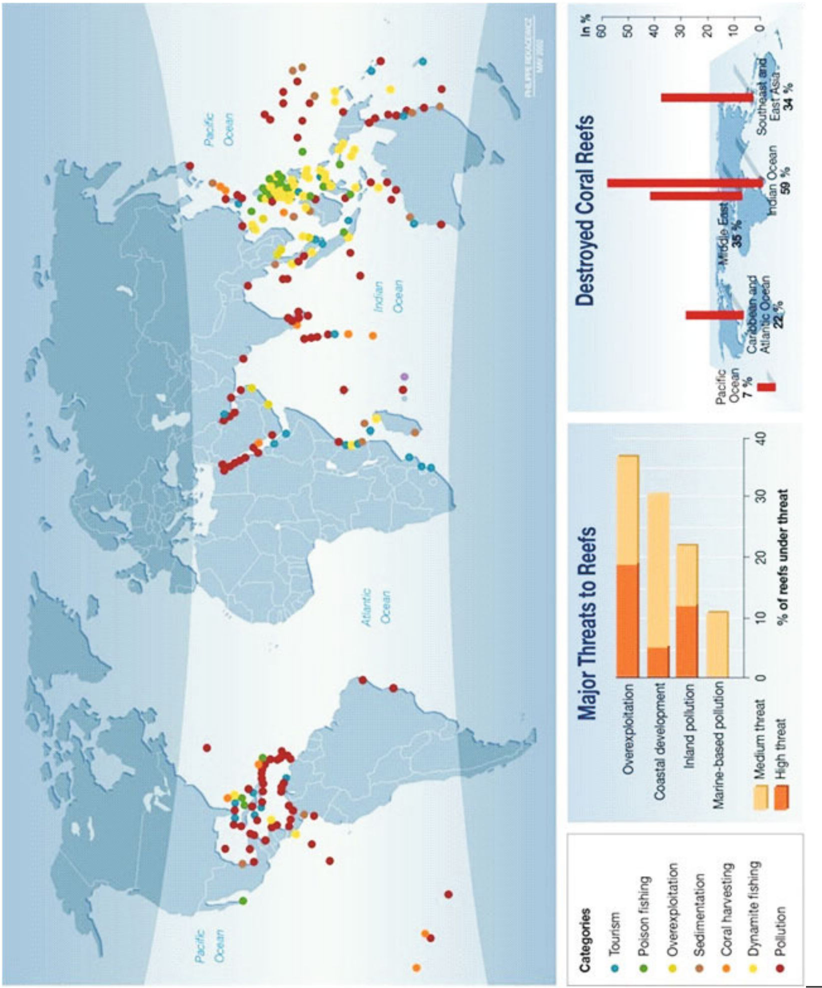

Fig. 2: Threats to the world's coral reefs.

development, inland pollution and marine pollution, and the degree to which they are under threat. Figure 1b shows the percentage of coral reefs that have been destroyed in the world's major regions. Studies in the Philippines and Indonesia estimate that the damage to coral reefs from logging-induced sedimentation greatly exceeds the economic benefits of logging, according to an UNEP report (UNEP Report, 2006).

In addition to coral reefs, the general health of coastal waters face serious threat in terms of quality due to discharge of chemicals in southeast and South Asian coasts. The fast growing economies and populations of East Asia are putting the region's marine ecosystem under increasing stress. A new study finds 90 per cent of Asia's sewage being discharged into the marine environment waters without treatment, threatening fisheries, mangrove forests, coral reefs and coastal wetlands. Sewage treatment access across Asia varies widely—from roughly 60 per cent of Japan's population to 15 per cent in Mumbai, India, to about six per cent in Karachi, Pakistan. Discharges from many big industrial plants situated along the coast is also a threat and is a "common feature" in much of South Asia. In 2001, close to 80 red tide events occurred affecting 15,000 square kilometres of coastal waters. Two thirds of the world's total sediment transport to the oceans occur in South and South East Asia, and deforestation is adding to soil erosion and sediment loads in waterways.

Coastal erosion is widespread, between a fifth to a quarter of sea grass beds in Indonesia, Malaysia, the Philippines and Thailand have been damaged as a result of impacts including clearance for commercial seaweed farms, pollution, sedimentation and dredging.

The SE Asian region, that spans from Vietnam to Myanmar, contains 34% of the world's coral reefs, possibly a third of the worlds mangroves and vast areas of seagrass. But this region also contains a rapidly burgeoning human population that is creating an ever worsening marine pollution problem. Pollutants, originating from both land and sea, are responsible for significant lethal and sub-lethal effects on marine life. Pollution impacts all trophic levels, from primary producers to apex predators, and thus interferes with the structure of marine communities and consequently ecosystem functioning. Here we review the effects of sediments, eutrophication, toxics and marine litter. All are presently major concerns in Southeast Asia (SE Asia) and there is little indication that the situation is improving. Approximately 70% of SE Asia human population lives in coastal areas and intensive farming and aquaculture, rapid urbanisation and industrialisation, greater shipping traffic and fishing effort, as well as widespread deforestation and near-shore development, are contributing towards the pollution problem. As SE Asia encompasses approximately 34% of the world's reefs and between a quarter and a third of the world's mangroves, as well as the global biodiversity triangle formed by the Malay Peninsular, the Philippines, and New Guinea, the need to reduce the impacts of marine pollution in this region is all the more critical. Rapid urbanization is transforming Asia. Eighty-seven Asian cities have more than a

Oil ♥
DDT, Organochlorine, Pesticide ♣
Heavy Metals ♠
Organic, Biological Pollutants and Fertilisers ♦
Silt ●

Fig. 3: The coastal region in Southeast Asia vulnerable due to several sets of human activities.

million inhabitants. By 2005, more than half the population of East Asia will live in cities. In South Asia, the urban population will overtake the rural population by 2025.

Not to be outdone, the South Asian coast is equally polluted due to discharge of a large amount and types of chemical wastes as shown in Table 1 (after Zigde, 1999).

Table 1: Pollution in South Asian coast

Sr. No.	*Input/pollutant*	*Quantum, annual*
1.	Sediments	1600 million tonnes
2.	Industrial effluents	50×10^6 m^3
3.	Sewage—largely untreated	0.41×10^9 m^3
4.	Garbage and other solids	34×10^6 tonnes
5.	Fertilizer—residue	5×10^6
6.	Synthetic detergents—residue	130,000 tonnes
7.	Pesticides—residue	65,000 tonnes
8.	Petroleum hydrocarbons (Tar balls residue)	3500 tonnes
9.	Mining rejects, dredged spoils and sand extractions	0.2×10^6 tonnes

More specifically for the Mumbai coast, the pollution load is very high as can be seen in Table 2.

Table 2: Selected contaminants entering coastal waters of Mumbai through domestic waste water

Contaminant avg.	*Concen., ppm*	*Load, kg/day*
Dissolved solids	1800	3.6×10^6
Suspended particulate matter	235	4.7×10^5
Biological Oxygen Demand	280	5.6×10^5
Nitrogen	35	7×10^4
Phosphorus	6	1.2×10^4
Manganese	0.7	1400
Iron	2.1	4100
Cobalt	0.03	20
Nickel	0.08	160
Copper	0.1	200
Zinc	2.3	4600
Lead	0.05	100

Fluvial sediment flux from Southeast Asia and Oceania accounts for 70% of the world flux although they account for only 15% of the land area draining into oceans (Silvbiski and Khittner, 2011). The South Asian region further contributes over a billion tonnes of sediments to the adjoining coastal oceans. Of importance to the region are the implications of such changes to sustainable development of marine, coastal and terrestrial resources. Key questions include: How do changes to coastal ecosystems and to catchment areas inland affect the long-term productivity of the coastal zones? How do the frequency and patterns of resource exploitation affect biodiversity, and what are the resultant consequences for ecosystem functioning? There is no doubt that the South and the Southeast Asian environment is changing at an accelerating rate, and these changes need to be monitored and analyzed so that people and institutions can devise appropriate management strategies to maintain both production and environmental amenities.

It is important hence to understand in detail the biotic control of water, gas and energy exchanges between the surface and the atmosphere, and the composition, structure and productivity of the land and coastal zones after modification. A crucial aspect of biogeochemical cycling is the transport of dissolved and suspended materials from upland areas through coastal zones to the sea.

Thus, marine pollution includes a range of threats from land-based sources, oil spills, untreated sewage, heavy siltation, eutrophication (nutrient enrichment), invasive species, persistent organic pollutants (POPs), heavy metals from mine tailings and other sources, acidification, radioactive substances, marine litter, overfishing and destruction of coastal and marine habitats. Overall, good progress has been made on reducing persistent organic pollutants (POPs), with the exception of the Arctic. Oil discharges and spills to the seas have been reduced by 63% compared to the mid-1980s, and tanker accidents have gone down by 75%, from tanker operations by 90% and from industrial discharges by some 90%, partly as a result of the shift to double-hulled tankers (UNEP, 2006; Brown et al., 2006). Some progress on reducing emissions of heavy metals is reported in some regions, while increased emissions are happening in others. Electronic waste and mine tailings are included amongst the sources of heavy metal pollution in Southeast Asia. Sedimentation has decreased in some areas due to reduced river flows as a result of terrestrial overuse for agricultural irrigation, while increasing in other regions as a result of coastal development and deforestation along rivers, water sheds and coastal areas, and clearing of mangroves (Burke et al., 2002; Brown et al., 2006; UNEP, 2006).

A major threat beyond over-exploitation of fisheries and physical destruction of marine coastal habitats by dredging, is undoubtedly the strong increase in coastal development and discharge of untreated sewage into the near-shore waters, resulting in enormous amounts of nutrients spreading into the sea and coastal zones (Brown et al., 2006; UNEP, 2006). This, together with changes in salinity, melting sea ice, increased sea temperatures and future changes in sea currents may severely affect marine life and their ability to recover from extreme climatic events.

Together with agricultural run-off to the sea or into major rivers and eventually into the ocean, nitrogen (mainly nitrate and ammonium) exports to the marine environment are projected to increase at least 14% globally by 2030 (UNEP, 2006). In Southeast Asia more than 600,000 tonnes of nitrogen are discharged annually from the major rivers. These numbers may become further exacerbated as coastal populations are depicted to increase from 77 people/km^2 to 115 people per km^2 in 2025. In Southeast Asia, the numbers are much higher and the situation more severe. Wetlands and mangroves are also declining rapidly, typically by 50-90% in most regions in the past four decades (UNEP, 2006). In addition to nitrogen, the carbon discharge by rivers to oceans in South Asia also is a serious quality issue in terms of dissolved and particulate carbon. Table 3 summarises the river-borne carbon in South Asian region. Also, it will severely exacerbate the effects of extreme weather and the productivity of coastal ecosystems to supply livelihoods and basic food to impoverished. Hence, the poor management of sewage not only presents a dire threat to health and ecosystems services, it may increase poverty, malnutrition and security for over a billion people (UNEP, 2006).

Table 3: Total carbon, inorganic carbon and organic carbon in Indian rivers (all in %)

River	*TC*	*TOC*	*TIC*
Sabarmati	0.69		
Mahi	1.63	0.10	1.54
Narmada	1.03	-	-
Tapti	0.71	-	-
Yamuna	0.15	0.05	0.11
Godavari	1.18	0.10	1.09
Krishna		1.55	
Ganges-Brahmaputra-Megna	0.45	0.24	0.33
Chaliyar	0.48	0.28	0.20
Kadalundi	1.09	0.90	0.19
Bharathapuzha	0.22	0.05	0.17
Chalakudi	0.44	0.11	0.33
Periyar	1.36	1.09	0.28
Muvattupuzha	2.15	1.95	0.20
Manimala	0.39	0.14	0.25
Pamba	0.24	0.12	0.12
Ackankovil	0.31	0.13	0.19
Kalada	0.27	0.10	0.16
Mandovi		1.00	
Brahmaputra (India)	1.53	1.14	0.40
Brahmaputra (Bangladesh)	2.01	1.53	0.48

POPULATION PRESSURE IN COASTAL AREAS

Population along the coast in Asia is a serious issue in terms of stress to the water body, vulnerability and food security. Figure 4 compares the population in various coastal cities in the world.

The graphic shows the proportion of the population that lives within 100 km of the coast, for each of the world's nations. It also shows the locations of selected coastal cities with a population of more than one million people. Coastal vulnerability can be thus viewed as a combined effect of man-made as well as some natural situations due to geological set up of Asia as indicated in Table 4.

The combination of wind-driven waves and the low-pressure of a tropical cyclone can produce a coastal storm surge—a huge volume of water driven ashore at high speed and of immense force that can wash away everything in its path. A massive storm surge left 300,000 people dead in the coastal wetlands

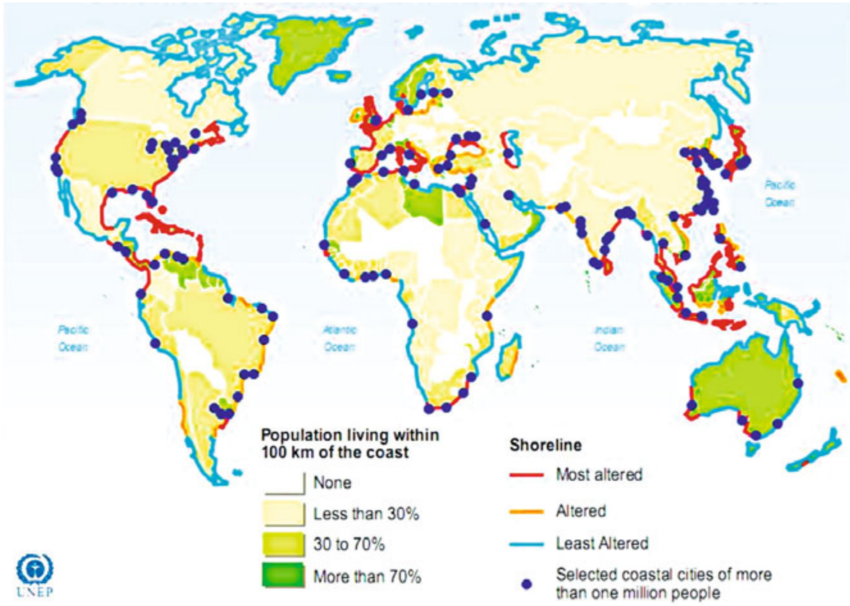

Fig. 4: Coastal population and coastal degradation.

Table 4: Relative intensity of geology-related hazards faced by some countries in Asia

Country	*Earthquakes*	*Tsunamis*	*Volcanoes*
Bangladesh	L	L	-
China	S	L	-
India	M	L	-
Indonesia	S	L	M
Iran	S	-	-
Nepal	M	-	-
Pakistan	S	-	-
The Philippines	S	L	M
Thailand	L	-	-
Viet Nam	L	-	-

S = severe M = moderate L = Low

Source: Asian Disaster Preparedness Center

of Bangladesh in 1970. About 80 tropical cyclones form every year. Their names depend on where they form: typhoons in the western North Pacific and South China Sea; hurricanes in the Atlantic, Caribbean and Gulf of Mexico, and in the eastern North and central Pacific Ocean; and tropical cyclones in the Indian Ocean and South Pacific region.

According to Neil Adger et al. (2005), natural hazards are an ongoing part of human history, and coping with them is a critical element of how resource use and human settlement have evolved. Globally, 1.2 billion people (23% of the world's population) live within 100 km of the coast, and 50% are likely to do so by 2030. These populations are exposed to specific hazards such as coastal flooding, tsunamis, hurricanes and transmission of marine-related infectious diseases. For example, today an estimated 10 million people experience coastal flooding each year due to storm surges and landfall typhoons, and 50 million could be at risk by 2080 because of climate change and increasing population densities. More and more adaptive responses will be required in coastal zones to cope with a plethora of similar hazards arising as a result of global environmental change. Coastal erosion, exacerbated by sea-level rise, also threatens vulnerable lands including deltas. In fact, many of Asia's largest cities, like the mega-cities analysed in this report, were built on such deltas and are consequently some of the most at risk to the impacts of climate change.

Hazards in coastal areas often become disasters through the erosion of resilience, driven by environmental change and by human loss in Bangladesh; in 1991 this resulted in over 100,000 deaths and the displacement of millions of individuals from widespread flooding. In many locations, environmental degradation such as land clearing, coastal erosion, overfishing, and coral mining has reduced the potential for economic recovery from the tsunami because of the loss of traditional income sources related to coastal ecosystems rich in biodiversity and ecological functions. An equivalent tropical typhoon that ravaged Bangladesh had reduced mortality associated with typhoons and flooding in the past decade through careful planning focused on the most vulnerable sectors of society.

COASTAL AND ENVIRONMENTAL VULNERABILITY IN ASIA

Vulnerability is an aggregate measure of human welfare that integrates environmental, social, economic and political exposure to a range of harmful perturbations. Quantifying vulnerability and resilience to climate change is an important exercise to predict, current and future scenario along Asian coasts. Swedish Environment Institute has formulated certain factors that are felt to be important in quantifying vulnerability:

"Sensitivity sectors—Settlement, Food, Health, Ecosystems, Water

Sensitivity Indicators: Coping and Adaptive Capacity sectors—Economics, Human Resources, Environment

Coping—Adaptive Capacity Indicators National Baseline Estimates and Projections of Sectoral Indicators, Sensitivity and Coping—Adaptive Capacity, and Vulnerability—Resilience Response Indicators to Climate Change"

Overall, the sustainability of our coast also depends on the total environmental problems on the inland regions. The significant component of coastal and regional sustainability can be quantified based on a few important aspects such as:

Environmental Systems: A country is more likely to be environmentally sustainable to the extent that its vital environmental systems are maintained at healthy levels, and to the extent to which levels are improving rather than deteriorating.

Reducing Environmental Stresses: A country is more likely to be environmentally sustainable if the levels of anthropogenic stress are low enough to engender no demonstrable harm to its environmental systems.

Reducing Human Vulnerability: A country is more likely to be environmentally sustainable to the extent that people and social systems are not vulnerable to environmental disturbances that affect basic human wellbeing; becoming less vulnerable is a sign that a society is on a track to greater sustainability.

Social and Institutional Capacity: A country is more likely to be environmentally sustainable to the extent that it has in place institutions and underlying social patterns of skills, attitudes, and networks that foster effective responses to environmental challenges.

Global Stewardship: A country is more likely to be environmentally sustainable if it cooperates with other countries to manage common environmental problems, and if it reduces negative transboundry environmental impacts on other countries to levels that cause no serious harm.

In a thought provoking article on processes that govern the environmental sustainability, the Stockholm Environment Institute has come out with a scale of 1 to 6 to quantify the relative vulnerability of our land including the coastal regions. In their publication (Ziervogel et al., 2006), they have classified many regions (see Fig. 5) on differential scale similar to earthquake scale: most vulnerable with a scale of 6 out of 6 covers such diverse regions as USA (scale of 5, may be due to extreme consumption based economy) or 2-4 (south and south east Asia including China due to population) or arctic region (scale of 6 out of 6) due to global warming effect.

Cities cover less than 1% of the planet's surface, and are home to around 50% of the world's population, and many of them see a rapid growth trend. Taken together, all cities and urban areas worldwide use 75% of the world's energy and are responsible for 75% of global greenhouse gases. The relative sensitivity of the 11 selected cities to climate change impacts is based on population, gross domestic product (GDP), and the relative importance of that city to the national economy. The adaptive capacity of the 11 cities by examining the overall willingness of the city to implement adaptation strategies were prepared by WWF (WWF, 2009).

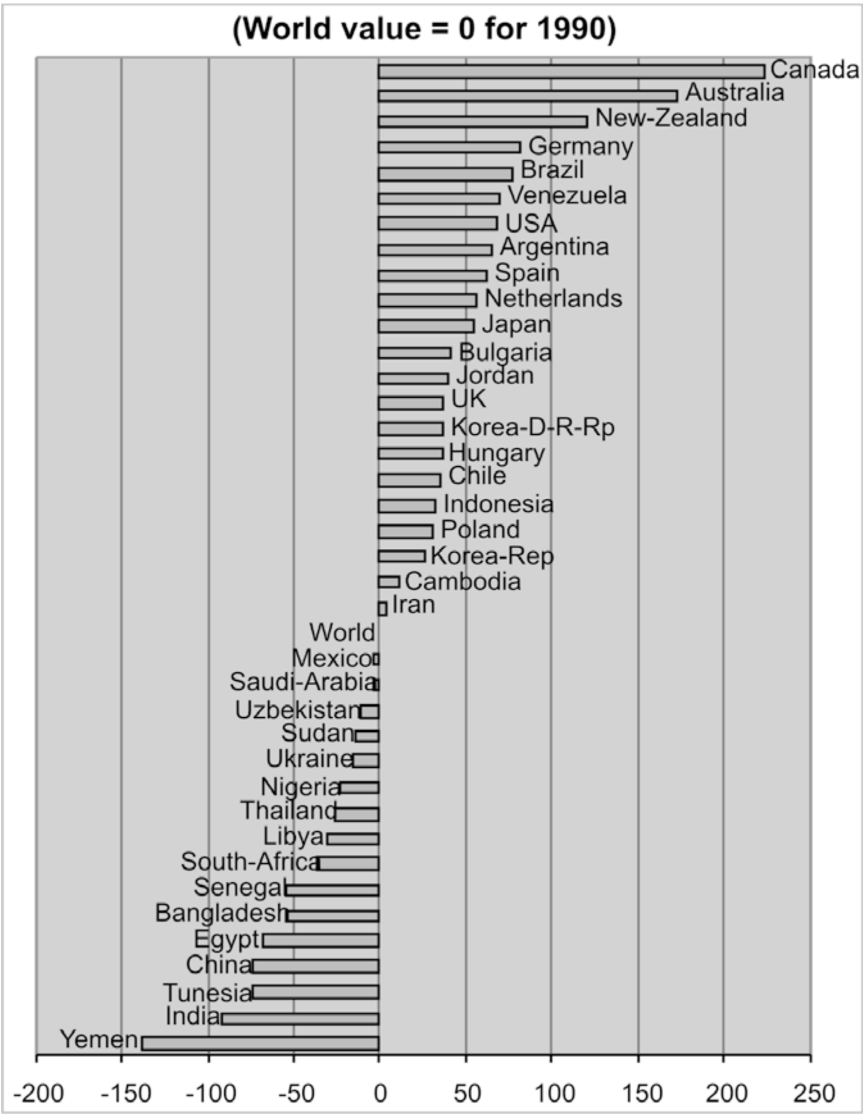

Fig. 5: World vulnerability.

Criteria compared for each city in WWF study:

1. Environmental exposure: Tropical cyclones, Storm surge, Sea level raise. Water flooding/drought
2. Socio-economic sensitivity
3. Population density (Gross Domestic Product), Contribution to GDP
4. Adaptive capacity
5. Existing examples
6. Per capita GDP

Accordingly, their study indexed cities with different degree of vulnerability on a scale of 10 (most vulnerable 10 to least vulnerable 1)

Overall vulnerability

9 Dhaka
8 Jakarta, Manila
7 Kolkata, Phnom Penh
6 Ho Chi Minh, Shanghai
5 Bangkok
4 Hong Kong, Kuala Lumpur, Singapore

Overall climate vulnerability

9 Manila
8 Dhaka, Ho Chi Minh, Shangai
7 Hong Kong
6 Jakarta, Kolkata
5 Bangkok
4 Phnom Penh, Singapore
3 Kuala Lumpur

Sensitivity Ranking: People, Assets and GDP under Threat

10 Jakarta
9 Shanghai
8 Dhaka
7 Manila, Kolkata, Bangkok
6 Hong Kong, Singapore
5 Kuala Lumpur

Inverse Adaptive Capacity

10 Dhaka, Phnom Penh
7 Jakarta, Manila, Kolkata
4 Bangkok
3 Ho Chi Minh, Kuala Lumpur
2 Shanghai
1 Hong Kong, Singapore

Asia is arguably among the regions of the world most vulnerable to climate change. Climate change and climatic variability have and will continue to impact all sectors, from national and economic security to human health, food production, infrastructure, water availability and ecosystems. The evidence of climate change in Asia is wide spread: overall temperatures have risen from 1°C to 3°C over the last 100 years, precipitation patterns have changed, the number of extreme weather events is increasing, and sea levels are rising. Because many of the largest cities in Asia are located on the coast and within major river deltas, they are even more susceptible to the impacts of climate change. In response, this report highlights the vulnerability of some of those cities—with the goal of increasing regional awareness of the impacts of climate change, providing a starting point for further research and policy discussions, and triggering action to protect people and nature in and around Asia's megacities from mega-stress in the future.

WAY FORWARD

India has initiated an exercise to map the hazard line along its coast that will assist in protecting the coastal communities and infrastructure from natural hazards such as cyclones, storm surges and tidal waves among others. The Survey of India in collaboration with the Ministry of Environment and Forests (MoEF) will map and delineate the hazard line along the coast. Based on the assessment, the coastal areas would be divided into high, medium and low erosion zones. Hazard-line mapping will cover the 5400-km coastline of Indian peninsula from West Bengal on one side to Gujarat on the other. After demarcation of the hazard line, it will give some picture as to which coastal areas are vulnerable to floods, cyclones and tsunami, which are annual phenomenon. Coastal erosion is a long-term phenomenon.

The mapping exercise, expected to be completed in four-and-half years, will benefit about sixty million people residing in the coastal areas and vulnerable to natural hazards.

On the academic front, Government of India has set up an exclusive coastal research institute in Chennai (National Centre for Sustainable Coastal Management, Ministry of Environment and Forests, Govt of India) with focus on:

1. Mapping (physical, coastal and social) vulnerability and tracking changes along the Indian coastline using the most modern geospatial technologies available in the country. This would be of immense benefit to the Ministry of Environment and Forests, to enable policy and enforcement decisions.

Mapping of shoreline changes, fishing space mapping, coastal land use, coastal structures and critically vulnerable coastal areas such as mangroves, coral reefs, sea grass ecosystems and other ecologically sensitive coastal ecosystems.

2. Enhancement of well-being of coastal livelihoods by providing energy security based on renewable systems, conservation of coastal and marine resources, addressing gender-based issues to enhance resilience, analyzing the consequences of sea level rise/climate change, changes in coastal fisheries, turning off freshwater flow to estuaries, causes and consequences in changes of human well-being.

3. Monitoring and assessment of critically vulnerable coastal areas (CVCA) through short and long term ecosystem assessment, participatory coastal and marine resources management, pollution impacts and coastal health monitoring, ecosystem services and ecological processes, cross-cutting: global change – interrelate social and natural elements and also evolve capacity building for coastal stewardship.

4. Ecology and vulnerability of islands by using disaster ecology approach for island vulnerability, provide scientific information for sustainable development of islands, pilot projects on energy and water security for the island communities.

Such a dedicated approach can become a trend setter for other Asian countries to organise their respective coastal regions in a sustainable way.

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Climate Change and Potential Impacts in Tropical Asia

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Abstract: The amounts of trace gases notably CO_2, N_2O and CH_4 have been increasing in the earth's atmosphere. Increased concentration of these gases leads to a warming of the Earth's surface and the lower atmosphere. The resulting changes in climate and their impacts such as sea level rise, coastal ecosystems etc, can be estimated without associating the origin of the warming to any one of these gases specifically. In this paper, an attempt has been made to review the processes involved in climate change and its effects on sea level rise and on the coastal ecosystems.

Key words: Climate change, tropics, Asia, hazards.

INTRODUCTION

In many studies relevant to tropical Asia, however, specific scenarios are not identified; in several cases, assumptions also have been made about the magnitude and timing of potential climate changes. Four other points are of special relevance: *First,* climate change represents an important additional external stress on the numerous ecological and socioeconomic systems in Tropical Asia that already are adversely affected by air, water, or land pollution, as well as increasing resource demands, environmental degradation, and non-sustainable management practices. *Second*, most of tropical Asia's ecological and socioeconomic systems are sensitive to the magnitude and the rate of climate change. They also have developed resilience through their long history of adaptation to environmental and cultural changes; identifying resilient features is a particular challenge. *Third*, tropical Asia's physical environment is extremely diverse, and traditional systems of land use are very closely adapted to these conditions. Such diversity has important implications for assessing the impacts

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of future climate change, which would vary greatly from area to area, depending not only on the climate change scenario but also on specific local conditions and changes in factors such as population and technology.

Finally, the potential impacts of climate change in tropical Asia rarely have been quantified. The results of impact studies usually are qualitative and often have been directed towards identifying the sensitivities of specific systems or sectors.

POTENTIAL IMPACTS OF CLIMATE CHANGE AND SEA LEVEL RISE ON MANGROVE ECOSYSTEMS

The fact that global mean surface temperature has risen 0.5° C (0.6 ± 0.2° C) over the last century is now widely accepted (Houghton, 1991). Similarly measurable increases in greenhouse gas concentration have occurred over the same period and recent evaluations of global sea level change suggest that the current average rate of rise is approximately 1.5 mm yr^{-1} (Rapper et al., 1990). A major constraint to impact assessment in biological communities such as mangroves is the absence of accurate scenarios of future rainfall, both seasonality and total quantity. Not only is rainfall a major determinant factor in limiting the distribution of terrestrial biomes on a global scale, it has major effects on a local scale through its influence on processes such as water and sediment flux from land to near-shore waters.

Given that mangrove ecosystems have their centre of distribution in the tropics and sub-tropics and that present limits to their latitudinal distribution appears correlated with temperatures, both air and sea surface temperatures, extension of the global range of such ecosystems to higher latitudes might be expected under warmer climate conditions. The present 24° isotherm displays this general pattern extending further into higher latitudes on the eastern than the western continental margins. Where the temperature of coastal waters is largely determined by upwelling or cool currents flowing from the poles towards the equator then, provided no major changes in basin scale ocean movements occur, the latitudinal extent of mangrove distribution is unlikely to change.

Areas of mangrove growing in deltaic and coastal plains (like in the deltaic regions of India) are likely, under conditions of rising sea level to undergo erosion and loss from the seaward edge. Simultaneously, as saline conditions penetrate further inland, the mangroves of the inner margins will begin to replace the terrestrial and freshwater swamp vegetation (Fig. 1). The entire ecosystem may therefore be viewed as "migrating" inland although the rate of landward extension may not be the same as the rate of loss of pioneer mangroves from the seaward edge of the system. The limitations to such landward 'migration' under natural conditions will be reached when the inland slope exceeds that of the seaward edge. At this point erosion of the seaward edge will outpace inland colonization, which will eventually cease and the mangrove ecosystem will be progressively compressed becoming converted ultimately to a mangrove community of a drowned bedrock coast or to beach vegetation.

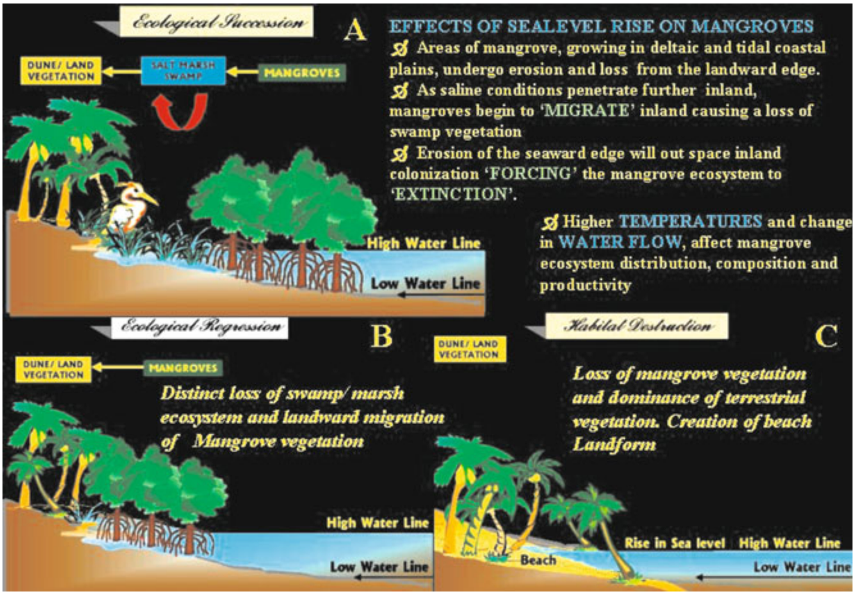

Fig. 1: Mangrove regression due to changing sea levels in deltaic regions.

Under conditions of accelerated sea level rise, gradual recession of the shoreline is likely to occur. Changes in the overall extent of mangrove ecosystems combined with the changes to the relative extent of different zones could dramatically alter the productivity of commercial and subsistence fisheries since the distribution of individual fish and prawn species reflects the gradients of salinity occurring through the mangrove system and the zonation and productivity of the entire system.

MANGROVES AND OTHER FACTORS OF CLIMATE CHANGE

No review of possible responses of mangroves to climate change and sea level rise would be complete without consideration of the potential consequences of changes to a variety of other environmental factors such as increasing CO_2 concentrations; changes in precipitation, alterations to coastal currents and wave climates; and changes in frequency of episodic events such as tropical storms.

Most mangroves have a C_3 pathway for carbon fixation during photosynthesis (Clough et al., 1982) and the consensus view is that such plants will increase their productivity under enhanced CO_2 partial pressures. Not only does the rate of photosynthesis increase but reduced stomatal conductance under higher CO_2 levels leads to more efficient water control through reduced transpiration loss. It should be recognized however that alteration to leaf production and subsequent changes to overall plant productivity within single species also alters the competitive ability of that species. The consequences of such changes at an ecosystem level are therefore difficult to assess since they represent a multi-dimensional, non-linear set of interactions. One consequence of increased CO_2 may be an increase in overall primary production in mangroves and hence an overall increase in litter production and vertical accretion areas. It is unlikely, however, that such changes will significantly alter the conclusions concerning potential sea level rise impacts.

Oxygen supply to the roots of many species is increased through *"pneumatophores"*, which project above the substratum as *"knees"* or vertical branches. Continued inundation in excess of the diurnal conditions to which the mangroves are adapted may prevent the lenticels from functioning resulting in lowered plant O_2 concentrations (Scholander et al., 1955), anoxia and mortality after varying periods. Harrington and Harrington (1982) document extensive mortality in Avicennia germinans and Rhizophora mangle following four months of inundation between 30 and 40 cm in an area with a natural tidal range of 10–20 cm.

Since mangroves occur in saline environments, they possess various strategies for salt regulation, which enable them to exclude, secrete or accumulate salt in order to control their water balance. Mangroves most effectively inhabit a physiological desert; hence, major structural modifications occur in mangrove leaves associated with the retention of de-salinated water and reduction of transpiration water losses. Most mangrove leaves are xeromorphic and display low transpiration rates (Lugo et al., 1972), with transpiration rates peaking prior to midday and declining throughout the afternoon. In general, increases in salinity result in increased respiration, decreased net primary production and consequently decreases growth rates (Ball and Farquhar, 1984).

Litter production has been estimated for Avicennia at 1.2–1.5 kg m^{-2} yr^{-1} for Rhizophora mangle at 0.9 kg m^{-2} yr^{-1}. Whilst litter production may increase, decomposition rates within mangrove peat will also change. General conclusions concerning changes in soils in terrestrial environments are that decomposition of organic matter may occur faster under warmer climates. In the case of tropical and inter-tidal mangrove soils a further factor needs to be considered. The pathways of anaerobic carbon catabolism during micro-decomposition differ in saline and freshwater soils. As saline conditions penetrate further inland to previously freshwater back-swamp areas, behind mangroves, then a shift from methanogenesis to sulfate reduction as a dominant decomposer pathway may occur.

Of considerably greater importance for a number of reasons are potential changes to rainfall, both in total volume and in terms of its distribution on a seasonal basis. Not only will changes to total volume and seasonal pattern alter the phenology and productivity of individual mangrove species but such changes will also alter the salinity gradient through mangrove ecotones with resultant impacts on the zonation of the ecosystem itself. In addition to the direct effects of changes in precipitation on the individual community, changes in rainfall at considerable distance may affect the coastal community via changes in runoff and erosion from inland catchment areas and hence sediment and nutrient flux within the mangrove ecosystem.

Whilst the IPCC (Houghton, 1991) assessment suggests that storms may increase in both frequency and intensity, scenarios are far from unanimous in this view. Mangroves, given their shallow root system and coastal location, are susceptible to wind-throw and other forms of storm damage, including crown and bole damage and death, where trees remain standing.

ROLE OF COASTAL OCEANS AND WETLANDS IN CLIMATE CHANGE

The average temperature of the earth's surface, currently at about 15ºC, is controlled by the gaseous composition of the atmosphere. Radiatively active or greenhouse gases in the atmosphere trap outgoing solar radiation which warms the earth. Important greenhouse gases in the atmosphere include water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), oxides of nitrogen (NO_x); tropospheric ozone (O_3); carbon monoxide (CO) and chlorofluorocarbon (CFC). Per molecule, CH_4 is 32 times more effective in trapping long wave radiation than CO_2 and N_2O is approximately 150 times more effective. Major natural sources of these gases are mainly from terrestrial ecosystems and partly from coastal wetlands. Emissions and reabsorption of these gases from natural ecosystems have been in equilibrium for millions of years. However, this balance has recently been disturbed by human activities. Consequently, atmospheric concentrations of several of these gases (CO_2, CH_4 and N_2O) have been increasing since the onset of the industrial revolution and more rapidly since 1950s. In this talk, an overview on the rising concentrations and effects of the key greenhouse gases will be highlighted. Also, the research work being carried out on CH_4 emissions from different coastal ecosystems will be presented.

Atmospheric methane concentrations were measured by our research group, on monthly basis for one year, in tropical coastal ecosystems along the Bay of Bengal (mangroves, brackish water lakes etc.) on the east coast of India. In addition, CH_4 emission studies were also conducted on the surface waters of the Arabian Sea, as a part of the German JGOFS "Arabian Sea Process Studies". Monthly variations in CH_4 emissions showed distinct trends in the unpolluted coastal wetlands (0.5 to 20.3 mg m^{-2} h^{-1}) in comparison to the polluted wetlands (1.9 to 45.97 mg m^{-2} h^{-1}). Environmental forcing factors such as salinity, sulfate content and localized anthropogenic stress were found to affect the seasonality in CH_4 emission in these coastal wetlands. The doubling of CH_4 emission in the polluted wetlands is significantly contributed by the inflow of domestic and industrial wastes into these coastal wetlands. Correlation has been made with the nutrient input to the coastal ecosystems, their retention and export characteristics.

Arabian Sea has only a small portion of shelf areas: however, it is one of the most biologically productive regions of the world's oceans. Mean CH_4 saturations in the surface waters range from 103 to 107% in the Central Arabian Sea. In the coastal upwelling areas, significant enhancement in CH_4 saturation was observed (156%) and 147% in the upwelling filament areas. Sea surface temperature was negatively correlated with CH_4 concentration in the upwelling area. From this study, it is estimated that about 11 to 20 Gg CH_4 is annually emitted from the Arabian Sea to the atmosphere, suggesting that previously reported very high surface CH_4 concentrations might be atypical due to the inter-annual variability.

Coastal ecosystems strongly modulate land-ocean interactions. Population pressures, inevitably affecting its use by future generations, are constantly altering the coastal environment. The exploitation of many coastal ecosystems is presently so intense and so weakly regulated, that major economic investment is likely to be required for their maintenance or restoration in the future. The creation of long-term, sustainable policies for coastal management requires an understanding of the impacts of changes in environmental quality along the coastline.

By the year 2000, it has been estimated that about 75% of the human population will live in the coastal regions of the world (United Nations, 1985). Even now, in South East Asia, 65% of cities with populations greater than 2.5 million are located along the coastline. Coastal areas are a magnet for tourists, as is evident from the fact that the Mediterranean coastline alone attracts one third of world tourism (UNDP-UNCED, 1992). All coastal zones are under increasing pressure from expanding human populations. We have only recently begun to realize the extent of damage caused in coastal waters, since environmental deterioration is not as obvious under the surface of the sea as it is on land. It is essential that every country develop an integrated Coastal Systems Management strategy, based on considerations of ecological sustainability, economic efficiency and social equity. For integrated Coastal Systems Management to occur on this scale, plans and programmes of the governmental, non-governmental, and corporate sectors need to be closely integrated. Above all, there is a need for the active participation of coastal communities. Local community participation will only be forthcoming if an integration between ecological security of coastal regions and the livelihood security of coastal communities is fully achieved.

Methane (CH_4) is considered as an important greenhouse gas because its relative potential for thermal absorption is 30 times greater than that of CO_2, though its atmospheric concentration is about 200 times less than that of CO_2 (Bouwman, 1990). The present atmospheric CH_4 concentration is more than double its pre-industrial level of about 0.8 ppmv. The current burden of CH_4 in the atmosphere is approximately 4700 Tg, and the global annual emission is about 500 Tg with an apparent net flux of 40 Tg y^{-1} (Cicerone and Oremland, 1988). Methane comes mainly from natural and anthropogenic sources. Natural sources include wetlands, ruminant animals, termites and oceans. Anthropogenic sources include coal mining, land fills and flooded rice fields. Isotopic measurements of atmospheric CH_4 show that 70-80% is of biogenic origin (Wahlen et al., 1989). The biogenic sources of atmospheric CH_4 are mainly microbial mineralization of organic matter under strictly anaerobic conditions (Schütz et al., 1990). Natural wetlands (105 ± 55 Tg) account for about one-fifth of the total global estimated annual methane source strength of 515 Tg ± 75 Tg. Although wetlands make up only 5% of the earth's land surface, they play a disproportionately large role in CH_4 emission. Wetlands are believed to be the single largest source of CH_4 and therefore extensive effort has been made to quantify their emission rates to the atmosphere. Current estimate is between 55 and 150 Tg CH_4 yr^{-1} corresponding to approximately 20% of the total global CH_4 release. The uncertainty in the range of these estimates over the past few years has improved only slightly, due to a number of difficulties that arise when sampling wetland areas.

Although CH_4 production in wetlands occurs through strictly anaerobic bacteria, CH_4 reducing bacteria (aerobic) may partially oxidize the CH_4 formed in deeper soil layers as it passes through the soil to the atmosphere. Both processes, and therefore the resulting CH_4 emissions, are very sensitive to a large number of parameters, such as water table depth, soil temperature and carbon content. Also, vegetation cover and the geographical situation influencing drainage of wetland areas have an impact on the flux of CH_4 to the atmosphere.

There is also a wide range in estimates of wetland emission primarily due to uncertainties about the wetlands themselves as well as their emission characteristics. Considering the fact that CH_4 emissions from wetlands are the single largest natural source, the trend in flux could be further enhanced if pressure from human activities were to increase as well. India has a long coastline of about 7517 km including its island territories. The major wetland categories of the Indian coast include: mudflats, coral reef, mangroves, marsh vegetation, lagoon/ backwaters, flood prone areas, salt pans etc. With this as a background, we have undertaken CH_4 flux measurements from the coastal wetlands (particularly estuaries and mangroves) of South India. The main objective of this study is to estimate the CH_4 flux from such coastal wetlands and also to determine the influence of various environmental factors.

The coastal zone is characterized by a rich diversity of natural habitats, such as mangroves, coral reefs, beaches, continental shelf areas, sand dunes, grasslands, rocky shores, marshlands, flood plains, salt marshes, estuaries, mudflats, wetlands, seagrass beds and seaweed areas. A variety of natural resources, including corals, seaweeds and algae, fish and other aquatic life, plants, minerals, water, sand, oil and gas, provide food, fuel, construction material and other resources indispensable for human existence.

Coastal habitats and resources are also vital because of their role in stabilizing the shoreline and in protecting coastal areas and habitations from cyclones, tidal waves and other natural disasters, as well as because of their natural capacity to assimilate and absorb waste and pollutants. In addition there are a diversity of natural processes occurring in coastal areas, such as up welling, seasonal sand banks, sand dune formation, sea erosion and accretion, siltation and sedimentation, the lunar and diurnal cycles, seasonal winds and cyclones, sea breeze, waves, tidal bores and flows, salinity changes, seasonal migration of fish and birds, algal blooms and fish kills, all of which contribute to maintaining the coastal ecosystem in complex, and often unknown ways.

IMPACTS OF CLIMATE CHANGE ON CORAL REEF ECOSYSTEMS

Coral reefs have a pantropical distribution and are potentially ideal indicators of climate change since their components the benthic corals are highly sensitive to environmental forcing. As a consequence of their light, temperature and sea level limits growth, it has been recognized that coral reefs are good indicators of past climate. The environmental variables and their probable effects on coral reef ecosystems are as follows:

Sea Level Rise

As a single factor, its effects are expected to be positive because of increased colonization of sea level limited reef flats and enhanced flushing of 'stagnant' lagoon systems. Sea level interacts with all other variables and since most of those produce negative effects, the combined results are uncertain.

Increased CO_2 Concentration

Surface ocean equilibrium with increasing concentrations of CO_2 will result in lowered pH, lowered carbonate mineral saturation states, and increase availability of dissolved CO_2 (as opposed to carbonate ions). This may reduce both biomineralization and community calcification and increase organic productivity.

Temperature

This variable may be expected to have different effects at different scales; in the near-term increases in sea surface temperature may be expected to increase the frequency and/or magnitude of high temperature stress events. On a longer scale, warming trends at higher latitudes could have a modest positive effect by increasing the area suitable for coral habitat. Interactions will be with UV and nutrients. Elevated surface water temperatures, possible together with other stressors like salinity decrease after rainfall, lead to an increased occurrence of *"coral bleaching"*. Coral polyps expel their symbiotic zooxanthellae and their tissues turn pale with the white carbonate skeleton shimmering beneath

(Schumacher, 2001). Polyps can be re-colonized by zooxanthellae, if conditions turn back to normal within a certain period (a few weeks), but large scale dying of coral communities can occur.

Increased UV Radiation

Overall effects are uncertain because of limited data, but there is conern about possible effects on reproduction through larval mortality and genetic damage. Interactions with temperature and nutrients for an overall negative impact are evident. Biological effects are expected to be primarily on species diversity, with uncertain or no effects to other variables.

Storms

The postulated increase in major storm frequency or intensity was expected to have negative net effects both at the individual and community level through impacts on community structure and metabolism. Short-term catastrophic degradation of coral communities can occur, while their recovery takes at least a decade. Higher frequencies of storm disturbance events no longer allow sufficient time for coral reef communities to undergo the natural succession series of algae-soft corals and to long-living continuously calcifying scleratanian assemblages.

Sediment Dynamics

Sedimentation will have negative effects on all biological variables. For convenience, sedimentation may be considered as proxy for hydrology and other land use effects and toxic chemical transport as well as sedimentary processes. Local anthropogenic sources due to land use practices such as deforestation and coastal construction are major reef stresses in some areas at present and may be expected to increase with growing population.

Nutrients

In the pristine world, sources of nutrient stress are limited to those associated with sedimentation processes or possible future changes in upwelling. The overall effects are therefore likely to be negligible or slight. Nutrient loading as a result of agriculture practices and sewage disposal is considered to be a major source of contemporary reef stress and ones which may interact with UV and CO_2 effects. Biological impacts are complex but nutrient loading is considered negative for biodiversity, community structure and community calcification and coral biomineralization. It has positive effects on organic productivity and may enhance algal calcification.

Eutrophication of coastal waters brings direct profit for macro algae overgrowing light-dependant corals, with possible long-term shifting into stable communities (Done, 1992). Further, production of phyto- and zooplankton is stimulated, reducing light penetration into the water and thus narrowing the depth range available for colonization of zooxanthellae and calcifying species. Such changes of the trophic structure can further support filter-feeding organisms like boring sponges, which erode coral skeletons and the reef framework.

At present, the contribution of coral reefs as carbon sinks is estimated to be ~ 1–2% of anthropogenic CO_2 release. It might increase with the extension of shallow water reef areas developing without direct or indirect human interference. Since the end of the ice ages, coral reefs in tropical regions were able to keep with the rising sea level by high growth rates over extended periods. Thus, provided that recent coral reefs developed without restriction (e.g. bleaching) and other constraints (eutrophication, sedimentation, destruction, etc.) extending propagations of populations could be expected in tropical shallow water shelf areas.

HUMAN ACTIVITIES IN THE COASTAL ZONE

The coastal ecosystem is fragile, unique and complex. Important human activities such as those relating to agriculture, fishing, salt extraction and production, rare earth mining, mining of coral, limestone and beach sand, groundwater extraction, land reclamation, oil exploration and extraction, aquaculture, tourism and recreation, chemical and power industries, discharge of urban sewage and other effluents, construction and dredging of ports and harbours etc., take place in coastal areas. However, the impact of human activities on the coastal ecosystem is often highly negative. They deplete and destroy natural resources and habitats and interfere with processes occurring naturally in the coastal zone. While some human activities in the coastal zone can be classified as livelihood-related, others are primarily profit-motivated, commercial activities. Some parts of the coasts are particularly bad, affected by industrial and municipal effluents as well as by indiscriminate development of brackish water aquaculture. The damage done is often unintentional, being a consequence of bad planning, lack of basic knowledge and little coordination between agencies and authorities. The first step towards remedial action needs to be the collection of relevant data on the state of coastal environment and the processes that are changing it. In the following sections, increases in greenhouse gases (particularly CH_4) from coastal wetlands and the effect of sea level changes along the Indian coast is discussed.

Key Factors Governing Methane Emission from Coastal Wetlands

Natural wetlands can be classified into two main types: (i) coastal wetland ecosystems and (ii) inland wetland ecosystems (Mitsch and Gosselink, 1993). Since the characteristics of soil and vegetation are different between the two types of wetlands, the controlling factors are consequently different. Factors governing methane production and emission from wetlands include (i) substrate supply, (ii) dissolved oxygen, (iii) soil temperature, (iv) soil moisture, (v) sulphate and salinity, (vi) methanogenic, non-methanogenic bacterial populations etc.

CH_4 EMISSION FROM COASTAL WETLANDS OF INDIA

The area under major wetland categories of the Indian coast as given by the Space Applications Centre (1992) has been taken for computing the probable CH_4 emission from coastal wetlands. The mean monthly data obtained from the annual survey at various coastal wetlands in South India, has been used to compute a range in CH_4 emission for the wetlands along the Indian coastline. Based on this, an annual CH_4 emission ranging from 0.68 to 13.06 × 10^9 g yr^{-1} has been calculated for the major coastal wetland categories of India. For comparison, the global CH_4 estimates from wetlands at climatic zones are provided in Table 1.

Table 1: Summary of calculated global wetland CH_4 fluxes (Tg yr^{-1})

Climatic	*Wetland type*				
zone	*Forested bog*	*Non-forested bog*	*Forested swamp*	*Non-forested swamp*	*Alluvial*
Arctic	8.90	4.90	0.10	0.20	—
Boreal	12.60	4.90	0.50	1.40	—
Northern	21.50	9.80	0.60	1.70	—
Temperate	2.10	—	1.60	1.50	0.30
Tropics	2.40	0.50	26.90	5.00	5.00

Adapted from Wang et al., 1996.

Forested, non-forested swamps and alluvial soils in the tropics have potentially high CH_4 emission characteristics in comparison to other climatic zones. However, it can be observed from our study, that the coastal wetland is not a major source of atmospheric CH_4 due to the inhibiting effect of sulfate and salinity. On the other hand, if anthropogenic additions are to increase at the current pace, these ecosystems could also become major sources for the future. An increased number of observations under other different categories such as mud flats, coral reefs, floodplains etc., will help to refine this database further.

EFFECT OF SLR ON COASTAL ECOSYSTEMS OF INDIA

The coastal environments are particularly vulnerable to global climatic changes especially global warming and its consequences such as changes in rainfall pattern, storm frequency, sea level changes etc. (Fig. 2). Recently, Rao and

Chakravarthy (1992), through their model studies, projected the climate impacts of global warming. The sea level changes in the past (ranging from 10 to 100 years) along the major port cities are illustrated in Fig. 3. Figure 4 shows the sea level changes observed for coastal cities in India in response to overall

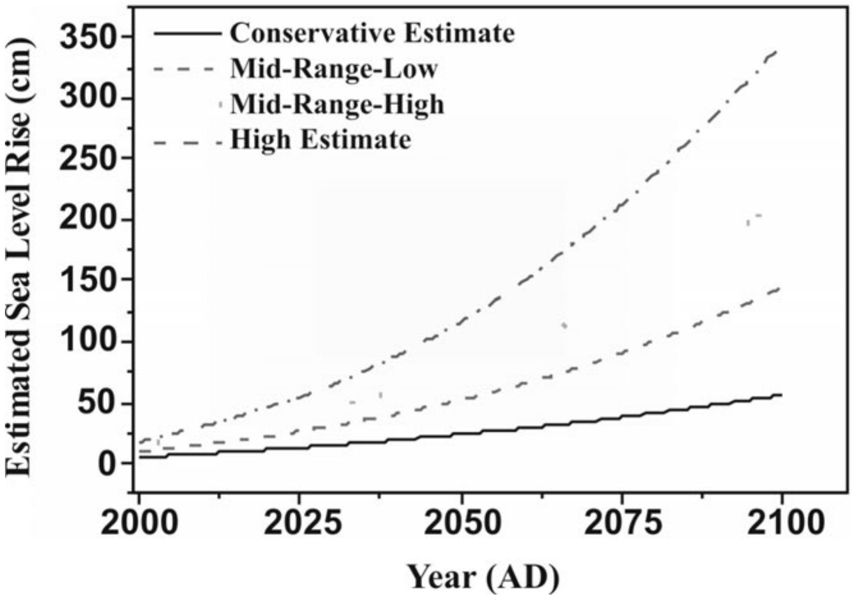

Fig. 2: Estimated sea level rise (cm) AD 2000-2100 (after Hoffman, 1984).

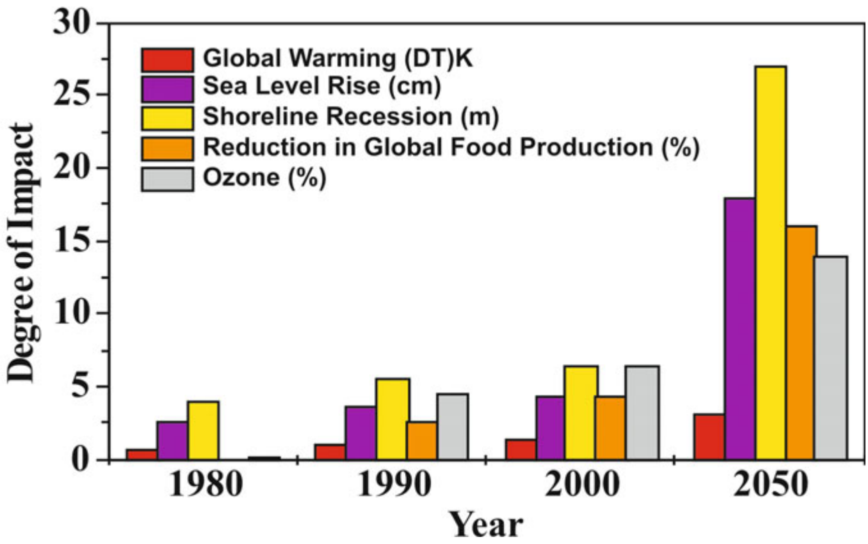

Fig. 3: Climatic impacts of global warming (after Rao and Chakravarthy, 1992).

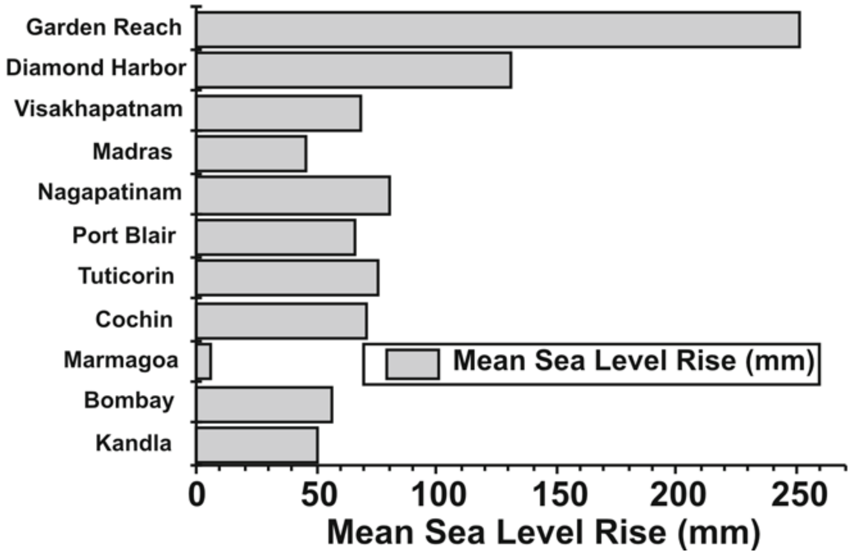

Fig. 4: Sea level rise along the Indian coast (Data from Survey of India).

predicted global sea level changes. Significant impacts of climate change on the coastal environment of India include changes in:

- Terrestrial input to the oceans
- Marine influence on coastal land systems
- Geomorphological processes
- Physical dynamics of coastal oceans
- Coastal productivity
- Ecosystems

All these changes could be studied through their effects on the physical, chemical and biological characteristics of the coastal environments.

Effects of Climate Change in Physical and Chemical Characteristics

The shoreline may change due to increased flooding resulting from sea level rise and storm surges. Dubey and Rao (1989), through their modelling studies, have established that maximum inundation takes place between Nagapatinam and Kalingapatnam in the east coast of India due to its low lying nature. The coastal inundation follows linearity with scenarios of sea level rise. The rise in sea level may also rearrange the coastal unconsolidated sediments and soils. The other likely effect of increasing sea level is accelerated coastal erosion. All these may result in the transport of sediments to offshore beyond the depth at which they participate in seasonal cycles, which may lead to the disappearance of local beach environments. The chemical processes in coastal waters are dependant on factors such as temperature, salinity, pH and terrestrial inputs such as organic matter, nutrients etc. Since climate change will alter these factors, the chemical characteristics of the coastal environment will experience significant changes.

Projection of ozone depletion as described in Fig. 3 is based on increase of CFCs at the present level of growth rate and without considering the impact of implementation of the Montreal Protocol.

IMPACTS OF SEA LEVEL RISE ON CHEMICAL AND ECOSYSTEM CHARACTERISTICS

The chemical processes of coastal waters are dependant on factors such as temperature, salinity, pH and terrestrial inputs such as organic matter and nutrients. Since the climatic changes will alter these factors, the chemical characteristics of the coastal environments will also experience significant changes. These are discussed in detail below.

Loss and Reduction of Coastal Ecosystems and Habitats

Wetlands in the vicinity of the area temporarily flooded by the sea (salt marshes, tidal flats, mangroves) as well as coastal dunes and coral reefs are the ecosystems with the largest spatial extent on earth. These ecosystems serve as breeding grounds and habitats for a vast number of marine and terrestrial species and serve as a basis for the development of complex food webs. Due to the increase in intensity of hydrodynamic and morphodynamic processes, and due to water contamination and other human impacts, many important spawning and breeding grounds (sea grass meadows, mangroves) are degraded. According to various studies, the coastal wetlands and other littoral ecosystems are now increasingly threatened in their spatial extent or even in their basic existence (Boer and DeGroet, 1990). The extent to which they are endangered depends mainly on:

- The rate of sea level rise
- The frequency of storm surges and other extreme events
- How much sediment is available in the long run for flood prone areas to grow upward
- Whether an inland migration of wetlands is inhibited or made impossible by man-made structures along the coast such as dikes or revetments

If sea level were to rise more than 5 mm yr^{-1}, an overall reduction of coastal wetlands by about 30% is expected globally, assuming that the current level of structural coastal stabilization is maintained.

Changes of Biological Production

In case of a rapidly rising sea level, it has to be expected that the biogeochemical cycles in the shallow waters are changed massively, because the continued flooding of low lying areas with salt water causes the remobilisation of nutrients and other mineral and toxic compounds. In general, such a mobilisation is immediately followed by an increase in growth of algae and plankton, leading to enhanced eutrophication of coastal waters. The rate at which this process occurs increases with the water temperature. Considering a constant anthropogenic input of nutrients and contaminants into the near-shore waters, these interactions would particularly lead to the degradation of extremely sensitive ecosystems such as coral reefs (Bijlsma et al., 1996).

Negative Effects on Species Diversity and Food Webs

On the basis of the "best estimates" scenarios for climate change, the ecological carrying capacity of coastal zones is expected to decrease significantly due to loss of habitats and space, temperature stress, mobilization of sediments and chemical compounds and other similar stress factors. Drastic negative effects will almost certainly be felt in ecosystems with a high sensitivity to temperature change. Ecological equilibrium of coral reefs, which are also known as the *"rain forests of the sea"* because of their vast species diversity, will be offset if the water temperature exceeds 30°C. Enhanced by the poor water quality in the vicinity of many coral reefs, the phenomenon of *"coral bleaching"* can already be observed along many tropical coasts today. Similar trends are appearing in mangroves; as in these ecosystems, only a limited number of species that can readily adapt to changed environmental conditions will survive if certain stress levels (temperature, salinity, currents, lack of substrate) are reached (IPCC, 1992). Such ecological adaptation has particularly adverse consequences for equilibrium of the food web.

Loss of Functions of Littoral Ecosystems

Besides the aspects already touched upon, the reduction or entire loss of tidal flats, salt marshes, dunes, mangroves and coral reefs will drastically diminish the buffering capacity of these littoral ecosystems. An important aspect is that these ecosystems protect the adjacent land against the sea since they dissipate a major portion of the wave energy before the waves reach the shore. They also contribute to a near-shore accumulation of sediments, which further reduces the energy of the waves and currents off shore (dunes). Additionally, these systems fulfil an important function in cleaning the coastal zones by absorbing dissolved nutrients and contaminants as well as contaminated sediments in accumulation zones, thus immobilizing the pollutants.

Thus, many coastal regions will certainly encounter severe ecological problems if the sea level rises at a rate of more than 3 mm yr^{-1} as the most plausible scenarios as suggested by the IPCC. On these grounds, integrated approaches towards a sustainable use of the coastal zones have to be sought (i.e. *"integrated coastal zone management"*).

CONCLUSIONS

Coastal zones are under close focus with respect to climate change since they are the most densely populated and intensely used areas of the world (Sterr, 2001). Furthermore, they are home to the most productive ecosystems of the Earth besides tropical forests, such as mud flats, mangroves and coral reefs. The most crucial impacts on coastal waters and adjacent islands are expected to result from a significant acceleration of sea level rise as projected by climate models and possible changes in the regime of extreme events. Increased concentrations of CO_2 and other greenhouse gases lead to a warming of the Earth's surface and lower atmosphere. The resulting changes in climate and their impacts such as sea level rise, ecosystem losses etc, can be estimated without associating the origin of warming to any of these gases specifically. It is however necessary to study the effects of these specific greenhouse gases in greater detail in order to estimate their relative contributions to warming at any given time and consequently to develop strategies for reducing their possible harmful effects.

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Status of Oil Pollution in the Arabian Gulf and Shatt Al-Arab Estuary: A Review

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Abstract: The Arabian Gulf has enormous number of offshore oil and gas platforms and many major oil terminals. It is also extremely busy shipping line for oil transports. Accidental spilling is unavoidable. About 25,000 tanker movements sail in and out of the Strait of Hormuz annually and transport about 60% of all the oil carried by ships. In combination, these sources provide on a long-term a kind of input sources of petroleum. Activities associated with oil traffic include shores heavily contaminated with oil residues, tar balls and trace metals. About two million barrels of oil are spilled annually from the routine discharge of dirty ballast waters and tank washing, partly due to the lack of shore reception facilities. Some major spills, either unintentional or as consequence of military activities, have added occasional dramatic pulses of oil contamination to long-term background. The present review brings about valuable sources of information regarding oil pollution status in the Arabian Gulf and the adjacent areas of Shatt Al-Arab Estuary and Mesopotamian marshes.

Key words: Oil pollution, Arabian Gulf, Shatt Al-Arab.

INTRODUCTION

The Arabian Gulf is an extremely shallow sea. Its maximum depth is only about 110 m, its average depth is just over 35 m, and large areas near the coast are less than 10 m deep. It is the very gentle slope of the Arabian Peninsula's eastern edge that accounts for lack of depth. And that in turn determines other

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ecological factors. Shallow water warms and cools faster; so life forms must be able to tolerate an annual temperature range of some 7 °C. Shallow water is more easily mixed by wind and tide, so the temperature of water changes relatively little with depth and mineral nutrients recycle more efficiently in shallow water than deep (Sheppard et al., 2010).

The Arabian Gulf is also a remarkably salty sea. Less than 25 cm of rain a year falls on the surrounding land, and there are few rivers to contribute a flow of fresh water such as Shatt Al-Arab river which in turn suffer from freshwater flow. Moreover, because of high temperatures, the shallow water evaporates faster than it is replaced by the inflow from the Tigris and Euphrates rivers and from the smaller rivers of the eastern shore. Thus, though the salinity of the world's oceans averages 35 parts per thousand, in the Gulf the study found salinities ranging from 38 to 70 in open waters. The high salt content of the water, like high temperatures, is a stress that Gulf creatures such as fish and mammals must be able to tolerate if they are to survive. Many, in fact, have learned to thrive on it, through very effective osmoregulatory and thermal adaptability mechanisms.

Exceptionally high salinity embayments are common in many locations along the southern shores of the Gulf. The relative richness and productivity of these areas is poorly understood; salinity rises to between 55 and 65 psu, yet benthic diversity remains moderately high (Loughland and Zainal, 2009), but where salinity rises to over 60–90 psu, algae ultimately grade to cyanophyte dominated zones, with diminishing diversity. In extremes of these gradients, fauna become very limited though a very few species may remain abundant.

The third characteristic is the Gulf's relative isolation from the rest of the world's salt waters. The only connection is through the Strait of Hormuz—only 48 km wide and not radically deeper than the rest of the Gulf—through which Gulf water flows out along the bottom, to be replaced by a current of less salty water from the Indian Ocean flowing inward on the surface. Because of the narrow passage, the volume of this water exchange is too small to have much of a damping effect on the Gulf's high salinities and wide temperature swings.

Despite these stresses, which generally decrease the variety and diversity of creatures exposed to them, the present study found that marine life in the Gulf was far richer than expected, even though some of the species live at the very limits of their ability to adapt to the harsh environment. Besides diversity, high productivity is also a possible measure of the health of the Gulf ecosystem.

The Arabian Gulf has about 800 offshore oil and gas platforms and 25 major oil terminals. The Arabian Gulf is also extremely busy shipping line for oil transports, with accidental spilling being unavoidable. About 25,000 tanker movements sail in and out of the Strait of Hormuz annually and transport about 60% of all the oil carried by ships. In combination, these sources provide on a long-term a kind of input source of petroleum. According to Kirby and Law (2008), activities associated with oil traffic include shores heavily contaminated with oil residues, tar balls and trace metals. About two million barrels of oil are spilled annually from the routine discharge of dirty ballast waters and tank washing, partly due to the lack of shore reception facilities. Some major spills, either unintentional or as consequence of military activities, have added occasional dramatic pulses of oil contamination to long-term background (Ehrhardt and DouAbul, 1989; Price et al., 1993).

STATUS BEFORE GULF WAR 1991

Among the first published studies on oil pollution in the Arabian Gulf was that of Oostdam and Anderlini (1978) who calculated the annual average of oil spilled on the shores of Kuwait to be 183 m^3. Oostdam (1980) used vessels reports and estimated volume off oil slick in the Gulf to be 16×10^3 m^3. It was concluded by Anderlini and Al-Harmi (1979) that slick dispersal patterns agreed with surface current circulation in the Gulf and the most tar (maximum 2 kg/m^2) was accumulated on the windward side of sand cusps or obstructions. Furthermore, according to Burns et al. (1982), the average quantities of tar in the beaches at the Strait of Hormuz ranged between 647 and 2325 g/m^2. Burnes et al. (1982) reported gas chromatographic analysis of sediments, oyster mussels and fish tissue in the Gulf of Oman and the Omani coast at the strait of Hormuz on the Arabian side of the Gulf. Resolved fractions of hydrocarbons in oysters collected at Hormuz amount 0.8 µg/g wet tissues while unresolved fractions reached 6.0 µg/g wet weight. Anderlini et al. (1981), IAEA (1981) and Badway et al. (1985) gave mean constrictions of hydrocarbons of 111, 257 and 111 µg/g dry weight in oyster collected from Kuwait, Bahrain and Oman respectively.

Among the most extensive work on marine pollution in coastal waters of the Arabian Gulf, was that conducted by Flower (1985) during a period of 18 months. In this work, he stated that the highest recorded loads of tar (14-858 g/m^2) were found in Bahrain beaches, while, less tar (4-233 g/m^2) was presented on the UAE beaches and the lowest loads for the entire 18 months period were reported at beaches of Abu-Dhabi. In the same work, Flower used fluorescence analysis to determine concentration of total petroleum hydrocarbons in seawater of Bahrain (up to 5.7 µg/l) and UAE (up to 3.75 µg/l). He stated that current levels of petroleum hydrocarbons in the Gulf were not exceptionally high (20 µg/l) and sediment oyster from Bahrain showed higher content of hydrocarbons (36.36 µg/g dry weight for sediment at the eastern coast of Bahrain) compared to lower values of 1.0 µg/g for UAE coast.

Literathy et al. (1985) gave a mean concentration of 5.8 µg/g for the clay-silt fraction of bottom sediments in near-shore Kuwait. Zerba et al. (1985) found hydrocarbons concentrations exceeding 100 µg/g for bottom sediment at the offshore area of Kuwait (close to the offshore drilling and oil production area at the border between Kuwait and Saudi Arabia). El–Samra et al. (1986) reported the highest range of total hydrocarbons (100-500 µg/l) in the surface water at the same area. DouAbul et al. (1984) and Zerba et al. (1985) gave values of total hydrocarbons around 13µg/g from sediment collected at Shatt Al-Arab mouth at the very north of the Arabian Gulf, while Grimalt et al. (1985) identified n-alkaline by GC/MS technique for sediment collected at the same area and found values ranging between 3.3 and 18.8 µg/g dry sediment. The levels of hydrocarbons in the water column were not exceptionally high in comparison with other areas of the world, being 4.4 to 63 µg/l (mean 15 µg/gl) (Emara, 1990). A study on oil pollution input from coastal refineries by Awad et al. (1990) which show that the Omani refineries adds 160.4 tonnes of Omani crude oil and refined product annually to Mina Al-Fahal Water, where it is situated with adjacent tank farms adding another 140 tonnes. Two reports (UNEP, 1984; Anonymous, 1986) provide some estimates of the amounts of oil contributed by different sources in the Arabian Gulf and gave models for oil transport mechanisms through the region. Mille et al. (1992) gave the distribution of hydrocarbons in low polluted surface sediment from Kuwait, Bahrain and Oman coast as before Gulf War.

STATUS AFTER GULF WAR 1991

In the wake of the Iraq-Iran war and Gulf War in 1991 huge amounts of oil were released into the North-Gulf. It added an additional source of oil pollution which is estimated as 6–8 million barrels of spilled oil into the Gulf during that war (Price and Robinson, 1993). Some habitats of Kuwait and the northern half of Saudi Arabia were extensively affected. Hinrichsen (1990) stated that many beaches are tarred, but background level in biota and sediments are not exceptionally high, due to rapid weathering biodegradation and flushing. The recent war has left productive areas of Saudi Arabian coastline heavily contaminated and many wildlife killed (Canby, 1991). El-Samra (1989) has estimated an oil budget of 30,000 tonnes for the Western Gulf coastal waters. Input of crude oil released into the water of the Arabian Gulf during Gulf War was estimated at Nov. 1991 to be between 6 and 8 million barrels (approximately 6.4 million) (GESAMP, 1993). The releases were from different sources, including oil tankers and terminal (MEPA, 1991).

Following the Gulf War in 1991, it was reported that an amount of four to eight million oil was directly released into the Arabian Gulf from sea island terminal in Kuwait. If these reports were true, such amount clearly would make the largest oil spill in history. Burning oil fields released enormous amount of smoke plumes into the air for 250 days. Fowler (1993) reported that 500 million barrels (67 million tonnes) of emitted or ignited oil were added to the Gulf as aerosols, soot, toxic combustion products, and gases, even if only a small amount of these emissions was deposited in coastal marine environment. It would further increase the amount of crude oil that actually spilled out. The commonly held belief was that the pollution could readily spread far beyond the Gulf (Fowler, 1993).

The deliberate 1991 oil spill occurred in an environment that was both far from pristine and already naturally high stressed (Price, 1993, 1998). Published figures put the spill at around 6–8 million barrels, although some estimates (Linden and Husain, 2002) consider the volume as higher. In addition to the oil spill, extensive pollution, a drop in temperature and reduction in photosynthetically active radiation (PAR) came about from the conflagration of more than 700 oil wells, which burned for several months (Munawar et al., 2002).

Khan (1992) reported that potable water produced from saline water of the Gulf desalination plants was facing total stoppage. Price and Sheppard (1991) reviewed the environmental importance of the Gulf region, and some of the threats it faced due to military activation. They reported that while attention was focussed on coastal and marine ecosystems and large species of wild (e.g. cetaceans, dugongs, birds and fishes), lower levels in the ecosystem (e.g. micro-organisms) may also be affected. They suggested possible approaches for dealing with war-related environmental problems in the region. Fisheries in the Gulf appear to have been directly and indirectly affected by the war (FAO, 1994). Literathy (1992) considered the effect of oil spill and atmospheric fallout including acid rain and petroleum related compounds associated with air-borne particulates.

Fayad et al. (1992) described the results of a study performed to evaluate the effectiveness of one of the bioremediation agents in degrading the oil spilled in the Gulf under controlled laboratory conditions. Satellite remote sensing may provide an appropriate tool, especially in war situations where air-borne monitoring is difficult. Legg (1991) gave an estimation of the extent and movement of the oil slick in the Arabian Gulf during Gulf War. Remote sensing technique was also employed by Al-Thukair (1993) to provide information on algal mat locations and damage intensity caused by the oil spill. Cekirge et al. (1992) used three mathematical models GULFSLIK I, GULFSLIK II and OILPOL to analyze the fate and transport of the spills originated at Al-Ahmadi.

The report by Readman et al. (1992) gave results of a rapid assessment survey of hydrocarbon contamination undertaken in coastal marine environment from Kuwait to Oman during mid-1991. The results showed that severe oil pollution was restricted primarily to Saudi Arabian coastline within 400 km from the spillages; and that during the four months following the military activities and preceding the survey, the spilled oil has extensively degraded. Concentration of petroleum hydrocarbons in sediment and bivalve molluscs from Bahrain in June 1991 were lower than those recorded from the pre-war (1983-1986). Ehrhardt and Burns (1993) measured the concentrations of hydrocarbons in sediment by spectroflurometry and found that they ranged from 540 μg/g dry weight and 0.5 to 103 μg/g as measured by gas chromatography with flame ionization detectors, while the concentration by bivalve in the Arabian Gulf ranged from 0.8 to 1.5 μg/mg by spectroflurometry and 0.1 to 0.3 μg/mg by gas chromatography. Carpenter (1992) discussed the effects of the military activities on commercial fisheries in the Arabian Gulf and mentioned that fishing operations were reduced.

Numerous research papers have been published after the 1991 Gulf War (Fayad and Overton, 1995; Readman et al., 1992, 1996; Jones et al., 1998). Reviews have been devoted to both immediate and wider environmental consequences. Price and Robinson (1993) have reviewed more than forty articles concerning environmental effects of the war in the region. FAO (1994) reported an overall reduction in oil pollution in the Gulf due to decreased tanker traffic. These studies and ongoing assessments, including those linked to environmental damage claims, have helped to make this part of the Gulf well studied.

OIL POLLUTION IN SHATT AL-ARAB ESTUARY

Oil refinery effluents and losses during loading operations have been identified as the major sources of oil contamination in the water of Shatt Al-Arab river which emptied into the North-west Arabian Gulf (Bedair and Al-Saad, 1992). It was estimated that this river transports about 48 tonnes of oil for residents to the Arabian Gulf annually (DouAbul and Al-Saad, 1985).

Among the first published studies on oil pollution in Shatt Al-Arab estuary was that by Al-Saad (1983) in which the baseline data for total hydrocarbons in upper part of the estuary were determined, while DouAbul (1984) studied the lower part of the estuary. DouAbul and Al-Saad (1985) estimated that this river transported about 48 metric tonnes of oil residues to the Arabian Gulf annually. Bedair and Al-Saad (1992) studied the dissolved and particulate adsorped hydrocarbons in the upper part of the estuary on samples collected during 1985. The distribution of petroleum hydrocarbons in sediment of Shatt Al-Arab estuary and North-west Arabian Gulf was studied by Al-Saad (1983 and 1987), DouAbul et al. (1984) and Grimalt et al. (1985). Seasonal variations of normal alkanes in the water of the Iraqi marshes at the northern part of the estuary was recorded by Al-Saad and Al-Timari (1993b). The use of the bivalves as indicators for hydrocarbons pollutions was carried out by Al-Saad (1983), Al-Saad and DouAbul (1984) and Mudaffer et al. (1992). The concentration of petroleum hydrocarbons in fresh and marine fishes from the area were studied by DouAbul et al. (1987), Al-Saad and Al-Asadi (1989) and Al-Saad (1990). Many scientific studies were conducted in the Gulf including those of Oostdam and Anderlini (1978), Burns et al. (1982), Fowler (1985), Grimalt et al. (1985), El-Samra (1989), El-Samra and El-Deeb (1988) and Emara (1990).

ASSESSMENTS OF ENVIRONMENTAL IMPACTS ON BIOTA

Early description of the extent of the spillages (Canby, 1991) showed that the slick have affected at least 500 km of coastline in Saudi Arabia, with an estimated large loss of wildlife especially seabirds, and probable loss of all coastal mangroves and most of the salt marshes (MEPA, 1991). Coral reefs and sea grass bed are also heavily impacted. However some self-cleaning by blue green microbial mats have begun (Hopner et al., 1994). Oil pollution accounts for 0.5–1.51% total organic carbon (TOC) compared to the 0.5 natural background level. Data by Al-Ghadban et al. (1994) showed an increase in TOC to 2.8%, which results in shifts in planktonic populations from diatoms to flagellates, dinoflagellates and benthic algae. Spilled deposits may persist for many decades (Owens et al., 2008). The enormous volume of ballast water from tankers may have introduced exotic biota. For example there has been an increase in recorded dinoflagellate species from <40 in 1931 to >200 species in 1996 (Subba Rao and Al-Yamani, 2000). A programme is underway to investigate this subject in more detail (Clarke et al., 2003).

Environmental assessments carried out in the area showed that damage to inter-tidal regions, especially their cyanobacterial mats, was severe (Al-Thukair et al., 2007). Overall impact was greatly influenced by geographical location; the Abu Ali island half way down the Saudi Arabian coast acted as an oil trap. Sub-tidal damage was relatively limited, and inter-tidal systems that were impacted showed considerable variability. Inter-tidal recovery in many oiled areas was well underway by the mid- to late-1990s. Jones et al. (1998) suggested a period of 3–5 years for return to normal diversity (species richness), and a period of 3–6 years for restored abundances on rocky shores and inter-tidal soft substrata. Later assessments for environmental damage compensation by claimant countries, believed recovery times to be substantially longer than half a decade, particularly for marsh areas and low-energy tidal flats.

Habitat Equivalency Analysis (HEA) was also used in the assessment of environmental damage and settlement of compensation for impacts arising from the 1991 Gulf War. As described by Dunford et al. (2002), it calculates the natural resource service losses in discounted terms and then determines the scale of restoration projects needed to provide equal natural resource service gains in the future.

CLEAN-UP OPERATIONS

Studies in 1991 revealed that in areas where cleaning was performed using high pressure flushing which caused the removal of the upper layers of sediment, recovery took significantly longer than if the oil had been left to degrade naturally or had been only partially removed (Watt et al., 1993). In many areas, large-scale clean-up operations increased damage (Linden and Husain, 2002). Toxicity and physical damage from clean-up operations, remains a problem, though responsible and appropriate use of dispersants and sorbents can result in substantial benefits. Another aspect of remediation is that of aquifers contaminated by petroleum, gas residues and seawater, the latter pumped to desert areas to help extinguish the burning oil wells. Although desalination has been the principal source of freshwater for several decades, aquifers are considered a critical resource that, like oil, is not renewable.

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4

Diatom Species Composition and Seasonal Abundance in a Polluted and Non-polluted Environment from Coast of Pakistan

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Abstract: Diatoms species composition and their seasonal abundance was analyzed at two stations (St. A, 24°49.77′N 66°57.85′E and St. B, 24°47.93′N 66°58.87′E) of Manora Channel, coastal waters of Karachi, northern Arabian Sea bordering Pakistan. Samples were collected bimonthly from May 2002 to July 2003 and examined using inverted microscope. There was no significant variation observed between species composition at both A and B stations. Distribution pattern and seasonal variations in cell abundance of dominant, abundant, frequent and rare species were observed in which seven dominant species were recorded from station B and six dominant species from station A. Among both centric and pennate diatoms, the genera *Chaetocerose affine, Pleurosigma* sp 1*, Thalassiosira* sp, *Navicula directa* and *Nitzschia longissima*, *Rhizosolenia setigera, Thalassionema nitzschiodes* remain dominated all year although seasonal variations in their cell abundance were observed for these species. Statistical analysis showed that most of the dominant species were positively correlated with the salinity and temperature at both stations A and B. It suggests that temperature and salinity are the most significant factors that give shape to the diatom community and control the community changes. Dominance of pennate species over centric types with high abundance of these pennate species showed that they have better tolerance against pollution and other environmental variables.

Key words: Diatom, species composition, seasonal abundance, coastal waters.

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INTRODUCTION

Diatoms are the main primary producers in the ocean (Smayda, 1978) and the number of species estimated is from 10,000 to 100,000 so is considered as the most suitable group for the study of biodiversity and ecology of the ecosystem. The pattern of distribution of diatom species can be determined by two important phenomena: one is the seasonal variability and other is eutrophication in the area (Stoermer and Smol, 1999; Admiraal and Harry, 1980; Qasim, 2003). Geography of an area also is considered as a main factor that plays an important role in distribution of diatom species. It is the ability of a species that can help them to survive in an environment, where mixing of different hydrographical factors is taking place consistently (Stevenson, 1997). According to Kociolek and Spaulding (2000), ratio of species which are confining to certain geographical areas are much higher than earlier thought.

Seasonality has great impact on species composition and diversity (Kristiansen, 1996; Patrick and Reimer, 1966; Stevenson et al., 1996; Potapova et al., 2002). The Arabian Sea is well known for its unique hydrographical conditions which are controlled by the Indian Ocean. The biological activity including distribution of diatoms is related with the monsoon driven wind forces which as a result cause the upwelling in the region (Currie et al., 1973; Qasim, 1977; Ivanova et al., 2003). SWM (South west monsoon) from June to September and NEM (North east monsoon) from November to February results in elevated primary production in the northern part of Arabian Sea (Parab et al., 2006). Strong upwelling and fluxes enhance the concentration of silicate which support the growth of diatom species and greatly affect the composition of different species in the community (Haake et al., 1993a; Haake et al., 1993b).

The role of diatom composition is very important in an ecosystem which is still unexplored from this side. The purpose of this research work is to contribute the knowledge about distribution and abundance of diatom species from the coastal waters of Karachi (bordering northern part of Arabian Sea) and assess the relative importance of hydrographical factors affecting their composition.

MATERIAL AND METHOD

Samples were collected bimonthly using 1.7 litre Niskin bottle over a period of May 2002 to July 2003 at the Manora Channel located on the estuary of Lyari river. Samples were taken at two stations established for regular sampling. 1. Station A (24°49.77′N 66°57.85′E) Manora Channel (inside) a polluted area with impact from Layari river and mangrove ecosystem. 2. Station B (24°47.93′N 66°58.87′E) Outside Manora Channel in the open water, a non-polluted station with more oceanic ecosystem influence. Samples were fixed in Lugols solution. Diatom species cell numbers were counted according to the procedure described earlier by Utermohl (1958). Triplicate samples were settled for 24 hours in a settling chamber (50 ml). The settled samples were observed using inverted microscope. Identification of diatom species was done using available identification keys (Thomas, 1997). Water parameters like salinity measured by refractometer and temperature by mercury thermometer. Species composition and their abundance was compared at both stations A and B and correlated with water parameters like salinity and temperature.

RESULT

There was no significant variation observed between species composition at both A and B stations. Distribution pattern and seasonal variations in cell abundance of dominant species were observed in which seven dominant species were recorded from station B and six dominant species from station A. Among both centric and pennate diatoms, the genera *Chaetoceros affine, Pleurosigma* sp 1*, Thalassiosira* sp, *Navicula directa* and *Nitzschia longissima*, *Rhizosolenia setigera, Thalassionema nitzschiodes* remain dominated all year round although seasonal variations in abundance were observed for these genera. Nine species were abundant at both stations and ten species were found frequently at stations A and seven species at station B (Table 1). In pennate types *Asterionella Formosa, Navicula transitranse, Navicula* sp*, Pleurosigma* sp 2, *Synedra* sp, *Pinnularia* sp, *Thalassionema nitzschiodes* and in centric types *Guinardia flaccida, Eucampia zodiac* were found abundant at station A. At station B *Amphora* sp, *Asterionella Formosa, Navicula* sp 6, *Pleurosigma* sp 2 in pennate types and *Guinardia flaccida, Eucampia zodiac, Odontella sienensis, Odontella mobileinsis* were observed as abundant species. The species found frequently at station A *Amphora* sp, *Asterionellopsis glacialis, Gyrosigma* sp, *Pseudonitzschia* sp belong to pennate types and *Odontella sienensis, Odontella mobileinsis, Odontella aurita, Planktoniella sol* and *Rhizosolenia imbricata* belong to the centric types. The species found frequently at station B *Navicula transitranse* and *Synedra* sp belong to pennate types and *Odontella aurita, Plantoniella sol, Chaetoceros decipience* and *Rhizosolenia imbricata* belong to the centric types.

Fourteen species at station B and eleven species at station A were found rare. *Licmophora paradoxa, Nitzschia clostrium, Navicula f delicatula, Pleurosigma directum, Pleurosigma normani, Pleurosigma macrum, Coscinodiscus radiatus, Corthrone criopilum, Chaetoceros decipiense, Ditylum brightwilli* and *Guinardia striata* were found rare at station A and *Asterionellopsis glacialis, Cylindrotheca clostrium, Gyrosigms* sp, *Pseudonitzschia* sp, *Pleurosigma directum, Pleurosigma normani, Coscinodiscus radiatus, Corthrone criopilum, Ditylum brightwilli, Guinardia striata, Rhizosolenia styliformis, Rhizosolenia bergonii, Skeletonema* sp and *Triceracium* sp were found rare at station B. The species were selected according to the average cell abundance and their presence throughout the period of this study. LM and SEM (Light and Scanning electron micrographs) of some diatom species are presented in Plates 1 and 2.

Table 1: Diatom species identified from stations A and B. Species selected according to total abundance ($\times10^3$ cell/litre) of all data

Diatom species	*St A*	*St B*
Pennate taxa		
Amphora sp	**	***
Asterionellopsis glacialis	**	**
Asterionella formosa	***	***
Cylindrotheca clostrium	A	***
Gyrosigms sp	***	**
Licmophora paradoxa	*	A
Nitzschia clostrium	**	A
Nitzschia longissima	****	****
Navicula directa	****	****
Navicula transitranse	***	A
Navicula f delicatula	***	A
Navicula sp 6	***	***
Pseudonitzschia sp	**	*
Pleurosigma sp 1	****	****
Pleurosigma sp 2	***	**
Pleurosigma directum	*	*
Pleurosigma normani	**	*
Pinnularia sp	**	**
Pleurosigma macrum	*	A
Synedra sp	***	**
Thalassionema nitzschiodes	****	****
Centric taxa		
Coscinodiscus radiatus	**	*
Corthrone criopilum	*	*
Chaetoceros danicus	A	**
Chaetoceros decipience	**	**
Chaetoceros affine	****	****
Ditylum brightwilli	***	*
Guinardia flaccida	**	***
Guinardia striata	*	*
Eucampia zodiac	***	***
Odontella sienensis	**	***
Odontella aurita	***	***
Odontella mobileinsis	**	**
Planktoneilla sol	**	**
Rhizosolenia setigera	****	****
Rhizosolenia imbricata	***	**
Rhizosolenia styliformis	A	*
Rhizosolenia bergonii	A	*
Skeletonema sp	A	*
Thalassiosira sp	****	****
Triceracium sp	A	*

Dominant****, Abundant***, Frequent**, Rare*.

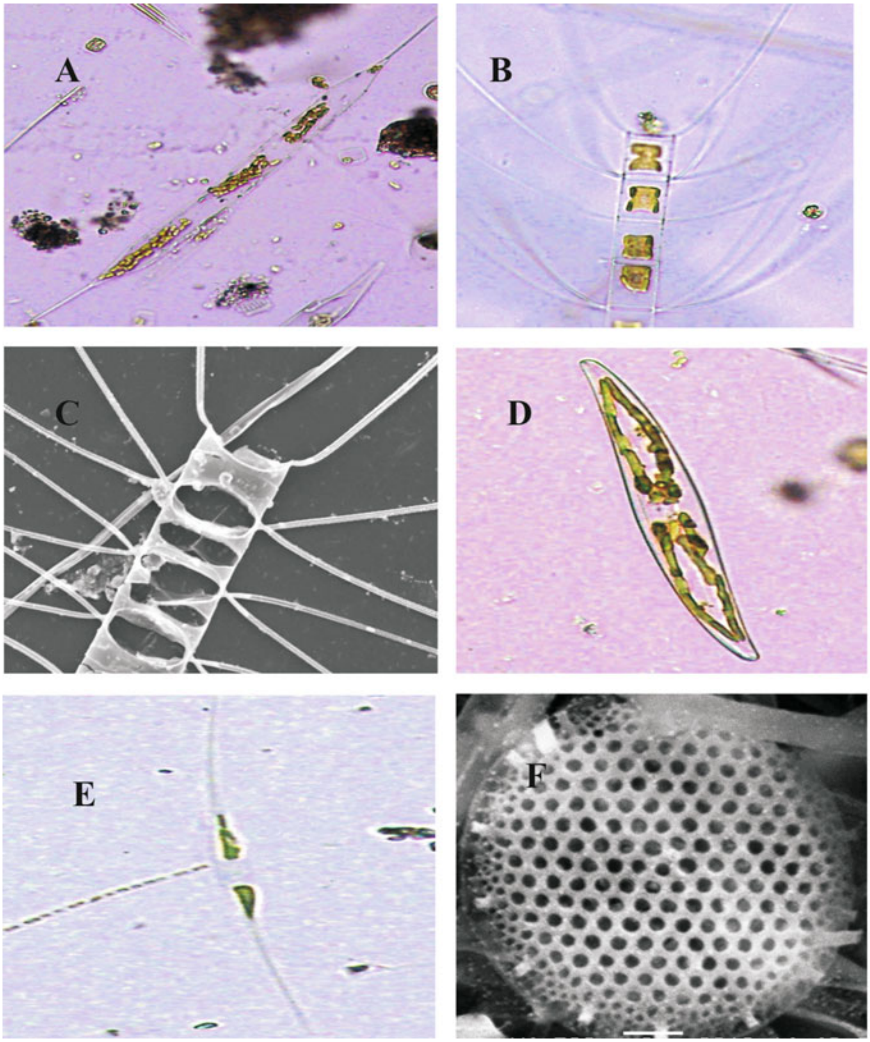

Plate 1: Light microscopy micrographs and scanning electron micrograph: A – *Rhizosolenia setigera*, B – *Chaetoceros affine*, C – *Chaetoceros decipiense*, D – *Pleurosigma* sp 1, E – *Nitzschia clostrium*, F – *Thalassiosira* sp.

SEASONAL ABUNDANCE OF DOMINANT SPECIES

In centric type ***Thalassiosira*** sp are cosmopolitan and have great diversity. Approximately 100 species are reported from various areas. This species was dominant and present throughout the year except in May-1-2003, June, July, 2002, Feb-1 and Mar-1-2003 from station B and from station A present throughout the year except in the months of May-1, Sep-2, December, 2002, and Mar, 2003. It constitutes 1.5% in the months of September, 2002 and April,

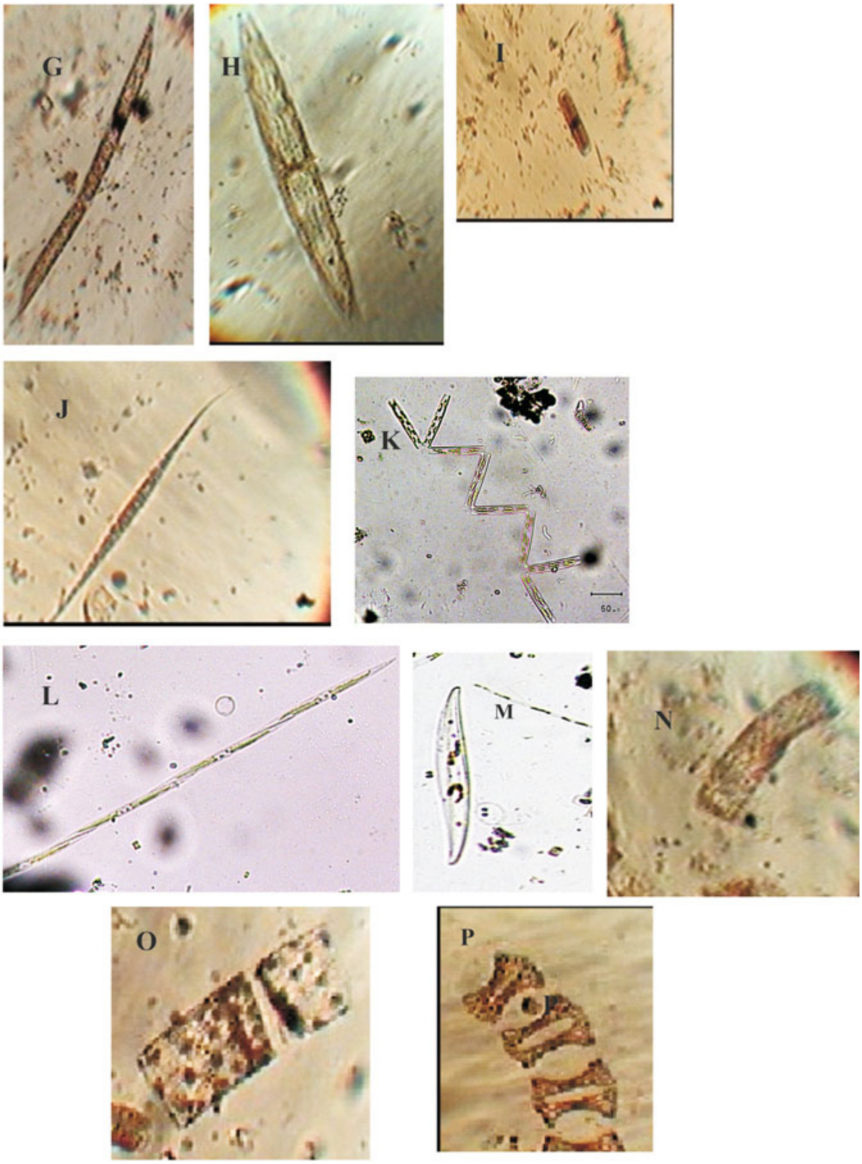

Plate 2: Light microscopy micrographs and scanning electron micrograph: G – *Rhizosolenia imbricate*, H – *Navicula* sp, I – *Pinnularia* sp, J – *Pleurosigma macrum*, K – *Thalassionema nitzschioides*, L – *Pseudonitzschia* sp, M – *Pleurosigma normani*, N – *Guinardia striata*, O – *Guinardia flaccida*, P – *Eucampia* zodiacus.

2003 of the total diatoms at station A and 4.41% in the month of January, 2003 at station B (Table 2). Distribution pattern of *Thalassiosira* sp shows seasonal variation in the cell abundance. This species has high abundance at station B as compared to station A. This species has a high peak in the month of May-1,

Table 2: Minimum to maximum range of percentage (%) contribution of dominant diatom species from stations A and B

Dominant species	*Percentage (%)*	
	Station A	*Station B*
Chaetoceros affine	0.7-3.9	0.06-19.4
Navicula directa	0.6-99.2	0.4-98.46
Nitzschia longissima	2.0-97.9	12.7-95.6
Pleurosigma sp 1	0.5-7.6	0.7-7.7
Rhizosolenia setigera	0.2-25.4	0.02-3.0
Thalassiosira sp	0.2-1.5	0.02-4.4
Thalassionema nitzschiodes	0.3-8.6	0.2-15.4

2002 at 0.19×10^3 cell/litre when salinity was 37‰ and temperature was 29.1ºC. Second highest cell abundance was recorded in the second half of the month of October-2, 2002 at 0.18×10^3 cell/litre at station B. Lowest cell abundance observed was in the months of March-2, 2003 and April-1, 2003 at 0.007×10^3 cell/litre (Fig. 1, a).

Chaetoceros affine was observed in almost all the months during 2002-2003 except in September-1-2002, January-1, February-1, and April-1, 2003 from station A but in contrast remain dominant all the months at station B. It contributed 3.9% in the months of December, 2002 and March, 2003 at station A and 4.4% in the month of January, 2003 at station B of the total diatoms (Table 2). Total cell abundance was high at station B as compared to station A. This species has a peak in the month of March-1, 2003 with cell abundance of 4.31×10^3 cell/litre with recorded salinity of 40‰ and temperature 26ºC. Second highest cell numbers were seen in May-2, 2003 with cell abundance of 2.94×10^3 cell/litre from station B. Lowest cell numbers were 0.02×10^3 cell/litre observed in the months of Sep-2, 2002 and May-1, 2003. Similar cell abundance 0.02×10^3 cell/litre was observed in the same months of June-2 in 2002 and 2003. At station A total cell abundance was low 5.12×10^3 cell/litre as compared to station B. Lowest cell abundance recorded was 0.013×10^3 cell/litre in the months of June-2, Nov-1, and Dec-1, 2002 from station A. Higher abundance observed in the month of July-1-2002 was 1.12×10^3 cell/litre (Fig. 1, b).

Rhizosolenia setigera: This centric diatom species was dominant at both stations all the year. This species has contributed 13.1% of the total diatoms in the month of June, 2003 at station A and 33.5% of the total diatoms in the month of June, 2003 at station B (Table 2). At station B maximum cell abundance observed was 1.007×10^3 cell/litre in the month of May-2, 2003 when salinity was recorded 36.3‰ and temperature 31.0ºC. Second highest cell numbers counted in the month of Feb-2, 2003 were at station B. Lowest cell numbers observed 0.007×10^3 cell/litre in the month of Sep-2, 2002. Low abundance was observed in the months of June-2, Sept-1, Nov-1, Dec-2, 2002 and

May-1, 2003. At station A maximum cell density 0.80×10^3 cell/litre was seen in the month of May-2, 2003 same as station B but with relatively lower abundance as compared to station B. Lowest cell numbers were observed 0.007×10^3 cell/litre in the month of May-1, 2003 at station A (Fig. 1, g).

In pennate type, ***Nitzschia longissima*** occupied a high proportion of the total diatom assemblage at both stations and was the most dominant species from all groups. It constitutes more than 97% of total diatoms in the months of February, 2003 at station A and more than 95% of total diatoms in the month of May, 2003 at station B (Table 2). Its dominancy was high at station B with peak numbers of the cells recorded 15.80×10^3 cell/litre in the month of February-1, 2003. At the time salinity was 40.0‰ and temperature 25.1ºC. Second peak observed in the month of April-2, 2003 was 15. 29×10^3 cell/litre. Lowest cell abundance recorded was 0.07×10^3 cell/litre in the month of August-1, 2002 at station B. Station A has a peak of 12.97×10^3 cell/litre in the same month February-1, 2003 but the abundance is lower as compared to station B. Cell abundance remain high at the second half of February-1, 2003 that was 10.5×10^3 cell/litre and showed little increase 10.6×10^3 cell/litre in the next month of March-1, 2003. Lowest cell abundance recorded was 0.04×10^3 cell/litre in the month of June-2, 2002 (Fig. 1, c).

Navicula directa was dominant throughout the year except in the month of June-1, 2002 and June-2, 2003. Almost similar cell numbers were observed at both stations except in the months of April-1, June-1 and July-1, 2003. This species was observed in bloom condition with the peak of cell abundance of 29.567×10^3 cell/litre in the month of September-2, 2002 from both stations, making up 99% of total diatoms in the same month (Table 4). Salinity values were 38‰ and temperature was 29.9ºC at both stations. Second highest cell numbers observed were 7.18×10^3 cell/litre in the month of March-2, 2003. Lowest cell abundance 0.05×10^3 cell/litre which was the same observed in the months of Aug-1, Dec-2, 2002 and May-1, 2003 at both stations. Rest of the months showed almost same and uniform distribution (Fig. 1, d).

Pleurosigma sp 1 was also dominant at both stations and comparatively had low abundance at station A than station B. Its contribution to total diatoms was 7.6% in the month of December, 2002 at station A and 7.2% in the month of January, 2003 at station B (Table 2). The salinity was 37.3‰, 41‰ and temperature was 24.0ºC, 24.5ºC at stations A and B respectively. This species also showed its presence throughout the year at station B but at station A absent in the months of Aug-2, Dec-1, 2002 and Jan-1, 2003. The highest cell density 0.253×10^3 cell/litre observed in the month of October-1-2002 at station B and at station A, 0.173×10^3 cell/litre in the month of March-2-2003. Lowest cell densities observed in the months of June-1, Aug-1 and September-1-2002 that was 0.007×10^3 cell/litre from station B and at station A lowest cell abundance was 0.01×10^3 cell/litre recorded in the month June-2, 2002 (Fig. 1, e).

Thalassionema nitzschiodes contributed 25% in the months of May and July, 2002 at station A and 22.7% in the month of July, 2002 at station B

(Table 2). This species attained its maximum abundance in the month of May-2-2002 with the cell abundance of 0.50×10^3 cell/litre at station A. At station B maximum cell abundance also observed in the same month but in the year May-2-2003 so the maximum abundance appeared only in summer months at both stations. A second peak of cells 0.28×10^3 cell/litre observed in the month of June-1-2003 at station B. Almost absent in winter months, the lowest cell abundance observed in the month of Nov-2-2002 and Dec-1-2002 was 0.007×10^3 cell/litre at both stations (Fig. 1, f).

In pennate group, ***Amphora*** sp was abundant at station B and frequently found at station A. It appears in May-1, Jun-1 and Jul-1-2002 at station A and in May-1, June-1, Sep-1-2002 and July-1-2003 at station B. This genus was found more or less in same months of summer at both stations. Highest cell abundance was observed 0.25×10^3 cell/litre in the month of Jul-1-2003 from station B (Fig. 1, h). ***Asterionella formosa*** was abundant at both stations. This species appears in May-1-2002 at both stations then disappears in Aug-1-2002 to Mar-2-2003 at station B. Again appears in the month of April to Jul-1-2003. *Asterionella formosa* is present all the year except in the months of Oct, Dec-1-2002, Jan-2-2003 and Feb-1-2003 at station A. Highest cell abundance observed was 0.25×10^3 cell/litre from station B (Fig. 1, i).

Navicula transitranse was encountered as abundant at station A and frequent at station B. Highest cell abundance was 2.9×10^3 cell/litre in the month of June-1, 2002 at station A and at station B 0.2×10^3 cell/litre was the higher cell numbers in the month of July, 2002 (Fig. 1, j). ***Pleurosigma*** sp 2 was abundant at both stations. Highest cell density was recorded 0.14×10^3 cell/litre in the month of Apr-1-2003 from station A. This species was completely absent in the months of August and September 2002 from both stations. Lowest cell abundance 0.007×10^3 cell/litre was recorded in June and July 2002 at station B (Fig. 1, k).

Navicula sp was abundant at both stations. This species was present from July to Oct-2-2002 at station B and at station A appears in the month of May-2-2002 with lowest abundance of 0.007×10^3 cell/litre. Highest cell abundance recorded was 0.14×10^3 cell/litre in the month of Oct-1-02 from both stations (Fig. 1, l). ***Pinnularia*** sp was found abundantly at both stations. This species was present in the month of Jun-1 and Jul-1-2002 at station B and appears in the month of Jul-1-2002 at station A**;** then disappears and again appears from Oct-2002 to May-2003 at both stations. Highest cell abundance recorded was 0.66×10^3 cell/litre in the month Sep-1-2002 from station A (Fig. 1, m).

Odontella mobiliensis was frequently present at station A and abundantly recorded at station B. This species showed presence from June-1-2002 to Feb-2003 at station B and May-1, Jun-2, Nov-2-2002 and Mar-2-2003 at station A. Highest cell abundance was observed 0.08×10^3 cell/litre in the month of Oct-2-2002 at station B (Fig. 1, n). ***Chaetoceros decipiense*** was frequently found at station B but in lower cell numbers. Higher cell abundance observed was 0.06×10^3 cell/litre in the month of Oct-1, 2002 (Fig. 1, o).

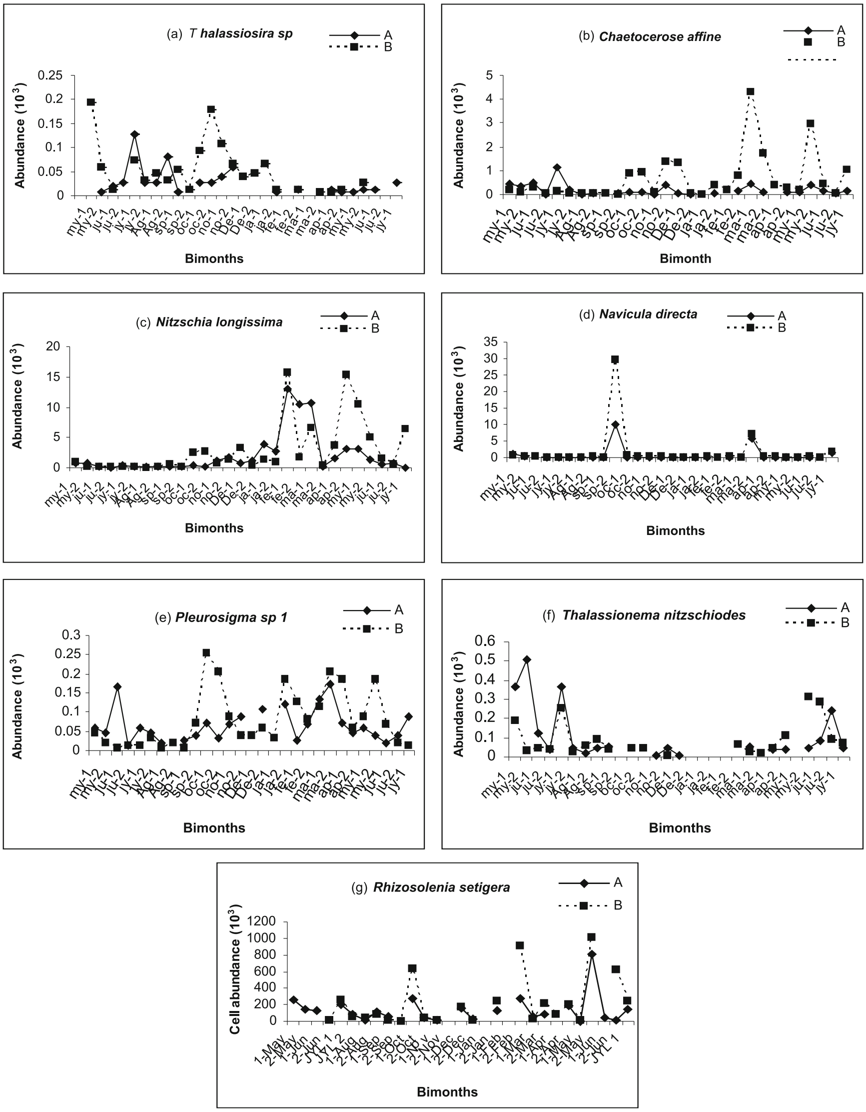

Fig. 1: Seasonal variation in abundance of dominant species of diatom assemblage ($\times 10^3$ cells/litre). Note that the scale of abundance is not uniform throughout the graphs. (a) *Thalassiosira* sp, (b) *Chaetoceros affine,* (c) *Nitzschia lonissima,* (d) *Navicula directa*, (e) *Pleurosigma* sp 1, (f) *Thalassionema nitzschiodes* and (g) *Rhizosolenia setigera.*

Guinardia flaccida was abundant at both stations. This species appears in the month of June to October, 2002 and then absent in November, 2002 and April, 2003 at station B. Highest cell abundance was recorded 0.28×10^3 cell/litre in the month of Jan-2-2003 from station B. *Guinardia flaccida* was completely absent at station A in the months of August, 2002 and April, 2003

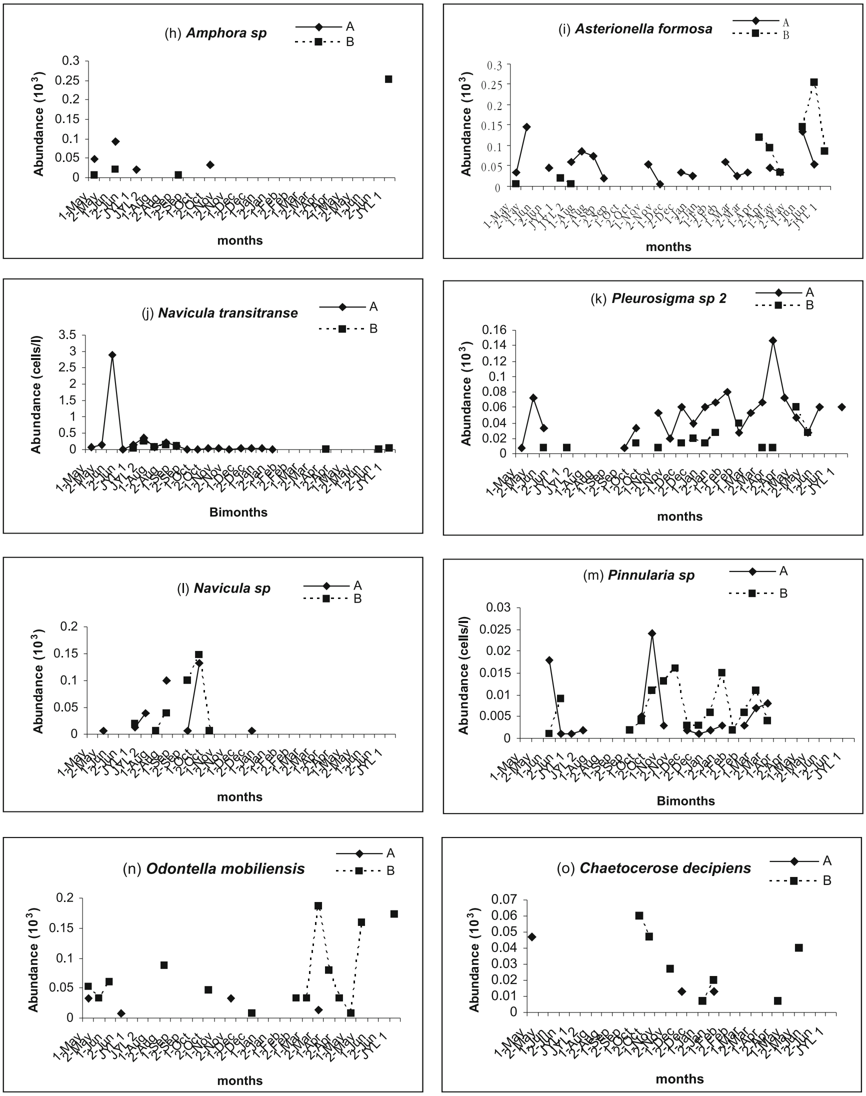

Fig. 1 (Contd): Seasonal variation in abundance of dominant and frequently found species of diatom assemblage. (h) *Amphora* sp, (i) *Asterionella formosa*, (j) *Navicula transitranse*, (k) *Pleurosigma* sp 2, (l) *Navicula* sp, (m) *Pinnularia* sp, (n) *Odontella mobiliensis*, (o) *Chaetoceros decipiece.*

(Fig. 1, p). ***Eucampia zodiac*** was abundantly found species at both stations. At station B this species was absent in the months of Aug-1-2002, January, Feb-1 and Apr-2-2003. At station A also it was absent in the months of Aug, 2002 and Apr, 2003. Highest cell abundance was observed 0.46×10^3 cell/litre in the month of Feb-2-2003 from station B (Fig. 1, q).

In centric group, ***Odontella sienensis*** was abundant at station B observed in May and June-2002; then disappears in July to again appear in August-2, Oct-2 and Dec-2-2002; then disappears in September, November, 2002 and January, 2003 then again shows its presence from February to July-1-2003. Highest cell abundance observed was 0.18×10^3 cell/litre in the month of March-2-2003. This species was frequently found at station A observed in the months of May, June, July and Oct-2-02 (Fig. 1, r). ***Odontella aurita*** was frequently found at both stations. This species appears in the month of Jun-02-2002 at station B and May-2 to Oct-2-02 at station A and disappears; then again appears in the same month of Jun-1-2003 at both stations. Highest cell abundance was observed 1.96×10^3 cell/litre in the month of Jun-02-2002 at station A (Fig. 1, s).

Planktoneilla sol was frequently found at both stations. At station B this species appears in the months of November and Dec-2002 and then again shows its presence in Feb-2 and July-1-2003. At station A it appears in Jun-2-2002 and then again shows its presence in Nov-1, Dec-1-2002, May and Jul-1-2003. Highest cell abundance recorded was 0.04×10^3 cell/litre in the month of Jul-1-2003 from station A (Fig. 1, t). ***Pseudonitzschia* sp** was frequently observed at station A, whereas it was found only at four occasions at station B. Highest cell numbers of *Pseudonitzschia* species were observed in July (2307 cell/litre) at station A and in April (1587 cells/litre) at station B (Table 3).

Table 3: Cell abundance (10^3 cells/litre)—Minimum and maximum of rare species from stations A and B

Rare species	*Station A*	*Station B*
	Abundance (10^3 cells/litre)	
Asterionellopsis glacialis	-	0.027-0.10
Cylindrotheca clostrium	-	0.13-0.2
Coscinodiscus radiatus	0.007-0.053	0.02
Corthrone criopilum	0.007-0.01	0.007
Ditylum brightwilli	0.01-0.833	0.007-0.01
Guinardia striata	2.82	3.68
Licmophora paradoxa	0.007	-
Nitzschia clostrium	0.64	-
Navicula f delicatula	0.01	-
Pseudonitzschia sp	0.1-2.30	0.007-1.5
Pleurosigma directum	0.007	0.007
Pleurosigma normani	0.027-0.073	0.007-0.02
Pleurosigma macrum	0.007	-
Rhizosolenia styliformis	-	0.02
Rhizosolenia bergonii	-	0.01
Skeletonema sp	-	0.02
Triceracium sp	-	0.02

Rhizosolenia imbricata was frequently found at both stations. This species has shown similar cell abundance of 0.093×10^3 cell/litre in the month of July-1-2002 at both stations. At station A maximum cell abundance recorded was 0.446×10^3 cell/litre in the month of June-2-2003 (Fig. 1, u). ***Synedra*** sp was abundant at station A and frequently found at station B. It appears in the month of May-2-2002; then disappears in June, Sep-2002 and Feb-2003. *Synedra* sp was present in the months of March and April, 2003 but in lowest

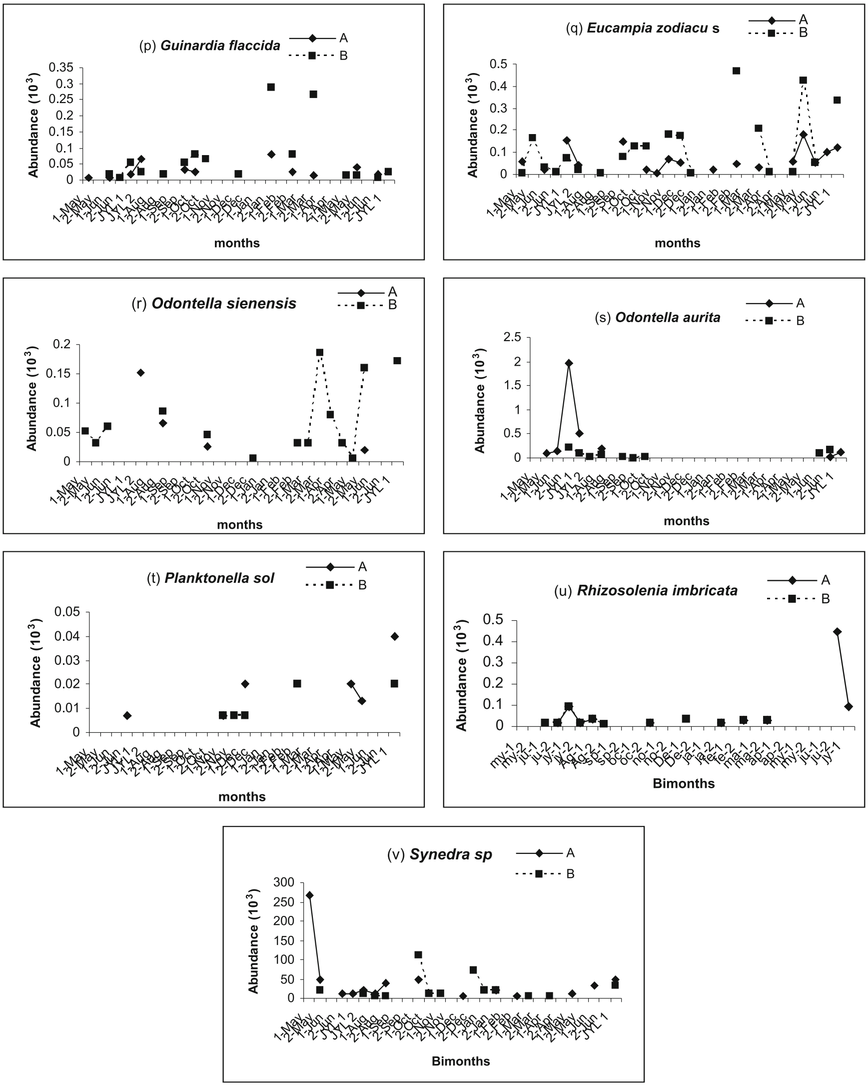

Fig. 1 (Contd): Seasonal variation in abundance of dominant and frequently found species of diatom assemblage. (p) *Guinardia flaccida*, (q) *Eucampia zodiacus*, (r) *Odontella sienensis*, (s) *Odontella aurita*, (t) *Plantoneilla sol*, (u) *Rhizosolenia imbricate* and (v) *Synedra* sp.

cell abundance of 0.007×10^3 cell/litre, then again disappears in the months of May and Jun-2003. *Synedra* sp also appears in the same month of May-1-2002 with highest cell abundance 0.26×10^3 cell/litre at station A. This species is completely absent in the months of September, Nov, 2002, March and Apr, 2003 at station A (Fig. 1, v).

Few species with low abundance are rare species which occur once or twice in a year and can also be considered as indicator species with particular environments. Abundance of rare species is presented in Table 3.

WATER PARAMETERS

Temperature was high all the year except in winter months of November, December, 2002 and January, 2003 at both stations. It varies from 23.50 °C to 31.83 °C at station A in the months of January and July, 2003 respectively. From station B minimum temperature recorded was 22.00 °C in the month of December, 2002 and maximum was 31.17 °C in the month of July, 2003. Salinity shows highest value at station B recorded 41‰ in the month of January, 2003 and lowest value observed was 34.67‰ in the month of July, 2003. Maximum value observed at station A was 40.00‰ in the months of July, November, 2002 and January, 2003. Minimum value recorded was 34.33‰ in the month of August, 2002 (Fig. 2).

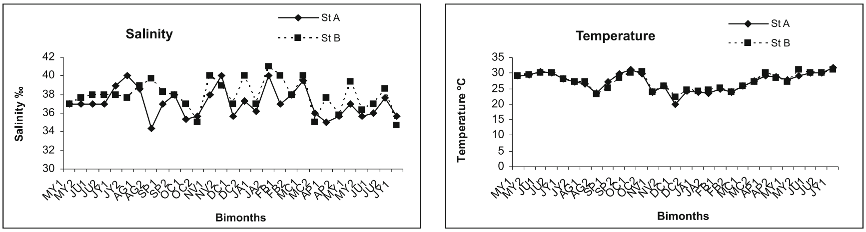

Fig. 2: Seasonal variations in salinity and temperature from stations A and B.

STATISTICAL ANALYSIS

Statistical analysis between the dominant diatom species and water parameters of both stations A and B was determined (Table 4). All dominant species were correlated with the salinity and temperature at both stations A and B. At station A all the species have shown positive correlation with the salinity except *Rhizosolenia setigera* = –0.2. At station B *Chaetoceros affine* = 0.05 and *Navicula directa* = 0.05 have shown positive correlation with salinity but *Nitzschia longissima* = –0.2, *Pleurosigma* sp 1 = –0.2, *Thalassiosira* sp = –0.05 *Thalassionema nitzschiodes* = –0.1 and *Rhizosolenia setigera* = –0.1 have shown negative correlation with salinity. All dominant species at station B have shown positive correlation with the temperature: *Chaetoceros affine* = 0.05, *Navicula directa* = 0.08, *Nitzschia longissima* = 0.02, *Pleurosigma* sp 1 = 0.15, *Rhizosolenia*

Table 4: Correlation of dominant diatom species with temperature and salinity at stations A and B

Dominant species	*Temperature*		*Salinity*	
	A	*B*	*A*	*B*
Chaetoceros affine	0.20	0.06	0.30	0.05
Navicula directa	0.22	0.09	0.07	0.06
Nitzschia longissima	-0.37	0.02	0.21	-0.22
Pleurosigma sp 1	-0.20	0.16	0.13	-0.22
Rhizosolenia setigera	0.16	0.24	-0.25	-0.14
Thalassiosira sp	-0.19	0.20	0.18	-0.05
Thalassionema nitzschiodes	0.34	0.29	0.12	-0.19

setigera = 0.23, *Thalassiosira* sp = 0.20, *Thalassionema nitzschiodes* = 0.29. At station A *Chaetocerose affine* = 0.20, *Navicula directa* = 0.2, *Rhizosolenia setigera* = 0.15 and *Thalassionema nitzschiodes* = 0.34 were positively related with temperature and *Nitzschia longissima* = –0.37, *Pleurosigma* sp 1 = –0.19 and *Thalassiosira* sp = –0.19 were negatively related with temperature (Table 4).

DISCUSSION

Diatoms are the dominant phytoplankton group (69%) of the coastal waters of Karachi in terms of their abundance. The diatom species observed during this study have been previously reported from Pakistani waters by Saifullah and Moazzam, 1978; Shameel and Tanaka, 1992; Ghazala et al., 2006 but their seasonal abundance and distribution data is lacking from this region. Diatoms composition showed typical temperate, tropical, subtropical and cosmopolitan species (Schiebel et al., 2004). This mix of species showed that Manora Channel is a port where different ships from various parts of the world visit with regular intervals that can transport the diatom species from different geographical areas. Some species were neritic which showed influx of open sea water into near-shore waters like *Odontella aurita* and *Triceracium* sp. The most diverse genera were *Pleurosigma, Chaetoceros, Rhizosolenia*, *Navicula* and *Odontella* at both stations. Auxospores in species like *Guinardia flaccida, Odontella mobileinsis* and *Rhizosolenia setigera. Ditylum brightwilli, Odontella sienensis* and *Odontella aurita* were found in a phase of active cell division at the time of sampling in different months.

The dominant species including *Nitzschia longissima, Navicula directa* and *Chaetoceros affine* are consistently seen in high cell abundance. Contrastingly *Pleurosigma* sp 1, *Thalassiosira* sp, *Thalassionema nitzschiodes* and *Rhizosolenia setigera* were seen almost throughout the sampling period but comparatively in less numbers. These all diatoms were also reported as dominant part from other upwelling regions (Lassiter et al., 2006; Chavez et al., 1991; Kobayashi and Takahashi, 2002). It suggests that these diatoms species are more tolerant to nutrient-rich upwelling systems of northern Arabian Sea. Monsoon system is a pronounced feature affecting hydrographics of the Arabian Sea throughout the year. It causes upwelling and brings nutrient-rich cold waters to the upper water columns. The response of diatom species was clearly seen when in late monsoon periods bloom condition of diatom species *Navicula directa* and *Nitzschia longissima* was observed in the months of September, 2002 and February, 2003 respectively contributing high biomass in the diatoms community. The water is anoxic and a minimum value 0.7 mg/litre for dissolved oxygen was recorded at that time. Chaghtai and Saifullah (1992) reported a bloom of *Navicula Boray* (a parent species of *Navicula directa)* from mangrove habitat of Sands pit Karachi, Pakistan. Similar result was reported by Parab et al. (2006) from eastern Arabian Sea.

During high concentrations of diatoms the community consists of pennate species. In pinnate, *Nitzschia longissima* and centric *Chaetoceros affine* was found in high abundance at both stations. *Nitzschia longissima* was also reported as the dominant component of the diatom community with high concentrations from south eastern Arabian Sea by Jayothibabu et al. (2008).

The estimated abundance among species were variable from both stations A and B. The species encountered relatively high abundance at station B as compared to station A indicating differences of their contributions to diatom community biomass. Dominant species are commonly used to analyze nature of habitat in the ecosystem. Among seven dominant species four species belong to the pennate type. Dominance of pennate species over centric types with high abundance suggests that they have better tolerance against environmental variables and pennate species are successful diatom species in this region. Similar result was reported by Gomi et al. (2005) from surface waters of Indian sector of Southern Ocean and Turkish waters by Cetin and Sen (1998).

The abundant and frequent species with both high surfaces to volume ratios (*Navicula* sp, *Pleurosigma* sp, *Pinnularia* sp, and *Synedra* sp) and low surfaces to volume ratios (*Chaetoceros* spp) have difference in their nutrient absorbing capabilities (Panigrahi et al., 2004). It could be a possibility that during the seasonal changes regarding low nutrients and high nutrient conditions in the area the diatom species successive competition occurs.

Temperature is a very important factor and was found positively and strongly related with all the dominant species at station B. At station A three dominant species were negatively related with temperature. At station A salinity was positively related with all dominant species except centric diatom *Rhizosolenia setigera* and at station B all dominant species were positively related with salinity except *Chaetoceros affine* and *Navicula directa.* It suggests that temperature and salinity are the most significant factors that give shape to the diatom community and control the community changes. The abundance of these dominant species throughout the year was influenced by the seasonal change in temperature and salinity. Similar results were reported by Gasiunaite et al. (2005) from Baltic Sea and Wang et al. (2006) from subtropical area of South China Sea.

The Manora Channel is facing eutrophication problem due to the input of sewage and industrial effluents brought by Lyari river. The region is constantly affected by the pollution. It may be interesting to note that some species like *Licmophora paradoxa, Nitzschia clostrium, Navicula f delicatula* and *Pleurosigma macrum* were exclusively present in the samples collected from station A which is located inside the Manora Channel and has polluted waters. These species may consider as eutrophication indicator species.

This is the first detailed study regarding the diatom species composition, seasonal abundance and distribution from this region. Further assessment on ecological aspect may be useful to describe species in each genus and identify pollution indicator species. This study suggests further investigation of hydrographical and meteorological effects on species diversity in the region for understanding the interaction between the diatoms community and environmental variables.

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A Review on Nutrient Pollution of Coastal Aquifers of Sri Lanka

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Abstract: Nutrients such as nitrates and phosphates in the groundwater are a serious concern in certain parts of Sri Lanka where many rural communities depend on groundwater for their daily water supplies. In addition excess nutrients in water have lead to water quality problems such as algal blooms, eutrophication in a number of surface water bodies.

Sri Lankan coast line extending over a length of nearly 1585km is one of the highly sensitive and rapidly developing areas of the country. The coastal aquifers can be subdivided into four groups according to aquifer media by which the coastal areas are characterized. Those aquifers play an important role in supplying water both for domestic and agricultural activities in the areas concern.

Sri Lankan coastal groundwater resources at most places appears to be contaminated by nutrient pollutants. Elevated levels of pollutants have been often recoded in shallow karstic limestone aquifers of northern and sandy aquifers of northwestern and northeastern coastal zones. It is revealed that the behavior of nutrients in groundwater is mainly governed by intrinsic properties of aquifer media and the distribution of nutrients shows a clear correlation with anthropogenic activities and land use pattern of the coastal areas. The most commonly recorded nutrient in coastal groundwater is nitrate. With regard to phosphate concentrations however, Sri Lankan coastal groundwater is presently safe though shows increasing trend of future vulnerability.

It is inferred that coastal sandy aquifers in Sri Lanka are at risk and need an immediate protection effort with comprehensive investigations, introducing preventive measures and establishing a long term monitoring setup.

Key words: Nutrients, groundwater, coastal aquifers of Sri Lanka, vulnerability.

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INTRODUCTION

The coastal areas are one of the most valuable and vulnerable areas of developing countries. Significant inputs of nutrients to those areas arrive via anthropogenic activities. Nutrient pollution in both surface and groundwater has drawn greater attention world-wide and consistently ranked as one of the top causes of degradation of water quality (Liu et al., 2005). Excess nutrients, especially nitrogen and phosphorus, lead to significant water quality problems including harmful algal blooms and eutrophication, and even produce potential hazards to human health (Knobeloch et al., 1992; Fan and Steinberg, 1996; Gelberg et al., 1999; Fennesy and Cronk, 1997; Gulis et al., 2002; Gupta et al., 2001).

There is a high threat on coastal waters due to anthropogenic input of nutrients from fertilizers, sewage, erosion and atmospheric pollution (Nixon, 1995; Carpenter et al., 1998; Conley, 2000; Cloern, 2001). Nitrate and phosphate are most dominant nutrient pollutants in shallow coastal aquifer water in the world (Voudouris et al., 2004; Spalding and Exner, 1993; Suzumura et al., 2000; Min et al., 2002). In contrast, nitrate is one of the most mobile and soluble ions in ground water while phosphate tend to be immobile in most cases (Wakida and Lerner, 2005; Gardolinski et al., 2004).

Coastline of Sri Lanka which covers nearly 1585 km is one of the highly sensitive areas of the island (Natural Resources Sri Lanka, 1991). It is continuously being developed for past few decades and the population of the area has continuously been increased (Villholth and Rajasooriyar, 2009). Of total land mass of the country, 24% is occupied by coastal region with 25% of the total population, 70% of the total tourist hotels, 67% of the industrial units, 20% of the total home gardens and 17% of agricultural lands (International Union for Conservation, 2007). Therefore, the processes on the coastal area are multifaceted and interacted to a larger extent and at many levels. Industrialization, tourism and intensive agricultural activities are some of the major contributors for coastal degradation. Hence coastal fresh waters of Sri Lanka are highly vulnerable to contamination (Bhuvendralingam et al., 1994; Lawrence et al., 1992). Although such vulnerable situations were recorded, studies and application of remediation and precautionary methods are still at the preliminary stages. This may be due to lack of attention to the protection of coastal water resources.

GEOMORPHOLOGY AND GEOLOGICAL BACKGROUND OF SRI LANKA'S COASTAL AREA

Coastal area which is low lying diversifies in geology and geomorphology. As shown in Fig. 1 most of the coast belongs to Precambrian metamorphic terrain while the rest belongs to Miocene sedimentary limestone belt in northern area of the island. Quaternary formations lying on the above terrains make recent sedimentary deposits.

Northern coastal area including entire Jaffna Peninsula is characterized by Miocene limestone which is overlaid by Quaternary soils specially plateau deposits, red earth formations and coastal sands (Wayland, 1919; Cooray, 1984). The northern Miocene belt extends from south of Puttalam to Mullathive in the northwest. The scattered outcrops of the limestone are exposed along the coast of Aruwakkalu and Karative, and some sandstones and sands are exposed in small coastal cliff of Kudiramalai (Wayland, 1919).

Starting from Colombo up to Puttalam, the prograding West coast is geologically diversified with different formations such as recent beach sand deposits, river mouth deposits, marshy formations, lagoonal deposits, estuarine deposits, beach rock formations and cliffs of Wanni complex metamorphic rocks (Swan, 1983; Cooray and Katupotha, 1991; Senarathne and Dissanayake, 1991; Katuptha, 1994).

In contrast, the Southwestern coastal zone from Gall to Colombo is characterized by remnants of crystalline terrain and Quaternary sedimentary deposits such as the submerged lagoonal and estuarine deposits, marshy and coral formation and recent sand deposits (Cooray, 1984; Wadia, 1941; Katupotha, 1988). Since the area belongs to wet zone of the country, specific secondary formation of laterite covers most of the Southwest and Western coast (Herath and Pattiarachchi, 1963).

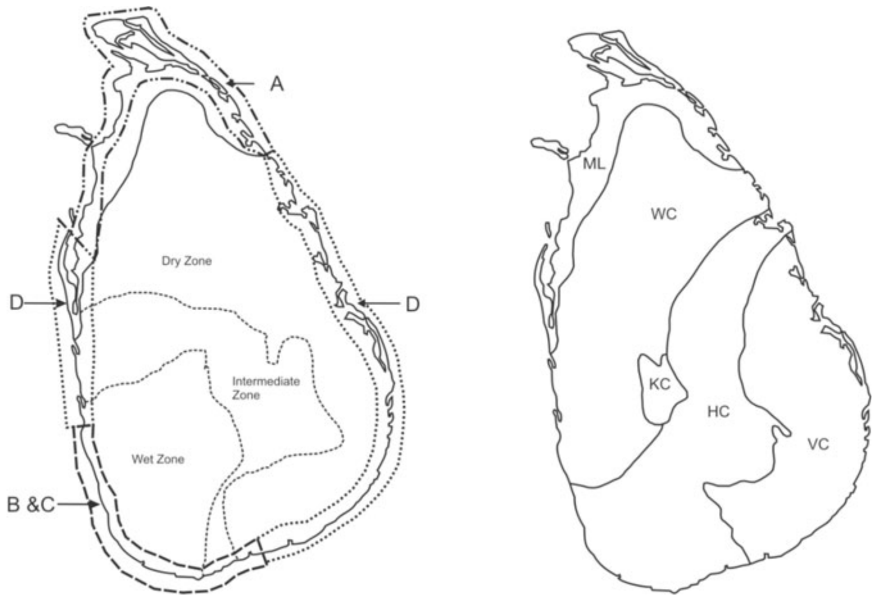
The southern coast is characterized by more eroded rocks of Highland and Vijayan complexes. Such coasts are observable in Ussangoda and Galle. Also sand dunes, recent sand deposits, lagoonal and estuarine deposits are dominant in Hambanthota, Pathirajawela, Kalamatiya, Kirinda, Sangamankanda Point and Bundala area (Swan, 1983; Katuptha, 1994; Deraniyagala, 1976; Katupotha and Wijayananda, 1989).

Southeast and Eastern coast is a prograding coastal stretch. North and West of the Batticalao are composed of sand dunes and beach sand formations originated from sea level changes during Quaternary period (Katuptha, 1994). Kuchchaweli area is identified as a shelly clay deposit of estuarine formations (Kumaraswami, 1905). Coast of Trincomalee area can be described as a high ground headland of highland crystalline terrain. In addition the eastern coast is also composed of different Quaternary formations as in other coastal belts of Sri Lanka.

COASTAL AQUIFERS

In general the coastal area of Sri Lanka is characterized by different types of aquifers and they can be categorized as follows (Fig. 1): (a) Northern and Northwestern limestone aquifers, (b) Combined regolith and fissured crystalline aquifers, (c) Coastal wetlands and estuary deposits and (d) Quaternary unconsolidated sandy aquifers (Davis and Herbert, 1988).

Generally 100 to 150 m thick, flat bedded and extremely jointed Miocene limestone belt forms shallow karstic and deep confined aquifer systems in northern and northwestern coast of Sri Lanka (Katupotha, 1988). Groundwater



(a) (b)

Fig. 1a: Generalized map of types of coastal aquifers of Sri Lanka. A: Northern and Northwestern limestone aquifers. B: Combined regolith and fissured crystalline aquifers. C: Coastal wetlands and estuary deposits. D: Quaternary unconsolidated sandy aquifers. **Fig. 1b:** General geology of Sri Lanka. HC: Highland complex. VC: Vijayan complex. WC: Wanni complex. KC: Kadugannawa complex. ML: Miocene limestone (after Cooray, 1994).

of coastal hard rock region is confined in deep fracture zone aquifers and shallow weathered overburden aquifers. The lateritic formations resting on the hard rock specially in Western areas of the country forms interconnected mosaic aquifer systems (Sirimanne, 1952). The Quaternary sandy aquifers cover Eastern, Southeastern and Northwestern parts of the coast and they are highly permeable unconfined aquifers which consist of considerable amount of fresh water (Cooray, 1984).

NUTRIENTS IN COASTAL AQUIFERS OF SRI LANKA

Nutrients in coastal aquifers of Sri Lanka have not yet been widely studied. Data for most of the areas is largely unknown. Some areas of the coast are not occupied for investigations, especially southeast coast which is covered by tropical dry zone forest. The occupation and access to eastern coast has also been restricted during the past three decades due to security problems of the country. However attention to the nutrient pollution of coastal groundwater has been ignored. Scattered data currently available are presented and discussed in this paper.

Northern Coastal Area

Most of the northern coast of Sri Lanka, specially Jaffna peninsular, depends on ground water due to lack of other fresh water resources (Nanthini et al., 2001). The groundwater basins are recharged by Northeast monsoonal rainfall during the very limited time from November to January. Therefore, excessive utilization for domestic and agricultural purposes makes rapid degradation of groundwater resources too. Two decades ago, elevated levels of nitrate in ground water of karstic aquifers in Jaffna peninsula were recorded due to intense agricultural activities (Nandakumara, 1983; Meegaswaran and Mahalingam, 1983; Nagarajah et al., 1988). Improper planning of soakage pits and latrines have also contributed to increase the nutrients in groundwater in the area (Navarathnarajah, 1994). Recently, as a result of continuation of agricultural practices, groundwater of 60% of the wells in Jaffna peninsula have shown exceeded levels of nitrate-N (Table 1) than the WHO guideline values (Rajasooriyar et al., 2002; Jeyaruba and Thushyanthy, 2009). Due to intensive application of chemical fertilizers and organic manures, soils of the area have been polluted and stored excess amount of nutrients (Vakeesan et al., 2008). The leaching of excess soil nutrients is possible by monsoon rains and rapid irrigation activities. The Miocene limestone of the area is highly fractured and characterized by interconnected dissolution cavities which enhance rapid

Table 1: Nutrient concentrations of different types of aquifers

Aquifer type and area	*Karstic aquifers –Jaffna peninsular*[a]	*Quaternary sandy aquifers Northwest coast/ Kalpitiya (authors unpublished data)*	*Quaternary sandy aquifers Northeast coast* [a,b]	*Combined regolith and crystalline terrain – Southern coast* [c]
Duration	From June 1997 to July 1999	From May 2008 to October 2009	July to December 2006	December 2005 to December 2007
Nitrate				
Maximum	17.41	212	40.5	5.8
Minimum	0.16	0.9	0.5	0.1
Mean	-	37.05	21.4	1.6
Phosphate				
Maximum	-	5.7	20.5	1.74
Minimum	-	0.05	0.42	0.01
Mean	-	0.59	6.33	0.2

Values are given as mg/l. a – Gowrithasan, 2007, b – Sugunathasa, 2007, c – Welagedara, 2009.

migration of leached pollutants in the aquifer water. Therefore, the nitrate flux in land areas of the peninsula resulted from rapid application of fertilizers can migrate to coastal areas and coastal groundwaters are possibly contaminated. Also, increased extraction of ground water for agricultural activities has created lowering of groundwater table and hence coastal aquifers are threatened by sea water instruction (Balendran, 1969). Therefore, shallow karstic aquifer of coastal area of the Jaffna peninsula is highly vulnerable at present.

Northwestern Coastal Area

Northwestern coastal area consists of highly productive quaternary sand aquifers of the country. Among them, ground water in highly permeable aquifers of Kalpitiya peninsula is used for irrigation and domestic purposes for decades. The area is characterized by different land use patterns. It has been evolved drastically during the past few decades dominating vegetable cultivated areas from previous coconut cultivations and most of the paleo sand dunes have been cut and flattened for cultivation. The aquifer media is mainly infertile sand regosols (Jayasingha et al., 2008). Therefore, farmers use excessive amounts of chemical fertilizers. Since the area suffers from high evapo-transpiration and less precipitation, which is the only way of recharging the aquifer, irrigation is done by extracting large quantities of ground water. Therefore, high nitrate levels in ground water (Table 1) have been recorded for decades (Lawrence et al., 1992; Kuruppurachchi and Fernando, 1999; Liyanage et al., 2000; Jayasingha et al., 2008). Recent investigation by the authors has shown an increasing trend of nitrate in ground water in the Kalpitiya peninsula especially in vegetable cultivated areas indicating a clear correlation of nitrate with land use pattern. The results further revealed that phosphate content in ground water is low and does not correlate with fertilizer application or human waste disposal.

Northeastern Coastal Area

The quaternary sandy aquifers in Nilavali-Kuchchaweli and Sainthamarudhu areas are another productive groundwater resource in Northeastern coast of the country. The aquifers are referred as raised beaches of unconsolidated coastal sands and they are bounded by the sea on their eastern side and by mud flats or land on their western side. In contrast a steady infiltration rate of the aquifers is between 65 cm/hr to 75 cm/hr. Several decades ago the ground water showed marginal values of nitrate to exceed the WHO guideline values (Dissanayake, 1988). Elevated levels of nitrate (Table 1) in ground water of this aquifer were recorded and have shown temporal variation during the year with the monsoonal climate (Nawas et al., 2005). High nitrate concentrations (up to 80 mg/l) have been detected in ground water of Sainthamarudhu area which is highly populated and septic tanks have been installed without proper screening and regardless of distances to the wells. Therefore, in contrast, poor management of human waste and organic waste disposal has caused elevated levels of nitrate in ground water. Although the Trincomalee coast is highly urbanized low nitrate content in ground water was reported (Dissanayake, 1988). This can be due to the low mobility of nitrate in the hard rock aquifer system.

Eastern Coastal Area

The Batticaloa area is characterized by series of wetlands with clayey alluvial soil and beach sandy soil. Improper management of waste disposal and drainage in the area has been resulted by the rapid urbanization and some areas have also been used for intense agricultural activities. Hence, nutrients specially nitrate content (Table 1) in ground water shows elevated levels especially in the urbanized and agricultural areas (Gowrithasan, 2007; Sugunathasa, 2007). Phosphate (Table 1) also shows elevated levels in urbanized areas probably due to improper waste management practices and poor drainage systems. Values of nutrients obtained from investigations, carried out by Gowrithsan (2007) and Sugunathasa (2007), show a temporal variation and an increasing trend with time.

West and Southwestern Coastal Area

West coast of the country is highly urbanized. Hence water usage is very high. Colombo, the capital city area is supplied with pipe-borne water and a limited number of deep tube wells are used for domestic and industrial purposes (Department of Statistic and Census). However, nutrient pollution of surface water bodies such as Baire Lake in and around the Colombo area can be observed. Due to the tourist activities, the small stretch of sandy aquifers along the West coast is possibly polluted. Several decades ago, high nitrate values (20 mg/l) have been recorded (Dissanayake, 1988) and it can be inferred that coastal groundwater in West coast must have been polluted at present.

In contrast, the nutrient content in ground water of Southwest coast shows low concentrations (Welagedara, 2009; Pitawala et al., 2007). This coastal area is characterized by inhomogeneous soil types such as beach sand, peaty soil, dune sand, lateritic soil and calcareous soil. In addition, very good variation of land use pattern can also be observed. Although the area is highly populated and dominated by tourist hotels and resorts, both nitrate and phosphate concentration (Table 1) recorded in groundwater samples are low and below the WHO guideline values in general. However, the water quality of this coastal aquifer has also been altered by the 2004 tsunami waves.

South and Southeastern Coast

The South coast is urbanized and dominated with tourist industry. Ground water of this area is expected to be contaminated with nutrients but presently data are lacking. However, two decades ago, ground water in the coast of

Ambalanthota and Hambanthota areas had shown very low values (less than 5 mg/l) of nitrates (Dissanayake and Weerasooriya, 1985).

The Southeast coastal areas are covered with Yala sanctuary; hence human impact to coastal area is insignificant. Therefore, it can be expected to have very low nitrate content in ground water unless there are any other natural causes.

The behaviour of nutrients in ground water is mainly governed by the geological nature of aquifers. High permeability and lack of natural removal processes may have caused elevated levels of nutrients in shallow aquifers in coastal area. Despite very high anthropogenic input, inland groundwater bodies contain relatively lower values of nutrients. It also confirms that clay and exchangeable ions in overburden can buffer the nutrient pollution (Dissanayake, 1988; Gunatilake and Gunatilake, 2004; Silva and Ayomi, 2004; Young et al., 2009).

CONCLUSION

Ground water in coastal aquifers of Sri Lanka shows contaminations with regard to nutrient pollutants. Among them, nitrate is the most dominantly recorded nutrient pollutant. The elevated levels are mostly recorded in highly permeable quaternary sandy aquifers in Northeast and Northwest coastal areas of the country. Northern coastal area which is characterized by karstic limestone aquifers also shows elevated levels. Higher concentrations of nutrients have a clear correlation with intense agricultural practices and urbanization in these areas. It is noticed that nitrates in groundwater of Northwestern and Northern coastal aquifers have exceeded WHO guideline values and are increasing at an alarming rate. Although coastal groundwater in these areas is safe from phosphate accumulation at the moment, there is a potential of exceeding the safe limits in future.

It is noticed that migration and behaviour of nutrients in coastal aquifers are largely governed by the aquifer properties. Highly permeable aquifers are easily contaminated and have accumulated large concentrations over the time. Although the inputs are high, less permeable aquifers in the areas of southern coast shows low nutrient contaminant levels.

FUTURE TREND OF GROUNDWATER IN COASTAL SANDY AQUIFERS

Sri Lankan coastal sandy aquifers will play an important role in supplying water for domestic, agricultural and industrial sectors in the future, with present development state of the country. Being highly permeable, the unconfined sandy aquifers are primarily vulnerable to contamination of nutrient pollutants. Vulnerability increases with the increase of industrial and agricultural development activities of coastal areas and boom of population. Hence it can be inferred that coastal sandy aquifers are in danger and need an immediate protection scheme with comprehensive investigations and preventive measures. Also, a long-term monitoring programme must be designed after setting up of base line data set by studying present state of groundwater quality and quantity.

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6

Heavy Metal Pollution in Sediments at Ship Breaking Area of Bangladesh

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Abstract: The research was carried out to assess the trace metal concentration in sediments of ship breaking area in Bangladesh. The study areas were separated into Ship Breaking Zone and Reference Site for comparative analysis. Metals like iron (Fe) was found at 11,932 to 41,361.71 $\mu g.g^{-1}$ in the affected site and 3393.37 $\mu g.g^{-1}$ in the control site. Manganese (Mn) varied from 2.32 to 8.25 $\mu g.g^{-1}$ in the affected site whereas it was recorded as 1.8 $\mu g.g^{-1}$ in the control area. Chromium (Cr), nickel (Ni), zinc (Zn) and lead (Pb) also varied from 22.89 to 86.72 $\mu g.g^{-1}$; 23.12 to 48.6; 83.78 to 142.85 and 36.78 to 147.83 $\mu g.g^{-1}$ respectively in the affected site whereas these were recorded as 19, 3.98, 22.22 and 8.82 $\mu g.g^{-1}$ in the control site. Copper (Cu), cadmium (Cd) and mercury (Hg) concentration varied from 21.05 to 39.85, 0.57 to 0.94 and 0.05 to 0.11 $\mu g.g^{-1}$ in the affected site and 33.0, 0.115 and 0.01 $\mu g.g^{-1}$ in the control site. It may be concluded that heavy metal pollution in sediments at ship breaking area of Bangladesh is at alarming stage.

Key words: Trace metal, affected area, control site, heavy metal, alarming stage, ship breaking area.

INTRODUCTION

The marine environment of the coastal water is vital to mankind on a global as

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well as on local basis concerning energy. The Bay of Bengal which is a potential bode of marine life as well as for its vast coastal communities is now continually polluted by different types of pollutant through influx of land base and other sources and put an alarming signal of awareness about pollution in the sea. The coastal areas of Chittagong, Bangladesh, support a complex trophic organization, sustain a high biodiversity including some endemic species and are highly susceptible to interference from activities. Coastal ecosystem makes a sustainable livelihood particularly to coastal fishing communities.

Ship breaking yards along the coast of Chittagong (Faujdarhat to Kumira), confined in an area of 10 km, has become of a paramount importance in the macro- and micro-economic context of poverty-stricken Bangladesh. Ship breaking activity presents both challenge and opportunity for coastal zone management in holistic manner. Ship breaking activities offer direct employment opportunities for about 25,000 people. Moreover about 200,000 are also engaged in different business related to ship breaking activities in Bangladesh (YPSA, 2005).

The Department of Environment (DoE) has categorized the Ship Breaking Industry (SBI) as 'Red' in 1995 (EIA guidelines for the Industries, 1997). Ship breaking operation is generally carried out in the beach along the coast of any country. Any discharge like spillage of oil, lubricant, grease, PoPs etc. are spilled or thrown into the coast during the ship breaking operation (Hossain and Islam, 2006).

Heavy metal concentration in aquatic environment is of critical concern, due to toxicity of metal and their accumulation in aquatic habitats. Heavy metals, in contrast to most pollutants, are not biodegradable and they undergo a global ecological cycle in which natural waters are the main pathways. A large part of the heavy metal input ultimately accumulates in the estuarine zone and continental shelf, since these areas are important sinks for suspended marine and associated land-derived contaminants.

Heavy metals (Fe, Cu, Zn, Pb, Cr, Cd, Hg and Ni) introduced into the environment by dumping domestic and municipal wastes, industrial effluents, urban run off, agricultural run-off, atmospheric deposition and mining activities as well as upstream run-off are absorbed on to depositions and incorporated into the marine sediments. A large part of the heavy metal input ultimately accumulates in the estuarine zone and continental shelf. These areas are important sinks for suspended matter and associated land-derived contaminants (Yeats and Bewers, 1983).

Sediments act as indicators of the burden of heavy metals in a coastal environment, as they are the principal reservoir for heavy metals (Fitchko and Hutchinson, 1975). Sediments are the sources of organic and inorganic matter in the river, estuaries, oceans and the other water supply systems. Aquatic organisms living in the sediments accumulate heavy metals to a varying degree (Bryan and Hummerstone, 1977). The bioavailability of heavy metals may widely depend on sediment characteristics, water chemistry, hydrography and biological factors etc. (Ahmed et al., 2002). The effect of toxic metals on marine biota like fish, mollusk, coelenterate, crustaceans, birds and benthic organisms are increasing nowadays (Sadiq, 1992) (Table 1).

Table 1: The effects of toxic metals on marine biota

Organisms	*Effects*
Fish	At 1 µg-cd/L earlier hatching occurs (Javeen et al., 1998) Increase mortality Reduction in body defense system
Coelenterates	At 1 µg-cd/L ctenophores loss growth and survivality Irregular cell division
Mollusk	At 5 µg-cd/L *Crassorstrea virginia* gets slightly delayed development Delayed the maturation system
Crustaceans	Increase mortality and delay development (Mirkes et al., 1978) Effects occur on the shell development Irregular cell division
Sea birds	Mortality increase Reduction in body defense Retardation of growth Loss of breeding capacity Reduction of shell thickness of eggs
Benthos	Irregular structure Acute toxic condition at the bottom Retardation of growth

METHODOLOGY

Flow Chart Methodology

The full activity of the research has been depicted in flow chart (Fig. 1A).

Site Selection for the Experiment

The ship breaking areas from Bhatiari to Kumira of Chittagong coast extending about 10 km and the eastern side of Sandwip island have been selected as the study area considering Bhatiari-Kumira as the most affected site and Shiberhat to Guptachar ghat of the eastern side of Sandwip as the control site (Fig. 1). The eastern side of Sandwip has been considered as the control site because these are diagonally opposite and off the SBYs and the water and soil qualities are apparently free from pollutants as revealed from the earlier studies.

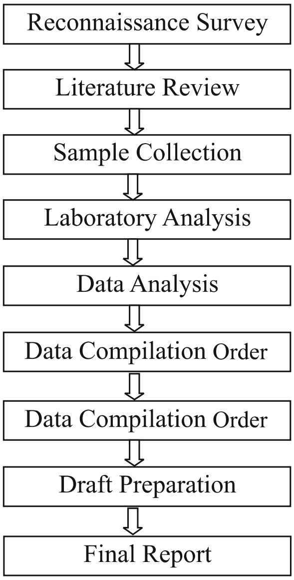

Fig. 1A: Working plan of the research.

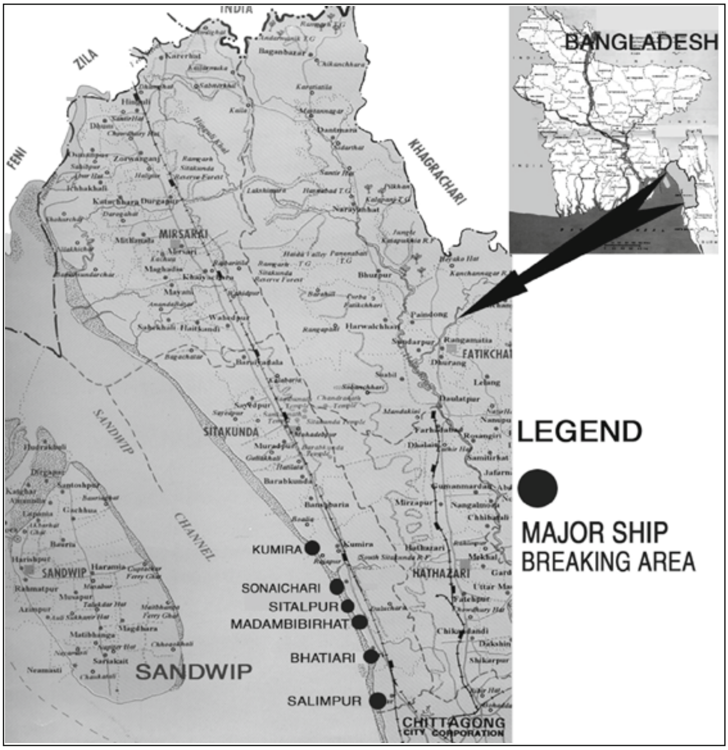

Fig. 1: Map of ship breaking area Chittagong, Bangladesh indicated by black spots and Sandwip Island as control area.

Sample Collection and Preparation

Sea water and bottom sediments from inter-tidal zone were collected simultaneously during high tide from the four sampling stations of the affected sites—Salimpur, Bhatiari, Sonaichari and Kumira. Sea water samples were collected with the nansen bottle and preserved in two-litre glass stopper bottles and soil samples with grab sampler in airtight polythene bags. All the samples were collected both at pre-monsoon and monsoon. Sediment samples were collected with the help of Ekman Grab Sampler. Then samples were digested by adding HCl, nitric, sulfuric and perchloric acids. The standard solution of the elements Fe, Cu, Hg, Zn, Pb, Cr, Cd and Ni were prepared by pipetting the required amount of the solution from the stock solution, manufactured by Fisher-Scientific Company (USA). The standard solution was prepared before every determination of the analysis of the present work. The water samples were then analyzed by using air acetylene flame with combination as well as single element hollow cathode lamps into an atomic absorption spectrophotometer (Shimadzu, AAS- 6800). The samples were injected by an automatic sampler and the absorbance and concentration data were automatically printed out and displayed. The analysis of sediment was carried out in BUET and BCSIR laboratories, Chittagong.

RESULTS AND DISCUSSION

The maximum concentration of iron (Fe) was observed 41,361.71 $\mu g.g^{-1}$ at Bhatiari of the affected sites and the minimum was as 3393.37 $\mu g.g^{-1}$ at Sandwip which is significantly lower than that of unpolluted marine sediment (27,000 $\mu g.g^{-1}$). Fe concentrations in sediments varied from 11,932.61 $\mu g.g^{-1}$ to 41,361.71 $\mu g.g^{-1}$ in the affected area and 3393.37 $\mu g.g^{-1}$ at the control site. The minimum and maximum concentrations were recorded at Sandwip and Sonaichari. The average value of Fe in the affected site was 27,370.63 $\mu g.g^{-1}$ (Table 2). This finding is in well agreement with findings of Banu (1995) in the sediment of the Karnafully River mouth. Fe has frequently been used as an indication of natural changes in the heavy metal carrying capacity of the sediment (Rule, 1986) and its concentration has been related to the abundance of metal reactive compounds not significantly affected by man's action (Luoma, 1990) (Table 2, Fig. 2).

Manganese (Mn) is an element of low toxicity having considerable biological significance. It is one of the more biogeochemical and active transition metals in aquatic environment (Evans et al., 1977). Mn concentration in sediment samples varied from 2.32 $\mu g.g^{-1}$ to 8.25 $\mu g.g^{-1}$ in affected area. Maximum level of Mn was observed as 8.25 $\mu g.g^{-1}$ in the affected site, Bhatiari and minimum as 1.80 $\mu g.g^{-1}$ in the control site Sandwip which is significantly higher than that of unpolluted marine sediment (1.17 $\mu g.g^{-1}$), recommended by IAEA (1990) but reflects the works of Mehedi (1994), Khan (2003) and Hossain (2004). The mean value of Mn in experimental area was 5.03 $\mu g.g^{-1}$ (Table 2, Fig. 2).

Table 2: Trace metals concentrations of sediment at both the affected and control sites

		Heavy Metal Concentration								
	Stations	*Fe* *(µg/g)*	*Mn* *(µg/g)*	*Cr* *(µg/g)*	*Ni* *(µg/g)*	*Zn* *(µg/g)*	*Pb* *(µg/g)*	*Cu* *(µg/g)*	*Cd* *(µg/g)*	*Hg* *(µg/g)*
Affected sites	Salimpur	11932.61	2.64	68.35	23.12	83.78	36.78	21.05	0.57	0.015
	Bhatiari	35216.35	8.25	86.72	35.12	102.05	122.03	39.85	0.83	0.02
	Sonaichhari	41361.71	6.89	78.36	48.96	142.85	147.83	30.67	0.94	0.117
	Kumira	20971.86	2.32	22.89	25.36	119.86	41.57	28.01	0.59	0.05
Control site	Sandwip Standard	3393.37	1.8	19	3.98	22.22	8.82	2.05	0.19	0.02
	Standard	27000 a	1.17 b	77.2 a	56.1 a	95.0 b	22.8 b	33.0 b	0.115 a, b	0.02 a

Legend: a = IAEA (1990), b = GESAMP (1982)

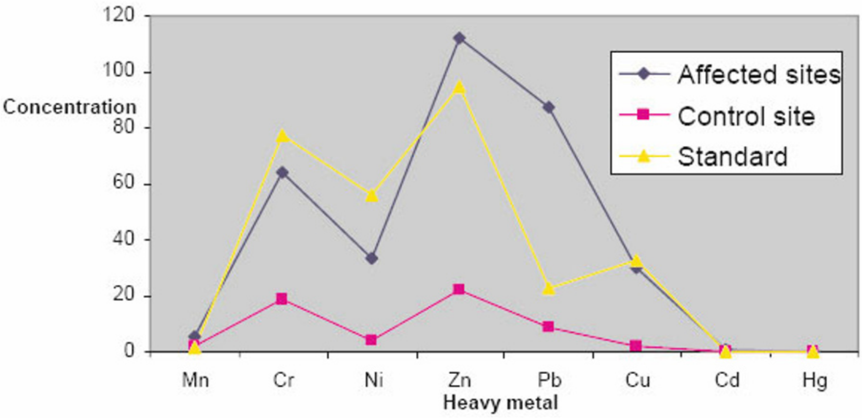

Fig. 2: Comparison of trace metals in affected, controlled and standard values.

Concentration of chromium (Cr) varied from 22.89 $\mu g.g^{-1}$ to 86.72 $\mu g.g^{-1}$ (Table 2) among the affected sites with the average of 46.53 $\mu g.g^{-1}$ in the affected sites whereas 19 $\mu g.g^{-1}$ in the control site. But the recommended value of Cr is 77.2 $\mu g.g^{-1}$ (IAEA, 1990) (Table 2, Fig. 2). Copper (Cu), nickel (Ni) and zinc (Zn) are essential heavy metals for living aquatic organisms. The value of Ni varied from 23.12 $\mu g.g^{-1}$ to 48.96 $\mu g.g^{-1}$ in the affected sites with the highest value at Sonaichhari whereas 3.98 $\mu g.g^{-1}$ at Sandwip (the control site) (Table 2) which are lower than the recommended concentration 56.1 $\mu g.g^{-1}$ (IAEA, 1990). This low concentration of Ni might be due to absorption of Ni from clay minerals. The mean value of Ni in the affected sites was 33.14 $\mu g.g^{-1}$. Cu is intimately related to the aerobic degradation of organic matter (Das and Nolting, 1993). The concentration of Cu ranged from 21.05 $\mu g.g^{-1}$ to 39.85 $\mu g.g^{-1}$ with the average value of 29.00 $\mu g.g^{-1}$ in affected sites with the highest value at Bhatiari and lowest at Salimpur. The present value is higher than that of recommended value 33.00 $\mu g.g^{-1}$ (IAEA, 1990). This finding showed that the Cu concentration is getting harmful for the inhibiting marine biota. The minimum concentration was recorded at Sandwip 2.05 $\mu g.g^{-1}$ (Table 2, Fig. 1).

The highest concentration of Zn was found at 162.05 $\mu g.g^{-1}$ at Bhatiari (the affected site) and 22.22 $\mu g.g^{-1}$ at Sandwip (the control site). Concentration of Zn were also higher compared to that of the recommended value of 95 $\mu g.g^{-1}$ (GESAMP, 1982). It is also mentionable that the level of Zn in soft water ranging from 0.1 to 1 $\mu g.g^{-1}$ is lethal to fish. The level of Zn in sediments of the affected area varied from 83.78 $\mu g.g^{-1}$ to 142.85 $\mu g.g^{-1}$ (Table 2) with the average value of 112.14 $\mu g.g^{-1}$. Literature survey indicates that marine sediment of Bangladesh contains higher amount of Zn than marine sediment from other parts of the world (Salomons and Forster, 1984; GESAMP, 1982) (Table 2, Fig. 2).

Lead (Pb) concentration in sediment samples of the affected areas varied from 36.78 $\mu g.g^{-1}$ to 147.83 $\mu g.g^{-1}$ with the average value at 87.05 $\mu g.g^{-1}$. The minimum concentration was recorded at Sandwip 8.82 $\mu g.g^{-1}$. Cadmium (Cd) concentration in sediment of the affected areas varied from 0.57 $\mu g.g^{-1}$ to 0.94 $\mu g.g^{-1}$ (Table 2) with the average value of 0.73 $\mu g.g^{-1}$. The minimum concentration was recorded at Sandwip 0.196 $\mu g.g^{-1}$. Mercury (Hg) level in the sediment samples of the affected sites varied from 0.115 $\mu g.g^{-1}$ to 0.942 $\mu g.g^{-1}$ (Table 2) with the average value of 0.356 $\mu g.g^{-1}$. In the control site it was recorded at 0.231 $\mu g.g^{-1}$.

The recommended value of lead (Pb), cadmium (Cd) and mercury (Hg) are 22.20, 0.11 and 0.01 $\mu g.g^{-1}$ respectively (GESAMP, 1982). The higher concentration of these elements were found to be 147.83, 0.94 and 0.942 $\mu g.g^{-1}$ respectively in the affected areas whereas 8.82, 0.196 and 0.231 $\mu g.g^{-1}$ in the control site. The present values are about six and half, eight and half and ninety four times higher than the certified values respectively. These could be attributed effects of oil and oil spoilage, petroleum hydrocarbon from ships, tankers, mechanized boats etc. as opined by Abu-Hilal (1987) and Laxen (1983) (Table 2, Fig. 2).

CONCLUSIONS

Wastes of the scrapped ships are drained and dumped into the Bay of Bengal. These wastes especially oil and oil substances, PCB's, TBT's, PAH's, etc. and different types of heavy metals (Fe, Cr, Hg, Zn, Mn, Ni, Pb and Cd) are being accumulated into the marine biota. As a result, marine fisheries diversity of Chittagong coastal region that supports highly diversified marine water fishes, mollusks and benthic organism etc. are at stake at this moment.

Finally, it could be said that the ship breaking operation involves serious environmental hazards. If the ship breaking industry is to develop in the country, the same may only be allowed ensuring minimization of pollution effect. A longer stretch along the seashore is in no way justified for continuation of this business, rather a certain separate zone like a dockyard should be selected by the competent authority. Preventive measures against environmental and health hazards, inherent in the process of ship breaking, should be undertaken at the right time, before it is too late.

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7

Hydro-Meteorological Impact on Residual Currents and Salinity Distribution at the Meghna Estuary of Bangladesh

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Abstract: In this article, a 3D numerical model has been applied for the simulation of residual currents in the Meghna Estuary, situated at the northern Bay of Bengal. Relevant meteorological and hydrological data at the Meghna Estuary has been analyzed to identify the seasonal variation which has been employed as model input. Numerical investigations revealed that during the monsoon as well as winter periods a counterclockwise circulation exists in the estuary with a northward flow in the Sandwip Channel and another northward flow in the Shabazpur Channel. Numerical experiments suggest that tidal current is the primary forcing factor behind the northward flow through the Sandwip Channel. During the monsoon period, residual current in the northern Bay of Bengal may be occasionally dominated by strong South-West monsoon wind (average 4 ~5 m/s and maximum 20~30 m/s) which may create back water effects in the Meghna Estuary and alter the salinity distribution in the estuary. During winter (dry) season the counter clockwise circulation in the estuary exists but the circulation becomes weaker and it is not influenced by the weak north-easterly (1.5~3 m/s) wind. Thus, tidal current and Coriolis force were found to be the primary forcing factors that govern the residual circulation in the Meghna Estuary.

Key words: residual currents, 3D numerical model, Meghna Estuary, seasonal variations, wind speed, tide.

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INTRODUCTION

During the recent period, coastal oceans and estuaries are the regions receiving a great deal of interest mainly due to the increased utilization of its resources. The coastal zone of Bangladesh, which consists of 19 districts with an area of 47,201 km^2 (exposed: 23,935 km^2 and interior: 23,266 km^2), still reflects a rural setting and extensive urbanization has not happened as yet. However, changes are underway: in 2001 a total of 35.1 million people lived in the coastal zone of Bangladesh, increasing from only 8.1 million a century earlier. The coastal population is projected to grow to about 41.8 million in 2015 and 57.9 million in 2050 (PDO-ICZMP, 2004). The coast of Bangladesh is known as a zone of multiple vulnerabilities as well as opportunities. It is prone to several natural and man-made hazards, such as storm surges, erosion, high arsenic content of ground water, water logging, water and soil salinity, etc. On the other hand the coastal zone contains distinctive development opportunities; it has a diversity of natural resources, including marine fisheries and shrimp, forest, salt, minerals, high potentials for exploitation of both on-shore and off-shore natural gas, infrastructures (e.g., sites for Export Processing Zones, harbours, airports, land ports, tourism complexes etc.) as well as several ecosystems like mangrove ecosystem (the Sundarbans) and coral ecosystem (around St. Martin Island).

Considering physiographic and hydrogeomorphological characteristics and the process by which it has been formed, Bangladesh's 710 km long coastline has been delineated into three major zones: the Ganges Tidal Plain, the Meghna Deltaic Plain and the Chittagong Coastal Plain. The Chittagong Coastal Plain has the longest sandy coast at Cox's Bazar and the active deltas of the Sangu and the Matamuhuri rivers and estuaries of the Karnafully and the Naf rivers. The Meghna Deltaic Plain runs east from Tetulia river to Sandwip channel, includes the mouth of the Meghna and is characterized by heavy sediment input, formation of chars and bank erosion. This region is most dynamic and most of the accretion and erosion occur here. The Ganges Tidal Plain is relatively stable and covered with dense mangrove forest in the west. The mangrove ecosystem, in the coastal belt, occurs upto a width upstream to which saline water from the sea intrudes with the tide. The nutrient distribution, water regime and salt balance determine the productivity of the mangrove as a whole. Most of the coastal area of Bangladesh extended along the Bay of Bengal is active and very sensitive to human intervention.

The Meghna Estuary is a 'coastal plain estuary' on the Bangladesh coastline in the Bay of Bengal. These kinds of estuaries are normally difficult to describe in physical terms, because they are sensitive to the driving forces (Fischer et al., 1979), which can be divided into bathymetry, oceanographic conditions outside the estuary (tides), hydrology of the adjacent watershed (river discharge) and meteorological conditions (e.g. wind) (Jacobsen et al., 2002). Many scientific investigations have focussed on cyclone surges in the Bay of Bengal (e.g. Flierl and Robinson, 1972; Murty et al., 1986; Flather, 1994; As-Salek, 1998; Chowdhury et al., 1998). But the erosion-accretion process in the Meghna Estuary still remains a challenge due to its complex hydrodynamic and morphological condition. One of the fundamental issues for long-term material transport in bays and estuaries is ‘residual current’, which is the net current after the tide induced current is excluded. Even though the magnitude of residual current is small compared to the tidal current it plays primal role for the net transport of scalars as well as suspended and bottom sediments which in turn dictate the erosion and accretion process of the estuary and coastal islands. The present paper focusses on the seasonal variation of residual flow during non-cyclonic conditions in the Meghna Estuary to enhance the present understanding of the hydrodynamic and morphological features of the region.

Jacobsen et al. (2002) performed numerical simulations through two-dimensional MIKE 21 model during the ‘Meghna Estuary Study’ (MWR, 1997) and obtained a counter-clockwise circulation with a northward flow in the Sandwip Channel and a southward flow in the Tetulia river and in the area from Hatia to Sandwip. During the study it was also observed that the residual circulation, to some extent, traps the river water inside the Meghna Estuary and thus increases the residence time, which is one of the reasons for the relatively low salinity in the estuary even during the dry season. During the study, wind stress was considered not to influence the residual currents of the Meghna Estuary significantly but earlier another numerical investigation in the northern Bay of Bengal by Ali (1995) established that south-westerly monsoon wind may increase water level in the estuary and create back-water effects in the rivers. Potemra (1991) also studied the seasonal circulation in the upper Bay of Bengal.

According to Azam et al. (2000), the incoming tides from the southern part of the Bay of Bengal are important for the flow features in the Meghna Estuary and they contribute to the residual circulation significantly. Also, MWR (1997) reported that the salinity in the Meghna Estuary varies significantly throughout the year. Wind field and river discharge are two of the important factors which are expected to have significant influence on the residual currents of the Meghna Estuary, and as they encompass considerable seasonal variation there is need for further clarification and in-depth research regarding this issue for the Meghna Estuary.

METHODOLOGY

Four seasons were identified based on previous studies (e.g. Chowdhury et al., 1997) on climatic conditions of Bangladesh, namely pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November) and winter (December-February). Meteorological and hydrological data have been analyzed for these periods to set-up a three dimensional numerical model which has been applied in the present study to compute residual currents in the Meghna Estuary.

Data

Meteorological Data

Meteorological data of previous six years (2003-2008) from thirteen BMD (Bangladesh Meteorological Department) stations (Satkhira, Mongla, Khepupara, Patuakhali, Barisal, Bhola, Chandpur, Hatiya, Sandwip, Chittagong, Kutubdia, Cox's Bazar and Teknaf) in the coastal zone of the country was collected to analyze the seasonal as well as spatial variation of nine meteorological parameters (wind speed, wind direction, air pressure, air temperature, precipitation, evaporation, relative humidity, cloud cover and solar radiation) which were used as input to the numerical model. Figure 1(a) shows the location of BMD stations in the southern Bangladesh and Figure 1(b) shows a map of the Meghna Estuary.

Hydrological Data

Although several large and tiny rivers discharge into the Meghna Estuary, discharge is not measured at any of these tidal rivers. Some of the measurements done during the MES project suggested that in an extreme year the discharge through the estuary is as much as fifteen times during the monsoon season compared to that during the dry season. It reported that in an average year the discharge through the estuary is about 20,000 m^3/s during the dry season whereas it is 100,000 m^3/s during the monsoon.

Water level data collected during the MES study was obtained at Shabazpur Channel (BTM coordinates X = 591,974.7 m, Y = 426,766.3) and Sandwip channel (BTM coordinates X = 664,455.4 m, Y = 500,204.2) to use as input to the numerical model as the open boundary data. The locations are indicated in Figure 1(b) by star marks. The water level data is shown in Fig. 2, which illustrates much larger tidal range at Sandwip channel. For the present study water level data at Shabazpur channel, south-west of Hatiya was employed as it was the southern-most point of tidal water level measurement in the central part of Meghna Estuary.

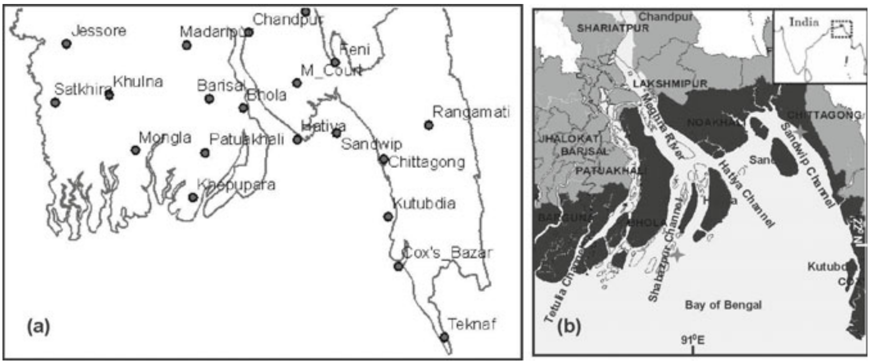

Fig. 1: (a) Location of BMD stations in southern Bangladesh and (b) Map of study area.

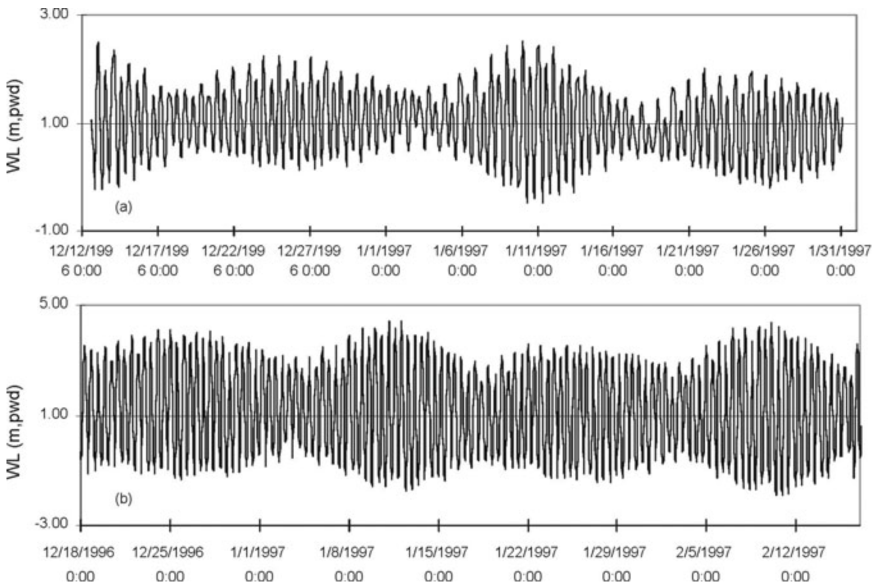

Fig. 2: Tidal water level observed during the MES project: (a) near Shabazpur Channel south-west of Hatiya and (b) at the Sandwip Channel.

Bathymetry

The bathymetry data used for the present study is the one which was measured during the MES project. Even though this measurement was done in 1997 and the present scenario may be different, this is the only measured data available for the estuary.

Numerical Model

A 3D numerical model which solves mass conservation equation and Navier-Stokes equations for the conservation of momentum was applied for the simulation of residual currents in the Meghna Estuary. The hydrodynamic model is an f-plane quasi-3D sigma-coordinate baroclinic circulation model including temperature and salinity (Sasaki and Isobe, 1996). In the present model, turbulence has been treated explicitly and equations for turbulent quantities such as turbulence velocity scale (or equivalently turbulence kinetic energy) and turbulence macroscale are solved following Mellor-Yamada's (1982) turbulence closure scheme (Hussain, 2006). In this model, boundary conditions were considered for the wind stress at water surface, friction at bottom of water body and frictionless along the lateral boundaries of the water body. Heat balance and moisture balance at sea surface have been considered for temperature and salinity boundary conditions, respectively. Constant values for horizontal viscosity and diffusivity were used.

Setup of Numerical Model

The hydrodynamic model was applied using a ten-layer sigma coordinate system and the calculated instantaneous currents were averaged over 25 hours to obtain the residual currents. To simulate the residual currents during the four above mentioned seasons, steady wind stress with average wind speed of the season and a constant river discharge of that season was applied. Other meteorological parameters were used taking the spatial and temporal average values. A uniform grid size of 2 km by 2 km has been employed in a calculation domain sized of 182 km by 182 km.

MODEL CALIBRATION AND VALIDATION

Model Calibration

The calibration period was selected so that it covers one spring tidal peak and one neap tidal peak. The selected calibration period was 1st April 2006 to 15th April 2006. Figure 3 shows the comparison between observed and simulated water levels. Even though there appears some discrepancy between tidal phases there is a reasonably good agreement between observed and simulated water levels. Bottom friction coefficient was found to be the most important calibration factor for adjusting the tidal amplitude effectively. For depths greater than 20 m, bottom friction coefficient was considered as 0.0026 and for shallow areas the value of the coefficient was increased proportionately.

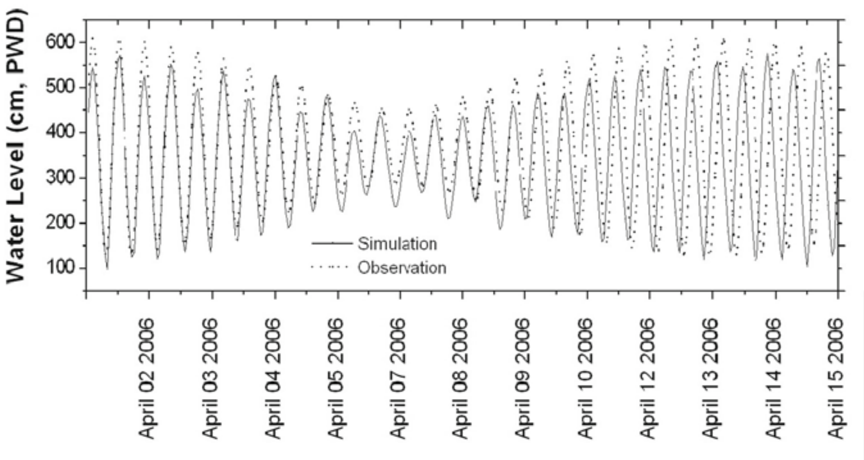

Fig. 3: Comparison between measured and simulated water levels at Rangadia, Chittagong.

Model Validation

The numerical model has been validated in a spatial manner with respect to tidal ranges at different parts of the Meghna Estuary, where the micro, meso

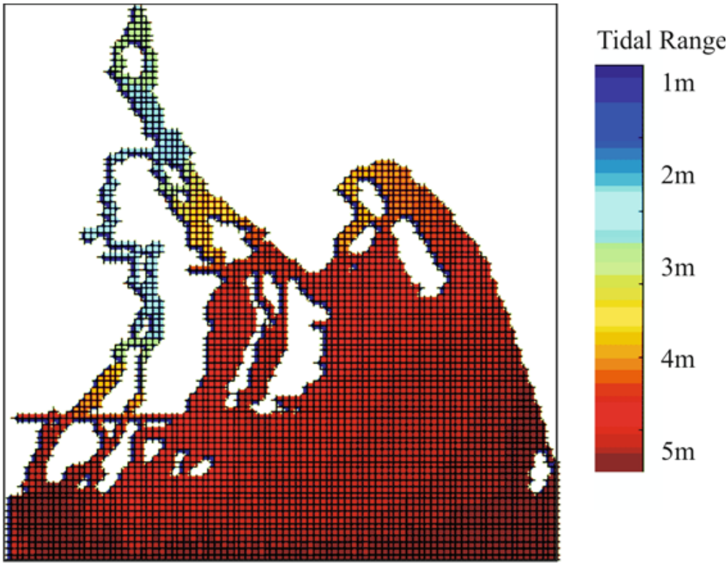

Fig. 4: Model validation simulated tidal zones.

and macro tidal zones of the Meghna Estuary has been simulated, as shown in Fig. 4.

SEASONAL VARIATION OF METEOROLOGICAL AND HYDROLOGICAL PARAMETERS

Meteorological Parameters

Wind data shows that its direction is mainly from South and South-East during pre-monsoon and monsoon periods and from North and North-West during post-monsoon and winter periods. Figure 5 shows the annual distribution of wind vectors during 2008 at Hatiya, Khepupara and Kutubdia stations.

An analysis of wind speed (m/s) at different BMD stations in the coastal region of Bangladesh is shown in Table 1. Average wind speed at different stations is quite small in the coastal region of Bangladesh, which is due to the fact that 30-40% of the time in a year wind remains calm (<1.0 m/s). The wind speed is strongest during monsoon period and weakest during winter. The spatial variation of maximum wind speed during pre-monsoon is 5.6-17.0 m/s, during monsoon 6.3-25.1 m/s, during post-monsoon 5.9-22.0 m/s and during winter 3.6-9.8 m/s.

Similar analyses are made for air temperature (°C) and air pressure (millibar) at the same BMD stations which is summarized in Table 2. Maximum temperature does not show significant variation throughout the year even though average temperature goes down after the end of monsoon season. Average air pressure remains maximum during the winter period.

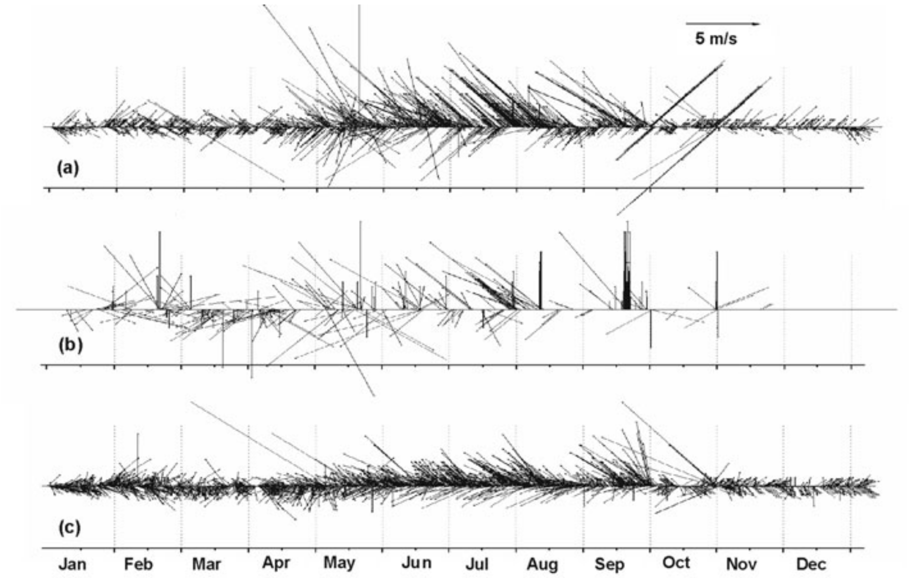

Fig. 5: Wind directions at (a) Hatiya, (b) Khepupara and (c) Kutubdia stations during 2008.

Table 1: Seasonal variation of wind speed at different BMD stations

	Pre-Monsoon		*Monsoon*		*Post-Monsoon*		*Winter*	
	Max.	*Avg.*	*Max.*	*Avg.*	*Max.*	*Avg.*	*Max.*	*Avg.*
Satkhira	6.8	1.6	6.6	1.1	9.8	0.5	4.0	0.7
Mongla	8.8	2.3	16.5	2.6	16.8	0.8	5.4	1.0
Khepupara	14.3	3.4	25.1	3.6	20.1	0.8	8.5	1.1
Patuakhali	11.4	1.8	9.6	1.8	14.1	0.8	4.4	0.9
Barisal	12.9	2.4	10.3	2.2	21.6	0.5	8.3	0.6
Bhola	5.6	1.5	6.4	1.4	5.9	0.4	4.3	0.6
Chandpur	6.1	1.1	6.3	1.1	11.0	0.4	3.6	0.5
Hatiya	17.0	3.1	17.9	4.2	16.9	1.2	8.0	1.4
Sandwip	10.4	2.5	11.9	3.2	22.0	1.3	8.3	1.5
Chittagong	10.1	2.2	10.6	2.0	11.5	0.7	9.3	0.9
Kutubdia	9.9	2.8	10.9	3.6	8.1	1.5	6.9	1.8
Cox's Bazar	14.6	2.8	13.8	3.4	9.1	1.4	9.8	1.7
Teknaf	12.6	1.6	9.3	1.7	6.3	0.7	7.3	1.3
Max.	17.0	3.4	25.1	4.2	22.0	1.5	9.8	1.8
Min.	5.6	1.1	6.3	1.1	5.9	0.4	3.6	0.5
Avg.	10.8	2.2	11.9	2.5	13.3	0.8	6.8	1.1

Table 2: Seasonal variation of air temperature and air pressure

	Pre-Monsoon			*Monsoon*			*Post-Monsoon*			*Winter*		
	Max.	*Min.*	*Avg.*	*Max.*	*Min.*	*Avg.*	*Max.*	*Min.*	*Avg.*	*Max.*	*Min.*	*Avg.*
Air Temp.	39.2	13.0	28.0	39.6	20.1	28.3	35.6	9.7	25.8	36.7	7.4	20.6
Air Pressure	1023	984	1008	1016	987	1003	1023	1001	1011	1023	1003	1014

Table 3 shows the summary for seasonal variation of average daily rainfall (mm), relative humidity (%) and cloud cover for the above mentioned BMD stations. Average daily rainfall during the monsoon period is significantly higher compared to other seasons and average rainfall during the winter is almost negligible. The values provided in the table are the average relative humidity and it does not show significant variation throughout the season. Cloud cover is significantly higher during the monsoon period.

Data for evaporation (mm/day) and solar radiation (Cal/cm^2/min) is only available at the Barisal station; they are summarized in Table 4. Average evaporation is the maximum during the pre-monsoon period and minimum during the winter, while average solar radiation is maximum during the pre-monsoon and minimum during the monsoon period.

Table 3: Seasonal variation of average daily rainfall (mm), relative humidity (%) and cloud-cover

	Pre-Monsoon	*Monsoon*	*Post-Monsoon*	*Winter*
Rainfall	3.6	15.5	4.9	0.3
Relative humidity	78.3	88.0	83.5	77.7
Cloud cover	0.37	0.71	0.30	0.13

Table 4: Seasonal variation of evaporation and solar radiation at Barisal station

	Pre-Monsoon			*Monsoon*			*Post-Monsoon*			*Winter*		
	Max.	*Min.*	*Avg.*	*Max.*	*Min.*	*Avg.*	*Max.*	*Min.*	*Avg.*	*Max.*	*Min.*	*Avg.*
Evaporation	53.0	39.8	46.3	41.8	27.7	35.0	43.7	26.6	34.9	36.0	23.2	29.9
Solar radiation	347	140	227	241	112	152	251	115	160	255	106	168

Hydrological Parameters

There is significant variation of fresh water discharge through the Meghna Estuary. Table 5 shows the discharge (m^3/s) through the Meghna estuary following Islam et al. (2002), which has been implemented as boundary condition for the numerical investigation for the present study.

Table 5: Seasonal variation of discharge of the combined Ganges-Brahmaputra-Meghna river system

	Pre-Monsoon	*Monsoon*	*Post-Monsoon*	*Winter*
Discharge	12,300	69,250	31,000	9,300

SIMULATIONS WITH TIDE AND FRESH WATER INFLOW

To start with the residual currents induced by only tide at the open boundary has been calculated. Figure 6(a) and 6(b) show the calculated residual currents at the surface and bottom layers, respectively. The surface layer currents particularly show an anti-clockwise tendency where strong north-westward flow is observed through the Sandwip and Hatiya channels. Strong north-westward flow is also observed through the Hatiya channel at the bottom layer.

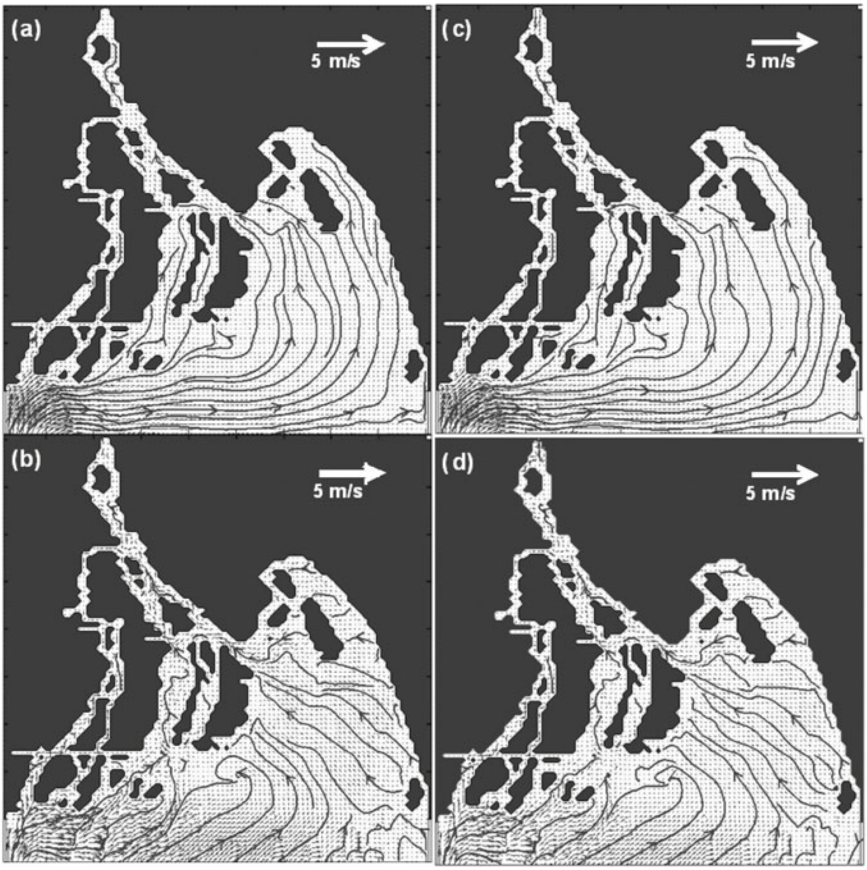

Fig. 6: Calculated streamlines of residual currents at the Meghna estuary. Left panel: Only tide-induced currents (a) Surface and (b) Bottom Layer; Right panel: Tide and fresh water induced currents (c) Surface and (d) Bottom Layer.

To evaluate the combined effect of tide and fresh water inflow from the Meghna river on the residual currents, especially during the monsoon period when large amount of fresh water flows into the estuary, another set of numerical experiment was conducted. Figure 6(c) and 6(d) show the calculated residual currents due to tide and fresh water inflow at the surface and bottom layers, respectively. River discharge employed for the numerical experiment was the one which is normally observed during the peak season, e.g. the maximum discharge. This set of result does not show significant change in the residual flow and there remains an anti-clockwise tendency of residual flow in the estuary with strong north-westward flow through the Sandwip and Hatiya channels. This suggests that the tide induced currents at the estuary is much stronger at the estuary compared to the freshwater induced currents even during the high flow season. For both the cases discussed so far, no wind stress was employed at the surface.

SEASONAL VARIATION OF RESIDUAL CURRENTS WITH AVERAGE WIND CONDITIONS

For the next set of numerical experiments, average wind speed (2.2 m/s, 2.5 m/s, 0.8 m/s and 1.1 m/s) obtained from the statistical analysis of the four different seasons (pre-monsoon, monsoon, post-monsoon and winter) was employed along with tide at the open boundary and respective fresh water inflow of that particular season. These sets of results (not included in the present paper) does not show any significant change in the residual flow in the Meghna estuary which is due to the fact that the average wind speed is quite small at all the four seasons and also the tide induced currents at the estuary is strong compared to the residual currents induced by the small average wind speeds at the estuary. So, tide along with Coriolis effect appears to govern the residual currents in the Meghna Estuary under normal circumstances. To investigate further, the average of maximum wind speeds at different seasons i.e. 10.8 m/s during pre-monsoon, 11.9 m/s during monsoon, 13.3 during post monsoon and 6.8 during winter has been employed in order to obtain and analyze the alteration in residual flow tendency at the Meghna estuary.

Figures 7(a), 7(b) and 7(c) show the calculated residual currents at the surface, middle and bottom layers, respectively, during the pre-monsoon season with average hydrological and meteorological parameters and with average of maximum wind speed from the south. These results show significant alteration from the previously obtained residual currents induced by tide, and tide and fresh water inflow. At the surface layer, strong south wind appears to create north-eastward flow due to the combined effect of Coriolis force at the estuary as well as along the Sandwip, Hatiya, Shabazpur and Tetulia channels. At the middle and bottom layers, the downwelling effect due to the south wind is clearly evident at the west coast of Chittagong and Kutubdia.

The calculated residual currents at the surface, middle and bottom layers during the monsoon season is shown in Figs 7(d), 7(e) and 7(f), respectively.

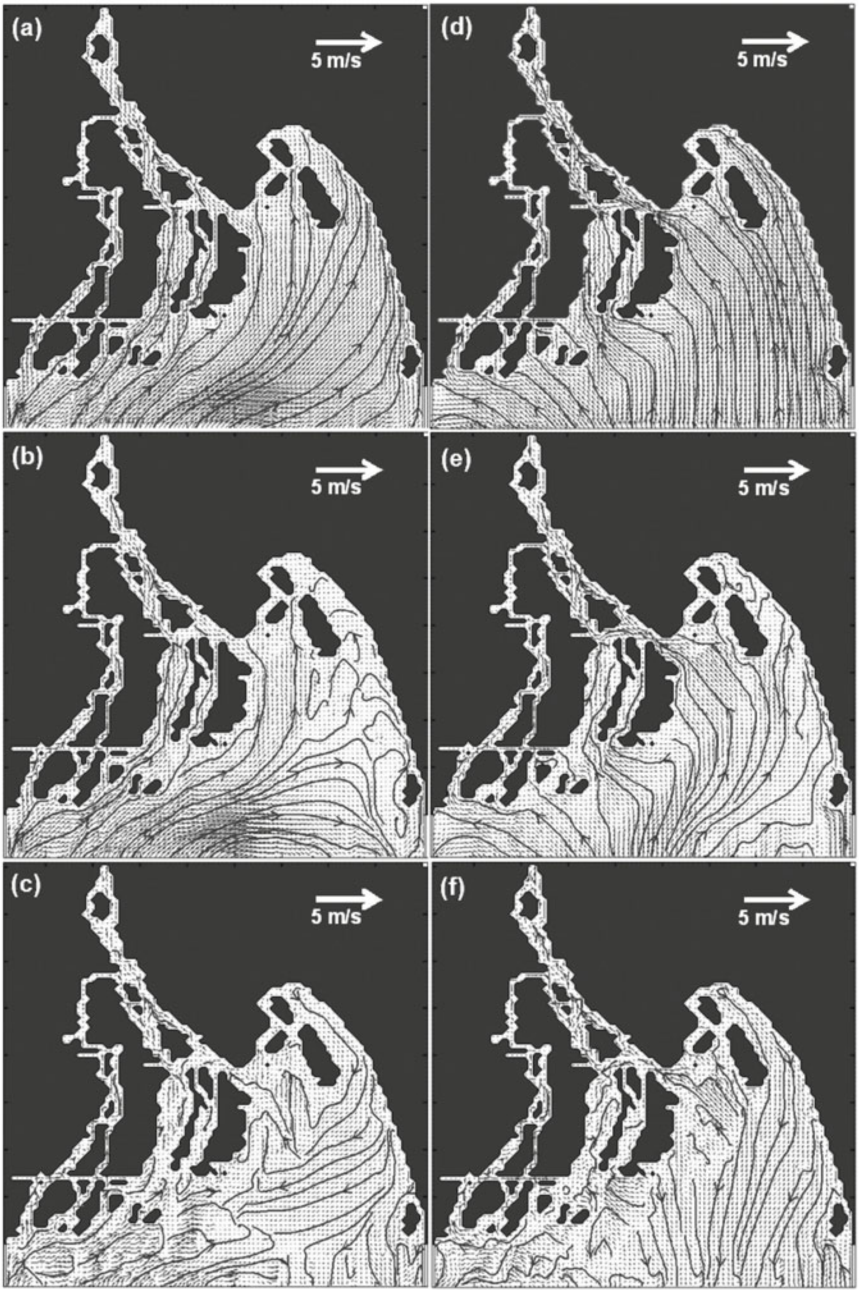

Fig. 7: Calculated streamlines of residual currents at the Meghna estuary. Left panel: During pre-monsoon (a) Surface, (b) Middle and (c) Bottom Layer; Right panel: During monsoon (d) Surface, (e) Middle and (f) Bottom Layer.

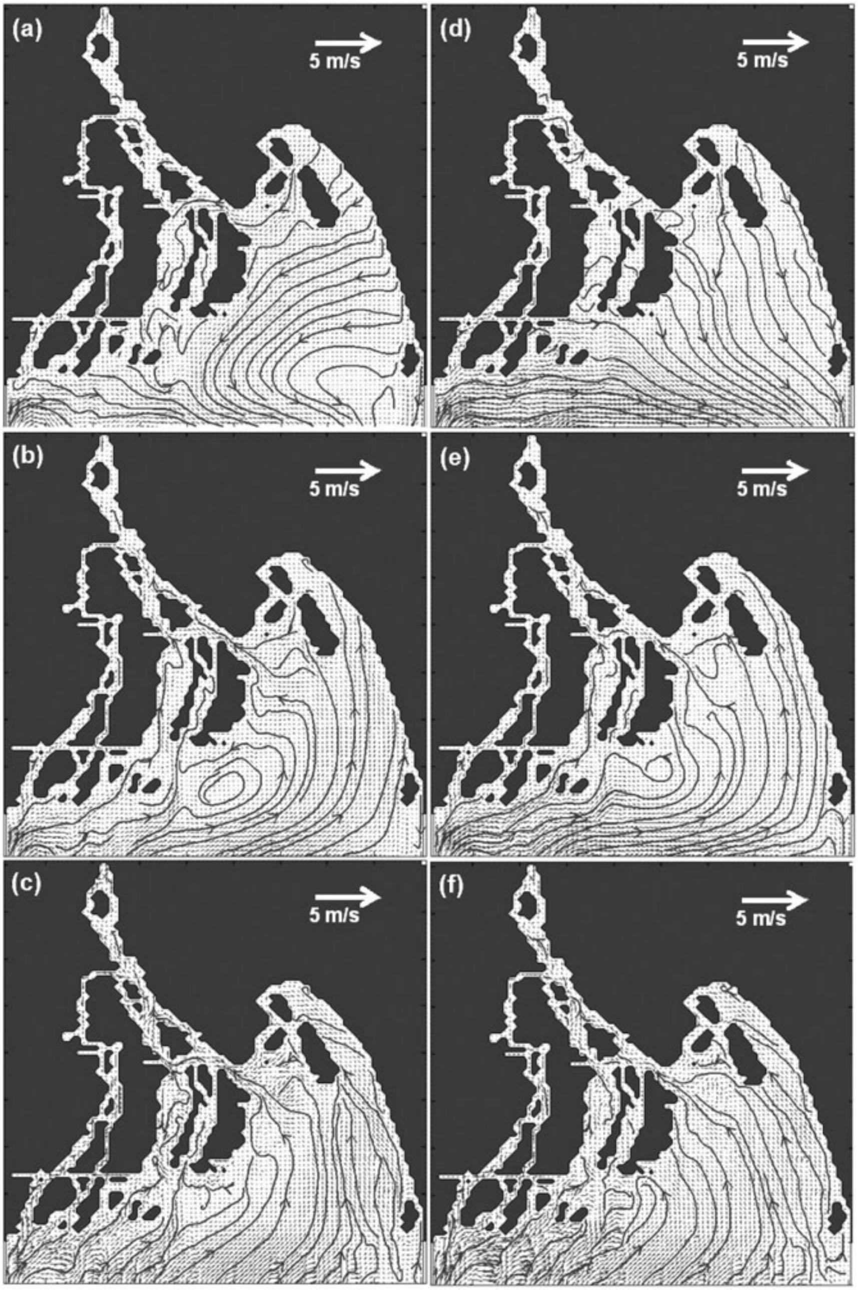

Fig. 8: Calculated streamlines of residual currents at the Meghna Estuary: Left panel: During post-monsoon (a) Surface, (b) Middle and (c) Bottom Layer; Right panel: During winter (d) Surface, (e) Middle and (f) Bottom Layer.

Here, average hydrological and meteorological parameters along with average of maximum wind speed from southwest have been employed. The results show, at the surface layer, strong southeast wind created north-westward flow at the estuary as well as along the Sandwip and Hatiya channels and northward flow through the Shabazpur channel. The tendency is similar in the middle layer but in the bottom layer southward flow is observed at the eastern part of the estuary and along the west coast of Chittagong and Kutubdia.

Figures 8(a), 8(b) and 8(c) show the calculated residual currents at the surface, middle and bottom layers respectively, during the post-monsoon season with average of maximum wind speed from the north. The north wind clearly generates upwelling at the west coast of Chittagong and Kutubdia and a south-westward flow is observed in the eastern part of the estuary at the surface layer. An anticlockwise circulation is evident at the middle layer and northward flow occurs through the Sandwip, Hatiya and Shabazpur channels.

Residual currents at the surface, middle and bottom layers during the winter is shown in Figs 8(d), 8(e) and 8(f), respectively. Here, average of maximum wind speed has been employed from the north-east. The results show, at the surface layer, strong north-west wind create south-eastward flow in the estuary. The currents in the middle and bottom layers show very similar tendency as those obtained during the post-monsoon period, with north-westward flow in the bottom layer at the eastern part of the estuary and along the west coast of Chittagong and Kutubdia.

IMPACT ON SALINITY DISTRIBUTION IN THE ESTUARY

Even though it is believed that the wind stress is of little importance for the residual flow inside the estuary, according to Ali (1995) south-westerly wind can occasionally create back-water effect in the Meghna estuary. To study this, another set of numerical experiment was done with a stronger southerly wind (20 m/s) keeping the other parameters same as a monsoon event. The results for residual currents as well as salinity (in psu) are shown in Fig. 9. The effect of wind stress on residual currents becomes considerable in this scenario. The residual current in the surface layer is more towards the north and it creates a downwelling effect along the eastern coast in the Chittagong region, which is evident from the bottom layer residual current (Fig. 9(e)). The residual flow in the central region being away from the boundary show signs of Ekman Layer effect on it.

The salinity distributions, especially in the middle and bottom layers, show the effect of wind stress on it. The highly saline water mass is pushed towards the river mouth and the low saline fresh water from the river is trapped maintaining relatively low salinity in the Hatiya, Shabazpur and Tetulia channels. Also, most of the high saline water mass accumulate in the eastern coast near the Chittagong region due to the downwelling effect evident from the streamlines of residual flow.

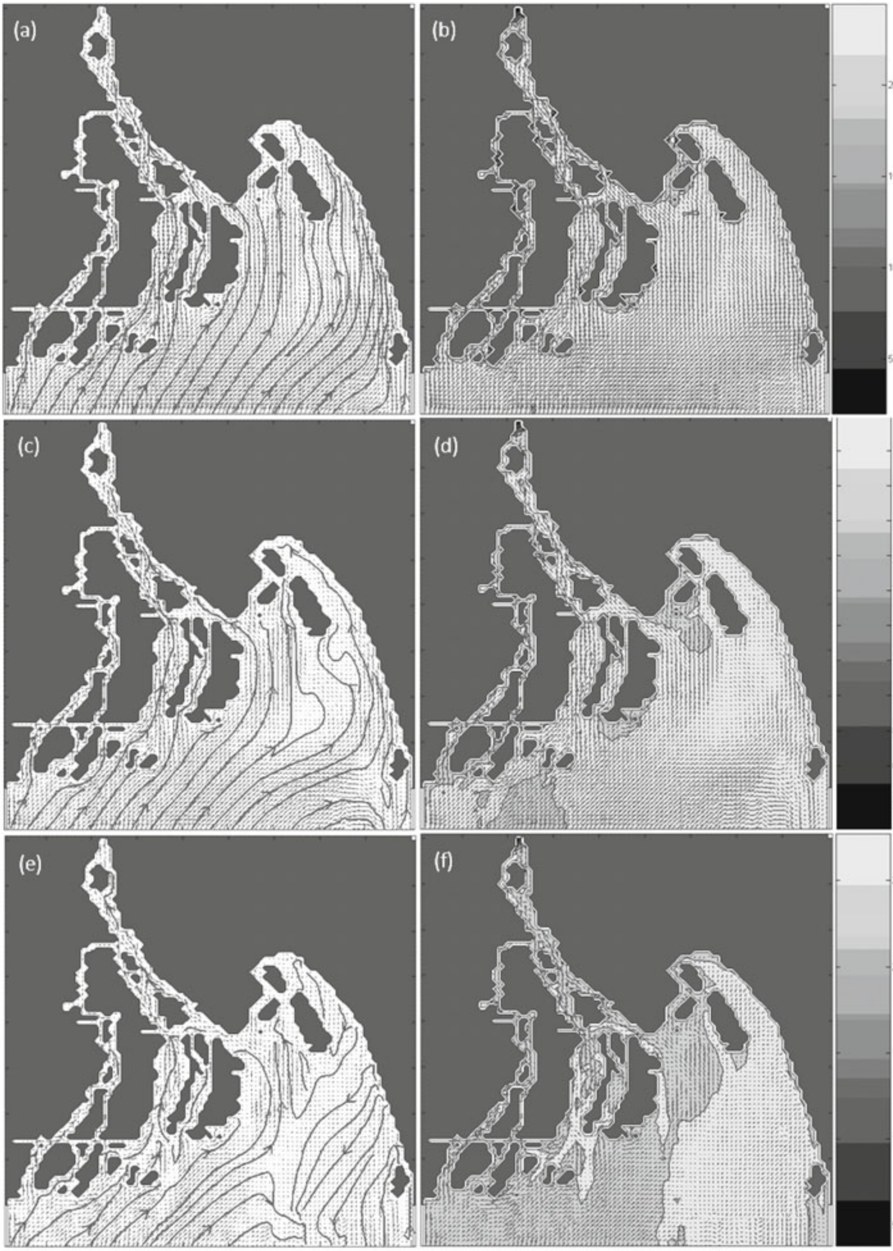

Fig. 9: Left panel: Calculated streamlines of residual currents and Right panel: Calculated salinity (psu) at the Meghna estuary during a strong (20 m/s) south wind; (a) and (b) Surface Layer, (c) and (d) Middle Layer and (e) and (f) Bottom Layer.

DISCUSSION

Under average meteorological conditions of four different seasons considered in the present paper, residual currents in the Meghna estuary appears to be strongly influenced by tidal currents and Coriolis Effect. Average seasonal variation of wind speed and direction as well as fresh water inflow does not seem to have significant influence on residual current. Average of maximum wind speeds have been employed to generate seasonal variation of residual currents in the Meghna estuary for four different seasons and the results show their dependency on wind stress under such circumstances. In general, in the surface layer northward and north-westward flow is created during the pre-monsoon and monsoon periods and southwest and south-eastward flow is created during the post-monsoon and winter periods.

Even though previous studies of residual currents in the Meghna estuary through numerical simulation using a 2D MIKE 21 model found southward flow through the Shabazpur channel especially during the monsoon season, the present model does not produce such phenomena. The southward flow through the river due to the high river discharge during summer is not evident from the model results.

The effect of wind stress on residual flows inside the river mouth may be debatable. Even though wind stress plays significant role for the residual currents in bays and estuaries, but due to the frictional effects the outcome of wind stress may be significantly attenuated inside the rivers.

Measurements on the vertical distribution of salinity and temperature in the Bay of Bengal have not yet been done and therefore the information on density stratification, which may have strong influence on residual currents, is unavailable.

CONCLUSIONS

Through numerical investigations it was observed that throughout the year a counterclockwise circulation exists in the Meghna estuary with a north-westward flow in the Sandwip and Hatiya Channels and another northward flow in the Shabazpur channel, in the surface layer. Average values of wind stress at different seasons of the year do not seem to alter this circulation pattern significantly. Numerical experiments suggest that tidal current along with Coriolis Effect is the primary forcing factor behind the counterclockwise residual current in the Meghna estuary. Average of maximum wind speeds have been employed to generate seasonal variation of residual currents in the Meghna estuary for four different seasons and the results show their dependency on wind stress under such circumstances. In general, in the surface layer northward and north-westward flow is created during the pre-monsoon and monsoon periods and south-west and south-eastward flow is created during the post-monsoon and winter periods. Along the west coast of Chittagong and Kutubdia in the eastern part of the estuary downwelling phenomena is clearly evident during the pre-monsoon season under the influence of south wind, while in the same coast during the post-monsoon period upwelling occurs under the influence of north wind. The north and north-west wind during the post-monsoon and monsoon seasons seems to create similar sort of residual currents in the middle and bottom layers of the Meghna estuary. To incorporate the influence of salinity, especially in the vicinity of the river mouth, and temperature on the residual flow measured data is necessary to provide as input to the numerical model.

ACKNOWLEDGEMENTS

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8

Soil Erosion and Heavy Metal Contamination in the Middle Part of the Songkhla Lake Coastal Area, Southern Thailand

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Abstract: Soil erosion and sources of heavy metal contamination were identified and their distributions were evaluated in the Songkhla Lake Basin, southern Thailand, by analyzing hundreds of soil and stream sediment samples from the middle part of the catchment area. The landforms in the study area are dominated by mountains and hills to the west, gently sloping and undulating terrains in the middle and alluvial plains with rivers flowing eastwards to the lake. The rates and amounts of erosion were determined using the universal soil loss equation (RUSLE) method. Subsequently, the distribution patterns of heavy metals were displayed onto Geographic Information System (GIS) maps to identify the likely sources of pollution and to assess the levels of contamination with the Dutch Standards. The maximum erosion rate of 1.64 mm/yr was found very close to the mountainous areas to the west and was also strong in the foothill areas due to deforestation. The levels of some heavy metals in the soils are mainly controlled by anthropogenic activities; they do not exceed the Dutch standard values in either the soil or the stream sediments. Areas with high Pb, Zn and As values in

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the stream sediments, especially near abandoned mines in the granite mountains to the west, however, require a follow-up survey because these metals may be transported down stream, especially with the higher current prevalent rate compared to that of the past.

Key words: Heavy metals, contamination, soil erosion rate, RUSLE, Songkhla Lake.

INTRODUCTION

Heavy metal contamination of the environment is one of the main concerns because of their peculiar pollutant characteristics (Wang and Qin, 2005). They do not decay with time, unlike many organic and radionuclide contaminants. Although heavy metals can be necessary or beneficial to plants at certain low levels, they are also toxic when exceeding specific thresholds. They are always present at relatively low but variable background levels from natural origins and their input into soils is related to the weathering of parent rocks and pedogenesis. Heavy metals frequently occur as cations, which strongly interact with the soil matrix (Jung, 2008).

In the last decade, the level of the natural input of several heavy metals to soils due to pedogenesis has largely been increased by human inputs, even on a regional scale (Mays and Edwards, 2001; Dearing and Jones, 2003; Shi et al., 2007). For example, the comparison of Cd, Pb and Zn levels between soils from remote and from more densely populated areas were analyzed and reviewed by several geoscientists (Wu et al., 2007; Yusuf and Oluwole, 2009). However, in areas with a heterogeneous lithology, natural heavy metal contents in the soil can exhibit a high degree of variability, which is controlled by the type of the parent material (Doelsch et al., 2006).

The areas of severe soil loss are often critical for agricultural non-point source pollution. Importantly, erosion includes not only the transport of sediment particles but also the transport of nutrients and pollutants (Schauble, 1999). Erosion models can be used to find out the critical areas of non-point source pollution (Sivertun and Prange, 2003) and can generally be grouped into two broad types. The first is the “statistical or empirical” group of models, such as the universal soil loss equation (USLE) developed by Wischmeier and Smith (1978), which is the most frequently used empirical soil erosion model worldwide. The Revised Universal Soil Loss Equation (Renard et al., 1997) is an empirical soil erosion model developed on the Universal Soil Loss Equation. It not only can predict erosion rates of ungauged watersheds by using knowledge of the watershed characteristics and local hydroclimatic conditions (Angima et al., 2003), but also can present the spatial heterogeneity of soil erosion

(Yue-Qin et al., 2008). Owing to its convenience to apply and compatibility with GIS, the RUSLE has been the most frequently used empirical soil erosion model worldwide. The second type of models is the "deterministic or physically based" models (Fu et al., 2006), which are developed using fundamental hydrological and sedimentological processes (Adediji et al., 2010).

In Thailand, currently very little research has focussed on soil erosion investigations using soil erosion models. In northeastern Thailand, Mongkolsawat et al. (1994) applied the USLE model to evaluate areas of high erosion in the Khon Kaen Province, whilst Shrestha et al. (2004) applied the RUSLE model for assessing the levels of soil erosion in the Phetchabun area. Recently, using the Integrated Model to Assess the Global Environment (IMAGE) and Land Degrade Model (LDM), Tingting et al. (2008) reported several strong erosion risk areas in northern Thailand, which identified particularly those areas with altitudes of 100 to 400 m above msl. However, only a few research reports have documented the heavy metal contamination in Thailand. Good examples are the report of Polprasert (1982), which showed high heavy metal contents, particularly Hg and Pb, in fish collected from the Chao Phraya River estuary system of central Thailand and the very recent report of Netpae and Phalaraksh (2009), which demonstrated high Cu and Pb levels in the sediments of Bung Boraphet Reservoir in central Thailand. In southern Thailand, the heavy metal distribution in the sediments of the outer part of Songkhla Lake were initially documented by Maneepong (1996) and then recently Sompongchaiyakul and Sirinawin (2007) reported on the levels of the heavy metals As, Cr and Hg in surface lake sediments in Songkhla Lake.

These rivers in the study area have transported voluminous amounts of sediments as well as nutrients, heavy metals and other toxic chemicals in the soil and water (Department of Mineral Resources, 2006). Because the water in Songkhla Lake flows very slowly and the outlet of this lake is very narrow (Fig. 1C), the exchange of fresh water and delivered sediment with the open sea is limited. This means that the sediments and pollution entering the lake may stay a long time or even build up. Consequentially, heavy metal concentrates may increase each year and may reach levels that are highly dangerous to the physical and ecological environments.

During 2003 to 2007, the Department of Mineral Resources (DMR) launched the SKC research project with the co-operation of Chulalongkorn University to evaluate the environmental situation and natural resource limitations, especially in heavy metal demands in the area. Therefore, the focus of this research paper is placed on the middle part of the SKC project area covering the southern part of Phattalung and the northern part of Songkhla provinces (Fig. 1).

The objectives of this study were (1) to document, investigate and model the spatial distribution of some heavy metals in the SKC study area and (2) to evaluate their environmentally harmful levels in the study area using GIS applications.

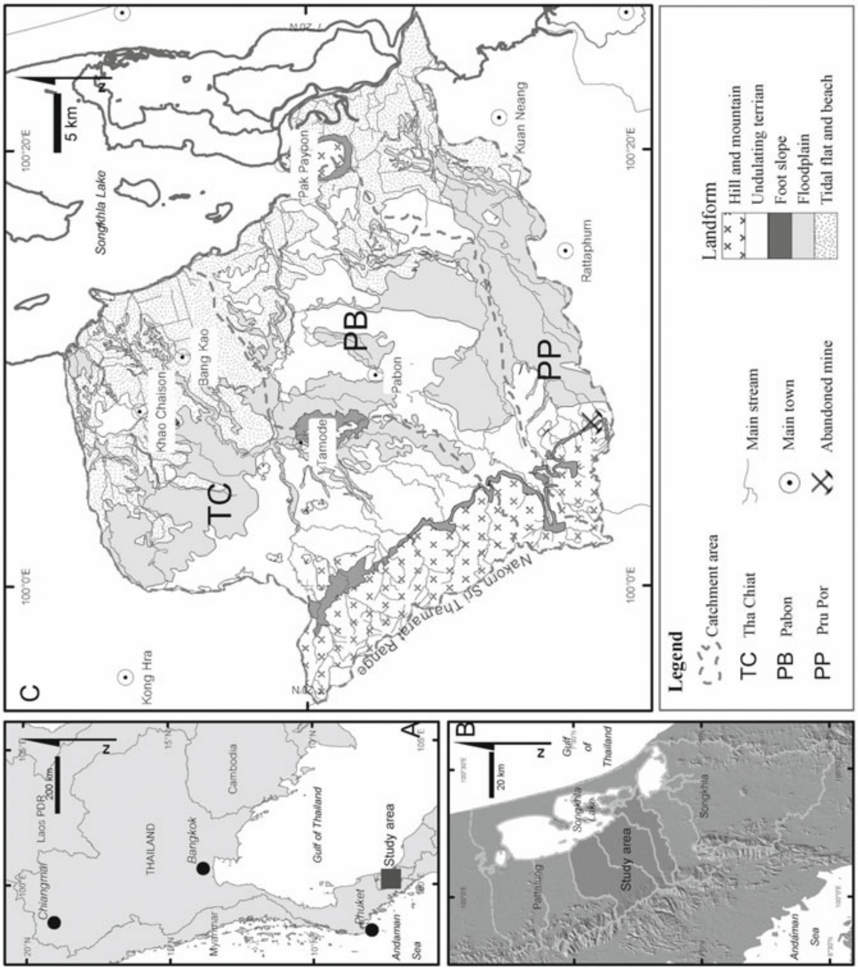

Fig. 1: Index maps of (A) Thailand, (B) the location of the study area in the form of shaded relief data and (C) landforms in the middle part of Songklha Lake, southern Thailand.

MATERIALS AND METHODS

The evaluation of the sources and levels of contaminated heavy metals in the study area was carried out using GIS based applications. A detailed description of the working procedure has been reported previously (Ladachart, 2008) and so only a brief description is described herein.

Study Site and Landform Setting

Songkhla Lake is located in southern peninsular Thailand (Fig. 1A), in the western Gulf Coast (Fig. 1B) and is surrounded by a large tropical coastal area. It is the largest coastal lake in Thailand with the aerial extent of some

1040 km^2 and borders the two provinces of Phattalung and Songkhla, with populations of 0.499 and 1.25 million people, respectively. The Songkhla Lake coastal (SKC) area is essential not only for the ecological environment but also for the para-rubber plantation and rice cultivation. The SKC area can be divided into eight catchment areas (Fig. 1B), of which three catchment areas, Tha Chiat (TC), Pabon (PB) and Pru Por (PP), in the middle part have been selected for this study (Fig. 1C). Each of these three catchment areas consists of a major river flowing from the mountainous ranges in the west, passing through the relatively flat-plain and undulating areas and ending up at the lake to the east.

Soil Erosion Estimation

The situation of soil erosion in the SKC area was examined using the RUSLE model. Thus, the expected soil loss potential (erosion hazard), expressed in tons/hectare/year, for the study area was determined using the RUSLE model in a GIS environment application following the method proposed by Winchell et al. (2008). Due to the scarcity of all the available data in the same year or recent period, the estimated RUSLE soil erosion results and maps (Fig. 2) for the SLK study area are based almost entirely upon the data up to the year 2002. Generally, the controlling factors of soil erosion are climate, soil, vegetation cover, topography and the management practice of the land. These factors are combined together in the empirical RUSLE as described in the equation (1) below.

$$A = R \times K \times LS \times CP \tag{1}$$

where A is the RUSLE calculated soil loss (t ha^{-1}year^{-1}), R and K are the rain erosivity (joules m^{-2}) and soil erodibility (t m^{-2}), respectively, LS is the slope steepness and length combined in a single index and CP is the cover and management practices.

This equation is designed for soil erosion assessment and prediction based on empirical research and the statistical analysis of field experiments. So each factor is considered as a thematic layer in the GIS. Determinations of the various factors are described below.

The R factor is the rainfall-runoff erosivity factor and is the average annual summation value in a normal year's rain. The rainfall data over 11 consecutive years (1990-2002), as recorded by the Thailand Meteorological Department, was used for calculation. The R factor is an indication of the amount of rainfall and the peak intensity sustained over an extended period.. For the rainfall distribution map, the equation (2) was proposed by Morgan (1986).

The K factor represents both the susceptibility of soil to erosion and the rate of runoff, as measured under the standard unit plot condition. Although the K factor represents a soil in its natural condition, past management or misuse of a soil by intensive cropping can increase a soil's erodibility. A systematic land resources inventory was conducted in this study following the Land

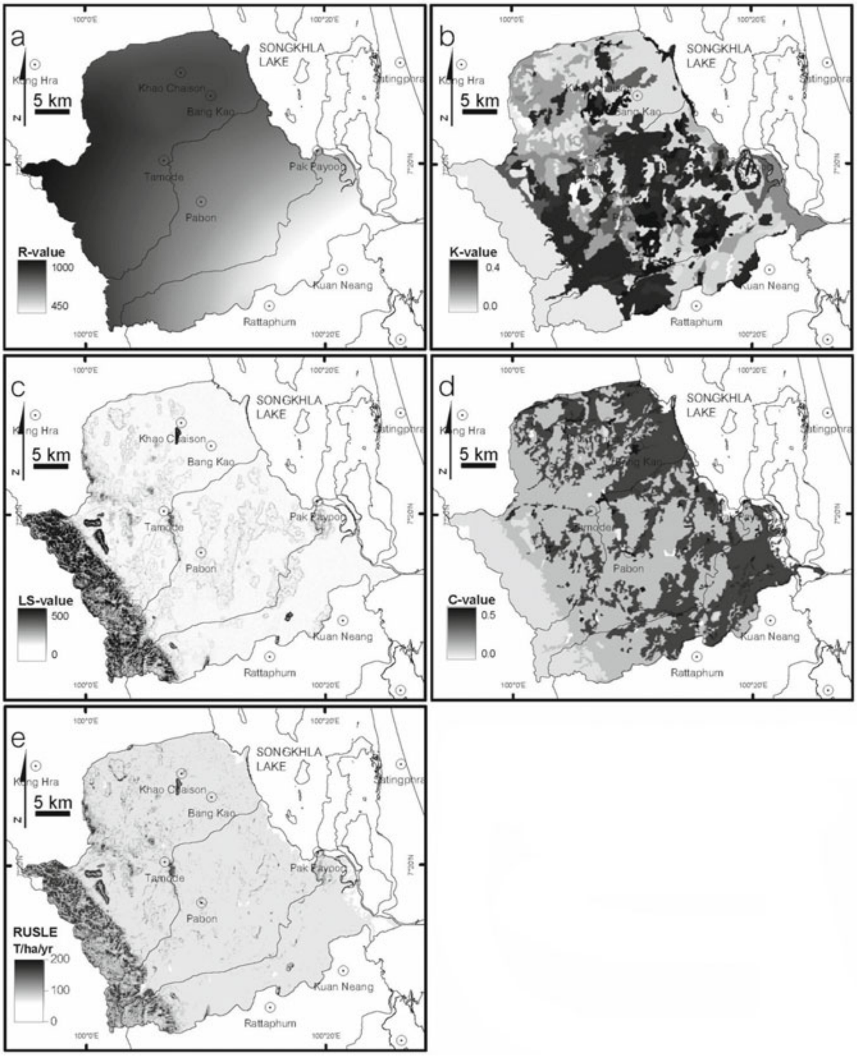

Fig. 2: Attribute maps showing the distribution of the (a) R value, (b) K value, (c) LS value, (d) C-value and (e) RUSLE results of the SKC study area, southern Thailand.

Development Department to produce a reconnaissance soil map (Ladachart, 2008) at a scale of 1:50,000.

The slope length and steepness (*LS*) factor was estimated using the method proposed by Moore and Burch (1986), based on the flow accumulation and slope steepness for each grid cell. In this study, one grid cell of about 30 × 30 m^2 is applied. The derivation of the *LS* factor is shown as equation (3) below.

$$LS = (\text{flow accumulation}) \times (\text{cell size}/22.13)^{0.4} (\sin \text{slope}/0.0896)^{1.3} \qquad (3)$$

The *C* factor (or spatial vegetative cover) is extracted from the Landsat TM5 imagery and by experiment (Table 1). In this study, the slope profiles were divided into segments with uniform slopes, which makes the evaluation of cropping patterns easier.

Table 1: Values for various vegetative cover types (C-value) used in the SKC study area, southern Thailand

Crop	*C-value*	*References*
Rice field	0.27	Mongkolsawat et al. (1994)
Fruit-orchard	0.30	Watanasak (1978)
Perrenial Plant	0.088	LDD (1983)
Grassland	0.02	Watanasak (1978)
Planted forest	0.088	Watanasak (1978)
Mixed deciduous forest	0.043	Mongkolsawat et al. (1994)

LDD = Land Development Department

The *P* factor reflects the impact of support practices and the average annual erosion rate. It is the ratio of the soil loss from contouring and/or strip cropping to that from straight row farming up-and-down the slope. So it can differentiate between cropland and rangeland or permanent pasture.

The result of RUSLE is reported as the amount of soil erosion (in tons/hectare/year) and that is then converted to the rate of soil erosion (mm/yr). Several maps showing the distribution of rainfall, soil, slope and topography, land use and geology and geomorphology are prepared. These maps constitute the main criteria for the RUSLE analysis. Results from this analysis (as shown in Fig. 2e) indicate the levels of soil erosion in each catchment area that appear to be the main sediment supply to the Songkhla Lake.

Assessment of Heavy Metals

The samples consist of 100 soil samples and 200 stream sediment samples. Analytical data of seventeen metal and non-metal values from these samples are also provided from Department of Mineral Resources (2006). These elemental data are then screened and selected for environmental analysis. Statistical techniques, including histograms and accumulation curves, were used to analyze anomalies of heavy metal distributions before their final distributions were complied as maps using the GIS spatial analysis. By comparison with the Dutch standard values, as recommended by Cairney and Hobson (1996), the distributions of some elements with high values are shown in several thematic maps, that is the land use, geology and soil erosion. Identification of the most reliable sources and transportations of the heavy metals in specific areas are then discussed.

RESULTS AND DISCUSSIONS

Rate of Soil Erosion and Sedimentation

The RUSLE result (Fig. 2e) indicates that the maximum erosion area is located in the mountainous area to the west of the regional study SKC area. Table 2 depicts rates of soil erosion for three catchment areas within the SKC study area. The Tha Chiat catchment has the highest amount of soil erosion (2.34 mm/yr) fold higher than that of the Pru Por and Pa Bon catchment areas, respectively. The Pa Bon catchment area shows the lowest rate of soil erosion (1.0 mm/yr), slightly less than that of the Pru Por catchment area (1.08 mm/yr). In general, the SKC study area has been affected by soil erosion at an average amount of 26 tons/ha/yr, which is equal to a rate of about 1.6 mm/yr. In comparison with the rates of erosion elsewhere in regions of similar climate (Zhang et al., 2005), the SKC rate falls within the ranges of India, southern China and Savanna, Ivory Coast and Ghana.

Table 2: Average rates and amounts of soil erosion in catchment areas of the SKC study area, southern Thailand

Catchment area	*Mean of soil erosion*	
	Amount (ton/ha/yr)	*Rate (mm/yr)*
Khlong Tha Chiat	37.53	2.34
Khlong Pa Bon	15.97	1.00
Khlong Pru Por	17.23	1.08
SKL study area	26.15	1.63

Ladachart (2008) reported that the present-day rate of the overall average sedimentation for the middle part of the Songkhla Lake is about 0.37 mm per year. The rate of sedimentation is slightly lower than the erosion rate, suggesting the deposition of sediment on the way to bay mouths of the major rivers.

As proposed by Zhang et al. (2008), this region of Thailand has average annual erosion rates that range between 1.0 and more than 2.0 mm per year. The erosion rate of the SLC study area is about 1.6 mm/yr, which falls within the rate reported by Zhang et al. (2005). However, for the Southeast Asian region, Wen (1993) argued that the recent erosion rate is higher at about 3.33 mm/year, which is over two-fold higher than the estimate for the erosion rate of the SLC study area of this report.

The higher rate of deposition at the beginning of the Holocene is suggested to be due to either (1) the changes in the shoreline becoming more emergent, (2) the presence of the high-relief terrain, (3) the changing world climate, or (4) the very low sea-water level at that time. However, much of the lake sediment is derived landwards. The rate of sedimentation becomes lower in the middle- and late-Holocene period due to a slightly higher sea level. As shown in Fig. 7, from about 50 years ago until the present day, the lake shorelines have been governed more by lake action than by river action. Therefore, it is suggested that the erosional shorelines are more prominent than the deposition shorelines (Fig. 7). This, perhaps, has caused the rate of deposition to become higher and given rise to the shallowness of the Songkhla lake floor at present.

Based on this observation, it is also suggested that the higher rate of lake deposition at present (within a 50-year period) is mainly attributed to the higher acceleration by human activities.

There are two kinds of sample analysis for heavy metal concentrations, one is mainly clay size sediments in soil samples and the other is sand-size sediments from the stream. It is quite clear that apart from clay with iron oxides, arsenic seems to show no contrast between the levels in clay and sandy materials. However, copper and zinc levels show a remarkable contrast in their concentrations between the two types of material. Clay-like materials are likely to contain lower Cu and Zn levels than sandy materials. Pb displays a different scenario, only clay with iron oxides contains a very high concentration of Pb, whereas sand contains less Cu than the clay. This may indicate the different modes of transportation. It is considered that Cu and Zn may be transported in the form of terrigeneous grains or fragments, whereas As and Pb are likely to be transported in solution and perhaps precipitate later when the environment becomes much more reduced.

Heavy Metal Distribution

A total of 100 soil and 200 stream sediment samples were analyzed for the following 16 elements; As, Ag, Al, Bi, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Mo, Sb and Zn, with the results of the 11 detected metals summarized in Table 3. In this study only six of these heavy metals, As, Cr, Cu, Ni, Pb and Zn, were found at levels of interest due to their geochemical affinities and environmental concerns. The distribution of these metal concentrations is presented in relation to landforms (in Fig. 1).

High arsenic (As) contents in soils (9 to 20 ppm) are located in a wide undulating area (up to 5 km in diameter) in the Tha Chiat catchment area (Fig. 4a). Small localized spots of high As concentrations (10 to 13 ppm) are also distributed westwards along the southern foot slopes of the granite range, where abandoned mines are located and also in the tidal flat/ coastal areas to the east of the Pru Por catchment. High As levels in stream sediments have been documented as large areas along the colluviums and foot slopes of the granite mountain to the west of the SKC area. The unusually high As contents (up to 680 ppm) occur as clusters on the foot slopes in the southwestern Pru Por catchment near the granite mountain.

High chromium (Cr) concentrations (20 to 35 ppm) in soils are found as sparsely distributed locations. The obviously high Cr levels occur as a wide coastal area (45 to 62.8 ppm) in the easternmost part and in isolated spots of undulating terrain and flood plain (39 to 42 ppm) in the central part of the Tha

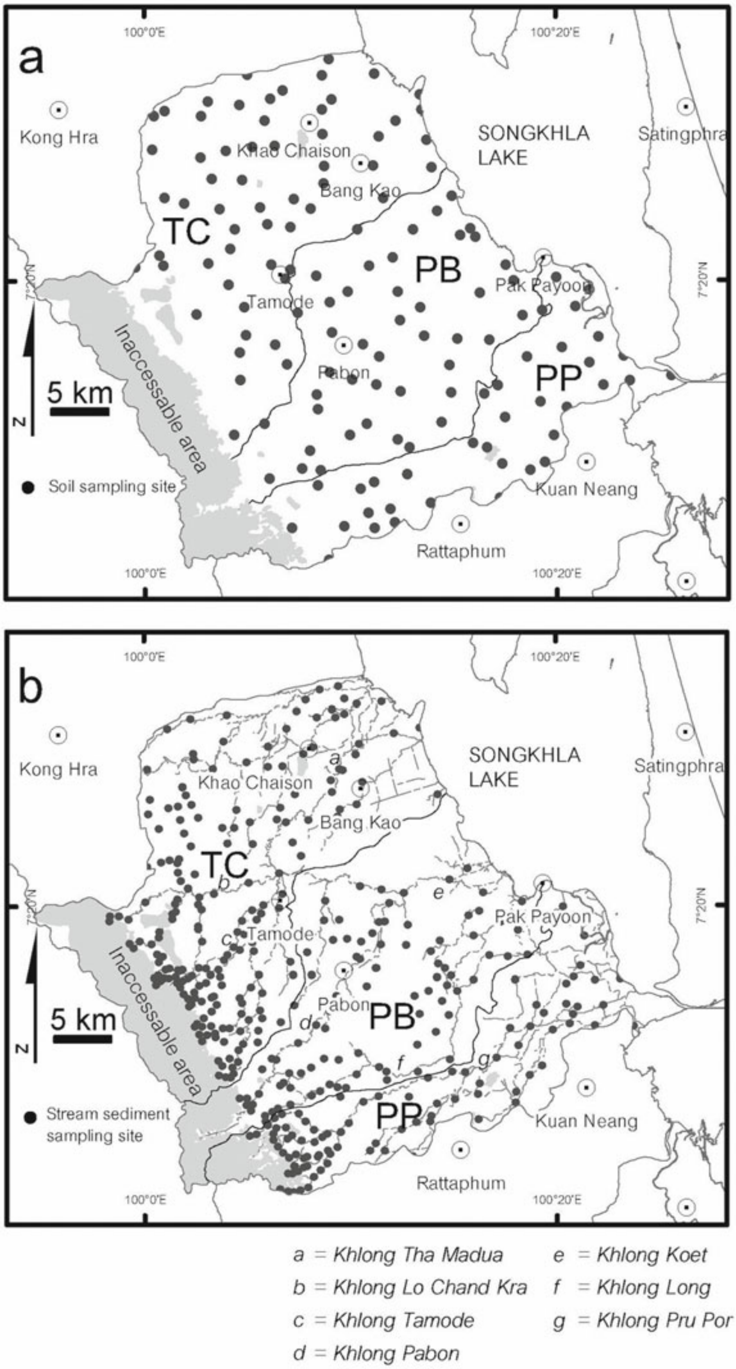

Fig. 3: Maps showing locations of (a) soil and (b) stream sediment samples in the SKC study area, southern Thailand. (TC = Tha Chait catchment area; PB = Pa Bon catchment area and PP = Pru Por catchment area).

Chiat catchment area. In the Pru Por catchment area, isolated spots of high Cr contents have been found at the western foothills and undulating terrain (32 to 40 ppm) to the east of the Pru Por catchment area. High Cr concentrations (>12 ppm) occur as isolated spots widely distributed in the tidal and coastal areas of the Ta Chiat catchment area. The more interesting stream sediment Cr concentrations (24 to 59 ppm) are located along the colluvial plains and foot slopes of the granite range and near abandoned mines to the west of the Pru Por catchment.

The interesting zone with high copper levels in the soil (30 to 111 ppm) is a flood plain area to the west of Khao Chaison district in the Tha Chiat catchment. High Cu contents in the stream sediments (up to 119 ppm) show no spatial relationship with those of the soil and have been found in the foot slopes and colluvial plains to the west of the Pru Por catchment.

Soils with higher lead (Pb) values are widely distributed in the large undulating and flood plains in the eastern and southern parts of the SKC study area, such as at Laem Jong Tanon of the Tha Chiat catchment (30 to 112 ppm) and east of Pabon district in the southern part of the Pabon catchment (35 to 100 ppm). For stream sediments, the widely distributed areas with unusually high Pb values (60 to 1063 ppm) are strictly located at the foot slopes and colluvial plains of the western granite mountain near the abandoned mines in the Pru Por and Pabon catchments. Isolated spots with high stream sediment Pb values (up to 40 ppm) are found in the flood plains of major districts in the Tha Chait catchment and tidal flat/coastal areas in the Pru Por and Pabon catchments.

The unusually high value of nickel (Ni) (133 ppm) in some stream sediments was found in the undulating terrains and flood plains near the abandoned mines in the granite mountain. Isolated spots with high Ni contents (7 to 17 ppm) also occur in the tidal flats and coastal areas of the Tha Chiat catchment. High nickel levels (15 to 89 ppm) on soil have only been found in the flood plain of the Tha Chiat catchment.

Higher zinc (Zn) concentrations in soil appear at two sites of the SKC study area, viz. a small coastal area (about 4 km diameter) in the east of Thamode catchment (41 to 141 ppm) and a larger area (about 10 km diameter) at the foot slopes in the west of the Pabon catchment (45 to 58 ppm). High values of Zn in stream sediments (35 to 2663 ppm) are mostly located at the foot slopes and colluvial plains of the high mountain. Isolated spots of high stream sediment zinc contents have been found in the tidal flat/coastal areas of the major districts.

Heavy Metal Variation and Their Physical Relationships

Heavy metal concentrations and distributions in the SKC study area were compared with the physical backgrounds of the study area, i.e., land use, geology and RUSLE, to find out if there were any clear relationships between the heavy metal concentrations and their spatial distributions in the study area.

In terms of land use, the high arsenic concentrations in soil were found to be mainly in the para-rubber (and mixed orchard) areas of the Tha Chiat catchment. Soils enriched in As (up to 19 ppm) appear in the alluvial and coastal areas. On the other hand, high values of As (up to 680 ppm) in stream sediments have been discovered in the south Pru Bon catchment area where the landform is characterized by foot slopes and colluviums of mountainous granite terrain. It is quite likely that the areas with high As levels in the stream sediments conform very well to the steeply sloping areas dominated by a high erosion rate (or RUSLE value). Interestingly, high As levels in stream sediments occur in areas where the RUSLE values are also high, particularly to the west of Pru Por and Pabon catchments. However, in contrast, the high As contents in the different soils does not seem to correlate with high RUSLE values.

High chromium concentrations in the different soils (up to 63 ppm) were found to the west of Pru Por catchment area where the major land uses are para-rubber and mixed orchard areas on colluvial and alluvial terraces in the western SKC study area. High Cr levels (up to 60 ppm) in the stream sediments were also found in colluvial and terrace deposits nearby the contact zone between the granite and sedimentary rocks. Other interesting areas with high Cr levels are the paddy fields that are developed on the alluvial deposits in the Pru Bon and Tha Chat catchments. High Cr contents in stream sediments generally conform well with that of the high As soil levels and high RUSLE values in the south of the SKC study area.

Copper levels in the soils show areas with very high concentrations (up to 111 ppm) in the paddy fields of the Quaternary flood plain area in the Tha Chiat catchment. However, generally copper levels in the stream sediments shows a different scenario, where high Cu concentrations mainly occur near the granite mountain to the west of the Pru Por and Pabon catchments where the RUSLE value is quite high. The highest Cu levels (~119 ppm) found in stream sediments also occurs in areas not far from the granite range where paddy fields are the major landform. It is likely that high Cu concentrations are related with areas occupied by unconsolidated sediments and hard rocks.

Soil nickel levels display the highest concentration (~89 ppm) in the paddy fields and para-rubber areas of the western Tha Chiat catchment, where the geology is mainly dominated by Quaternary terrace and colluvial deposits underlain by shale and clastic rocks. In stream sediments, Ni levels show a different spatial variation and seem not to be related to areas with a high RUSLE value. The high stream sediment Ni concentrations (up to 89 ppm) are located in forest areas to the west of the Pru Por catchment that are largely occupied by colluvial deposits of the underlying sandstones.

Pb concentrations show considerable variation in both soils and stream sediments. In soil, the high Pb concentrations (up to 112 ppm) are located in the relatively gentle sloping and flat-plain areas of the eastern Tha Chiat and central Pru Por catchments, where paddy field and para-rubber are the major land uses, respectively. In contrast, Pb levels in the stream sediments display a much higher concentration (up to 1062 ppm) in areas dominated by the steep slopes of undulating and colluvial deposits in the Pabon and Pru Por catchment areas. For the relationship between rock type and Pb concentration, the highest level was found in areas whose geology is characterized by the contact zone between sandstone and granite. The high levels of Pb in the stream sediments were well correlated to the RUSLE values.

Zinc concentrations in the soil and steam sediments show a largely similar variation to those shown by lead. Soil areas with high Zn concentrations (141 ppm) are located in colluvial deposits where the major land use is para-rubber plantations in the western Pabon catchment. The other area of high Zn soil concentrations is in the eastern Tha Chait catchment, whose geology is characterized by Quaternary alluvial deposits and a major land use is for paddy plantation. With respect to stream sediments, zinc shows high levels (up to 2663 ppm) to the west of the SKC study area where a major land use is para-rubber plantations developed on the colluvial deposits near the contact zone between granites and clastic rocks. High Zn concentrations seem to conform very well to the RUSLE values.

Chemical Data

The results of both the soil and stream-sediment analyses at the SKC study area (Table 3; Figs 4 and 5) allow the potential sources of the heavy metals to be inferred. The data for the stream sediments and soils analyzed for heavy metals in the SKC study area were screened, evaluated and then compared with contamination levels of trace elements in soils from various parts of the world (Notification of National Environmental Board No. 25, 2004). It is shown that soils of Thailand have heavy metal contents within the range of those of the other countries. However, it is found that As value is much lower whereas Cd and Hg are generally higher.

Spatial maps with high heavy metal levels are shown with respect to the land use (Fig. 6a), geology (Fig. 6b) and soil erosion or RUSLE (Fig. 6c). These maps use the standard of heavy metal levels suggested by the Dutch Ministry of Housing, Spatial Planning and Environment (2001) for soil/sediment remediation (Table 4). The result shows that there exists good correlation of granite geology to the west of the area, RUSLE values and mountainous and foot-hill landforms.

Sources of Heavy-metal Interpretations

This step attempted to identify the locations of heavy metals in the SKC area with respect to landform and geology. Among all the six selected metals analyzed, arsenic, lead and zinc were interesting. Histograms and cumulative curves of these three metals constructed by Ladachart (2008) reveal that there are at least two inflection points which are attributed to more than one source of contamination.

Table 3: Summary of heavy metal data in soils and stream sediments of the SKC study area, southern Thailand

	Al	*As*	*Cr*	*Cu*	*Fe*	*Mn*	*Ni*	*Pb*	*Mo*	*Sb*	*Zn*
Heavy metal concentrations in soils											
Min	758.77	0.10	0.39	0.71	349.40	0.49	0.59	0.17	3.99	3.99	0.21
Max	46,622.16	19.80	62.76	110.99	30,731.83	854.20	89.68	111.85	16.38	17.73	141.60
Mean	13,408.18	4.05	14.41	2.62	6,513.21	84.89	1.94	17.39	4.07	4.16	13.63
SD	9,497.51	3.20	13.55	8.82	5,025.33	132.01	6.57	17.26	0.90	1.24	17.19
Heavy metal concentrations in stream sediments											
Min	935.81	0.01	0.39	0.71	362.88	0.49	3.99	0.59	0.49	3.99	0.49
Max	31,273.47	680.00	59.64	119.08	51,061.90	38,384.00	277.91	133.00	1,062.80	61.08	2,663.03
Mean	7431.15	7.43	6.40	3.09	9,509.80	330.37	18.48	2.24	33.59	8.95	18.19
SD	3,849.88	31.43	8.48	6.41	6,128.09	1,700.61	20.52	9.42	96.64	7.44	111.26

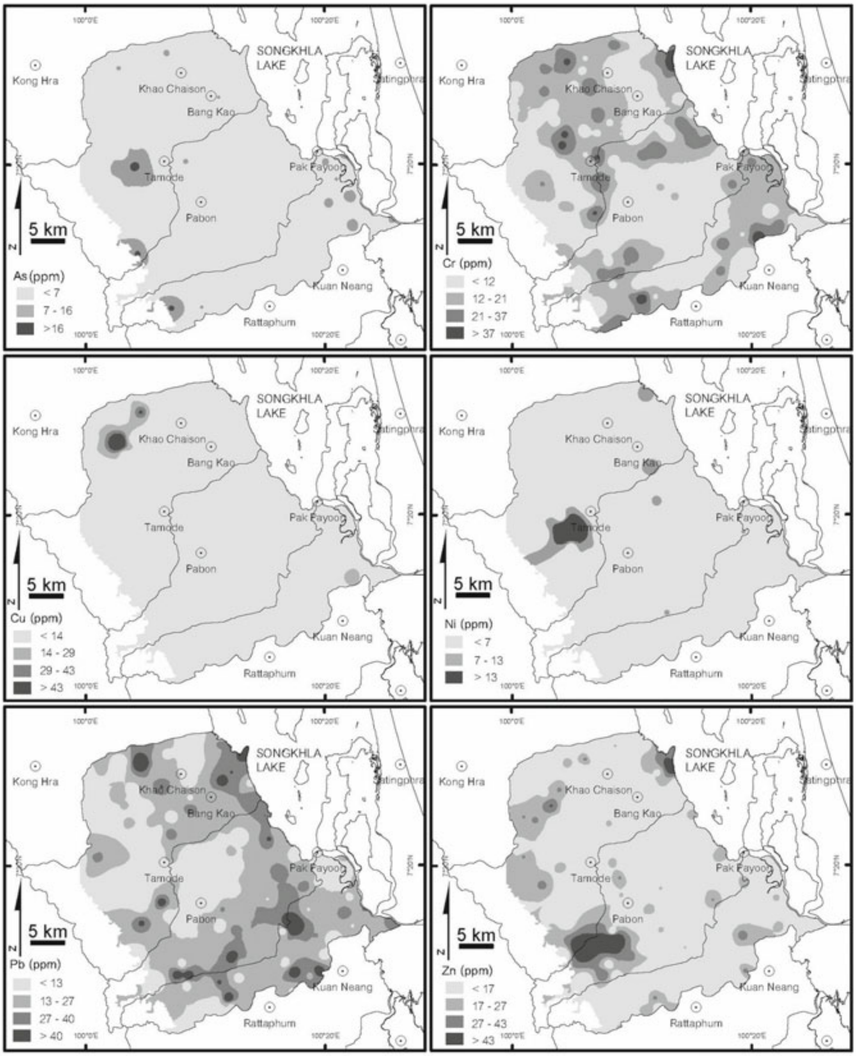

Fig. 4: Distribution maps of six heavy metals As (a), Cr (b), Cu (c), Ni (d), Pb (e) and Zn (f) levels in the soil in the study SKC area, southern Thailand.

Arsenic (As) is mainly located in the hilly area and swamp and is also present in each layer of the lake sediments (Ladachart, 2008). Lead (Pb) is located mainly in the high terraces, flood plains and swamps and it also exists in the lower part of the lake sediment. Zinc (Zn) is mainly located in the colluvial, flood plain and coastal areas and it also shows some significant relationship with human activities.

For identification of the sources of arsenic, it can be separated into two areas. The first area is located in the mountainous region where arsenic would have originated from the granitic rocks located in the high mountain ranges in

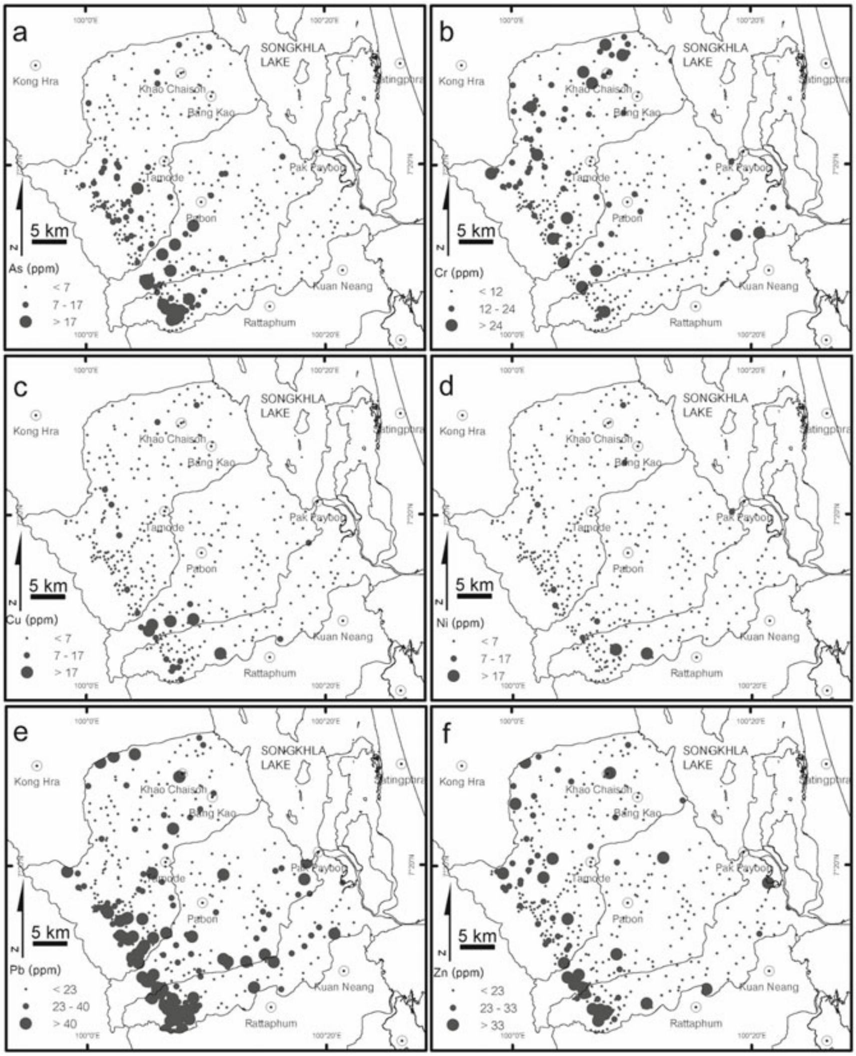

Fig. 5: Distribution maps of six heavy metals As (a), Cr (b), Cu (c), Ni (d), Pb (e) and Zn (f) levels in the stream sediments in the study SKC area, southern Thailand.

the western part of the study region. The second area is located in the low-lying and swampy areas, where As likely originated from the granitic terrain that is easily exposed and eroded and was then transported by water, after the oxidizing stage and then precipitated in the reducing environment of the swampy areas. However, since the swamp is very close to the densely human populated area, the high As contents could be mainly due to human activities, such as tin and rock mining and deforestations.

The high concentrations of lead are located in sediments, such as alluvial terraces and colluvial areas. As such lead is likely to have been deposited during

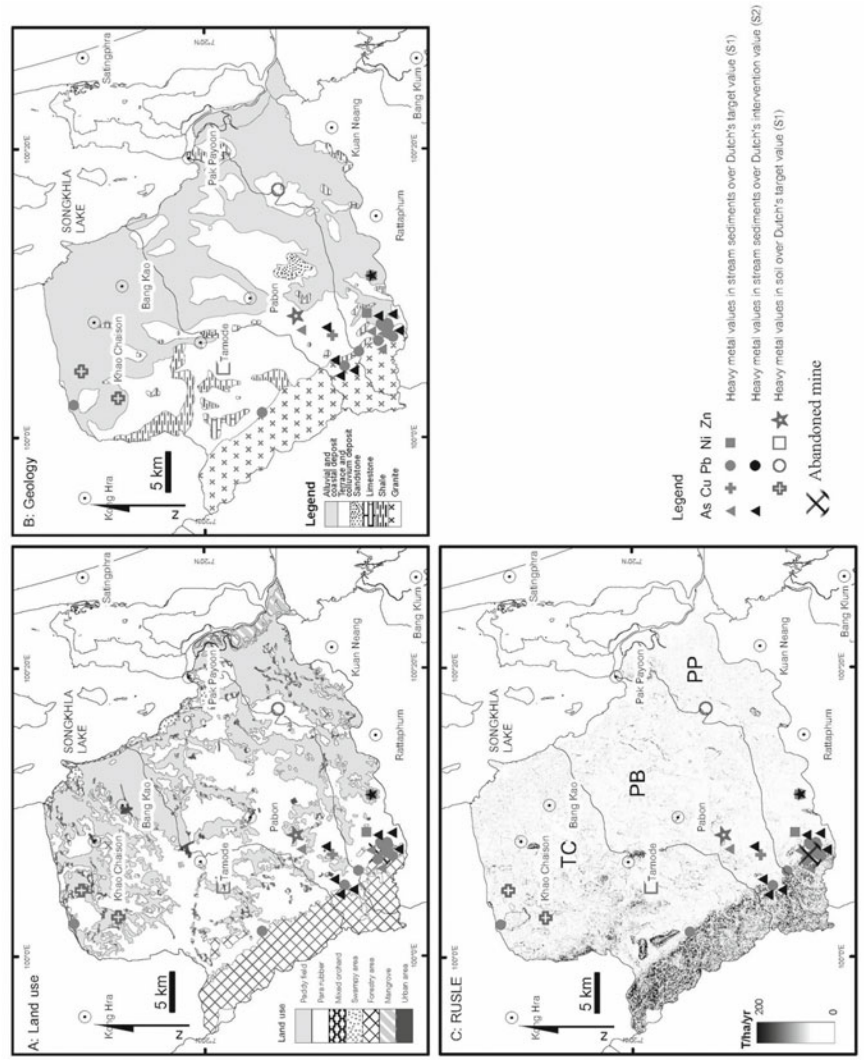

Fig. 6: Comparison of soil erosion and heavy metals concentrations over Dutch's standard values with the (A) land use, (B) geology and (C) RUSLE. (TC = Tha Chait catchment area; PB = Pa Bon catchment area and PP = Pru Por catchment area).

the fluvial process in the Late Tertiary period and subsequentially redistributed and transported by human activities, particularly in the urbanized areas.

With respect to zinc sources, there is no significance correlation to their natural occurrences. At present, it is widely accepted that zinc has been used for several purposes, including raw material for rubber industries, coating on steel, pharmaceutical and cosmetic industries, micronutrients for humans, animals and plants (Woodcock and Hamilton, 1993). So for the study area, zinc has higher concentrations in areas dominated by para-rubber plantations.

Table 4: Heavy metal concentrations and number of soil and sediment samples of the SKC study area having contents higher than Dutch standards for soil contamination assessment. (Dutch Ministry of Housing, Spatial Planning and Environment, VROM, 2001)

Element	*Target values (A) (mg/kg)*	*No. of samples over A*		*Intervention values (C) (mg/kg)*	*No. of samples over C*	
		In soils	*In stream sediments*		*In soils*	*In stream sediments*
Arsenic (As)	29	6	0	55	7	0
Chromium (Cr)	100	0	0	380	0	0
Copper (Cu)	36	2	2	190	0	0
Nickel (Ni)	35	5	1	210	0	0
Lead (Pb)	85	24	1	530	7	0
Zinc (Zn)	140	0	1	720	0	0

Target values (A) and soil remediation intervention values (C) for selected metals are expressed as concentrations in a standard soil (10% organic matter, 25% clay).

Thus, the source of Zn in this region is likely to be derived from human activities and in particular the para-rubber agriculture.

Heavy-metal Contamination on Land

From the soil and stream-sediment analyses of heavy metal contamination levels and locations at the SKC study area, the likely sources of heavy metals can be inferred and compared with contamination levels of trace elements in soils from various parts of the world.

The standard of heavy metal levels suggested by Dutch Ministry of Housing, Spatial Planning and Environment (2001) for soil/sediment remediation were applied in this study. This standard has long been established and the intervention values are based on extensive studies of both the human and eco-toxicological effects of soil and sediment contaminants. In addition, they assist in the assessment of contaminated soils/sediments and sites that pose a potential concern, as well as providing a means for screening out those soils/sediments that do not warrant additional attention (Macklin et al., 2003).

It is quite likely that the arsenic values of stream sediments are high in the mountainous and hilly regions, which are mainly granitic terrain to the west. The provenance of arsenic is thus considered to be more or less related to granitic rocks. Only the granitic terrain in the South is the most favourable likely source of As, near the abandoned mines. However, one location with high arsenic levels shows a different and interesting scenario in that it is found in the swampy area. This is somewhat suggestive of deposition from the reducing environment and so is likely to be from contamination derived from human activities causing arsenic dispersion, such as tin mining, rock quarrying, deforestation and so on.

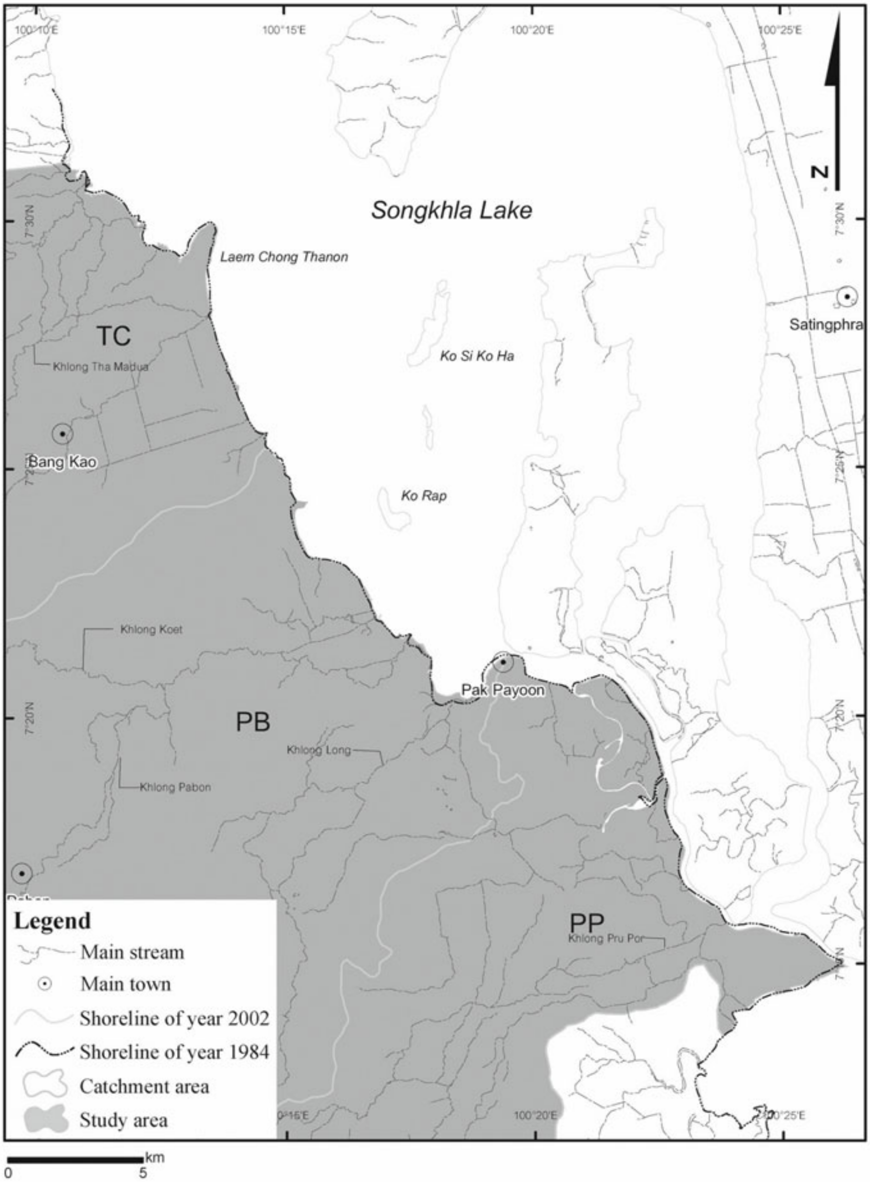

Fig. 7: Comparison of previous (1976) and present-day (2008) shorelines of the SKC study area in southern Thailand.

The three other heavy metals with high concentrations, Ni, Pb and Cu, in general fall within the range of the target values. These elements are mainly located on the hill slopes and colluvial deposits. However, they are essentially found along or at the western edge of the para-rubber and mixed orchard plantation. We therefore suggest that the high levels in stream sediments are likely to be from non-point sources, such as human deforestation and the severe use of fertilizers and pesticides.

For the results of the geochemical soil analyses, all the reported elemental concentrations are not higher than target values. However, as shown in Fig. 5, there are a few elements, such as Cu, Ni, Pb and Zn, which show high levels within the range of target values. Although these elements mainly occur in the alluvial terraces and colluvial areas, they are interpreted, based on land uses, to be non-point sources, having formed as a result of human activities similar to those of the stream sediments. It is interesting to note that none of the analyzed elements in soils are higher than the Dutch Ministry of Housing, Spatial Planning and Environmental intervention values at present.

CONCLUSION

The average erosion rate in the middle part of the Songkhla catchment (SKC) area, as determined using the RUSLE method, was about 1.64 mm/yr. The high rate of erosion in some parts is considered to be anthropogenic and due to deforestation, the overuse of agricultural chemicals and mining activities.

Soil and stream sediments were analyzed for heavy metal contamination and the results were compared with those of the Dutch standard values for environmental contamination. The results indicated that the soils and sediments in the SKC study area generally contain a low level of heavy metals and that the likely sources of the heavy metals are mainly derived from areas dominated by human activities. However, the results also indicate that the heavy metal levels currently do not exceed those of the Dutch standard. The rapid economic growth without a well-defined overall planning strategy in the SKC area is likely to create an environmental problem regarding heavy metal contamination. Additionally, the likely sources of these pollutants are fertilizers and pesticides for agricultural purposes and this perhaps promotes the non-point source leakages (Department of Mineral Resources, 2006; Sompongchaiyakul and Sirinawin, 2007). Therefore, it can be concluded that due to the overuse of chemicals, the soils in the central plain of the catchment area are contaminated and serve as the most probable source of heavy metal contamination.

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9

Comparative Studies of Concentrations of Cu and Zn in the Surface Intertidal Sediments Collected from East, South and West Coasts of Peninsular Malaysia

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Abstract: Malaysia is one of the fast economic developing nations in the region. From the ecotoxicological points of view, many environmental concerns are expected to continually rise up due to the potential anthropogenic inputs such as industries and urbanization. Although the heavy metal concentrations had been reported in the sediments from the west coast of Peninsular Malaysia, the east coast receives lesser attention since it is not as populous and industrialized as in the west coast. In this study, concentrations of Cu and Zn for surface sediments were determined and the samples were collected between 2002 and 2004, from west (five sites), south (five sites) and east (10 sites) intertidal area of Peninsular Malaysia. Total Cu concentrations ranged from 3.80 to 117 µg/g dry weight with south coast recording the highest mean concentration (38.8 µg/g dry weight), followed by west (31.13 µg/g dry weight) and east coasts (12.96 µg/g dry weight). Total Zn concentrations ranged from 36.6 to 395 µg/g dry weight with west coast recording the highest mean concentration (137 µg/g dry weight), followed by south (111 µg/g dry weight) and east coasts (73.8 µg/g dry weight). Apart from the comparison based on the conventional total concentrations of metals, three geochemical fractions (EFLE, acid-reducible and oxidisable-organic) were also useful in identifying the polluted sites in which the three geochemical fractions in the sediments of the west and south coasts of Peninsular Malaysia had significantly ($P < 0.05$) higher concentrations of Cu and Zn when compared

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to those in the east coastal sediments. This had strengthened our previous assumption that the east coast is less polluted by anthropogenic Cu and Zn when compared to the west and south coasts of Peninsular Malaysia.

Key words: West and east coasts of Peninsular Malaysia, Cu and Zn concentrations, surface sediments.

INTRODUCTION

Tropical Southeast Asian countries are now a fast growing region with their rapid economic and population growths. In particular, the economic expansion involving industries are the driving force to make a country rich. Following that, rapid urbanization in the localized area, mainly concentrated in cities, are sources where potential anthropogenic inputs arise due to domestic wastes and dumping. Among the Southeast Asian countries, Malaysia receives Gross Domestic Product (GDP) as 207.2 billion for the year 2003, as compared to Singapore's GDP as 109.1 billion for the same year (CIA World Fact Book, 2004) and this figure means Malaysia is one of the fast economic developing nations in the region. In the literature, industries and urbanization would potentially create environmental problems but how are these problems becoming significant? This is usually highlighted in local newspapers when massive death of fish is reported or how if humans are among the unfortunates? Therefore, monitoring the intertidal environment for its pollution level is necessary since it is important to predict if we are exposed to toxic contaminants in our surrounding or not.

Our previous studies (Yap et al., 2002, 2003a, 2003b, 2005), based on the sediment samples collected during 1999-2001, signified that the heavy metal pollution in the intertidal area of the west coast of Peninsular Malaysia are (1) localised and (2) near to anthropogenic sources. These findings seem to be typical of many developing nations in the world. However, what is the heavy metal pollution status during 2002-2004, awaits further investigation and this has been the focal point of this study. From the monitoring point of view, the trends of heavy metal variations temporally and spatially are important information to predict any possible outcomes due to the potentially anthropogenic discharges.

Previous studies mainly focussed on the west coast of Peninsular Malaysia but the east coast of the Peninsula receives less attention in the study of heavy metal pollution, based on the reports in the literature (Mushrifah et al., 1995; Shazili et al., 1997), when compared to the west and south coasts of the Peninsula. Therefore, the objective of this study is to determine the pollution status of concentrations of Cu and Zn in the surface sediments collected from east coast (Tumpat to Mersing) by comparing with a few known polluted sites in the west and south coasts of Peninsular Malaysia.

METHODS AND MATERIALS

Sampling and Storage

The sampling area covered the west, south and east coasts of Peninsular Malaysia (Fig. 1). The descriptions of all sampling sites are presented in Table 1.

The sampling procedure for the intertidal sediments was similar to that reported by Yap et al. (2002, 2003a) viz., an Ekman grab and a plastic spatula were used during the sampling. The top 3 to 5 cm of surface sediments were collected at each sampling site. Each sediment sample was placed in a clean plastic bag and was frozen (–10°C) prior to analysis. Triplicates from each sampling site were analysed.

Sample Preparation

Sediment samples were dried at 60°C for at least 96 hours until a constant dry weight (dw) (Fichet et al., 1999) by using an air-circulating oven. Afterwards, the samples were crushed to powder by using a mortal and pestle and sieved through a 63 mm stainless steel aperture sieve. During the process, the sieve was shaken vigorously to produce homogeneity (Yap et al., 2002, 2003a).

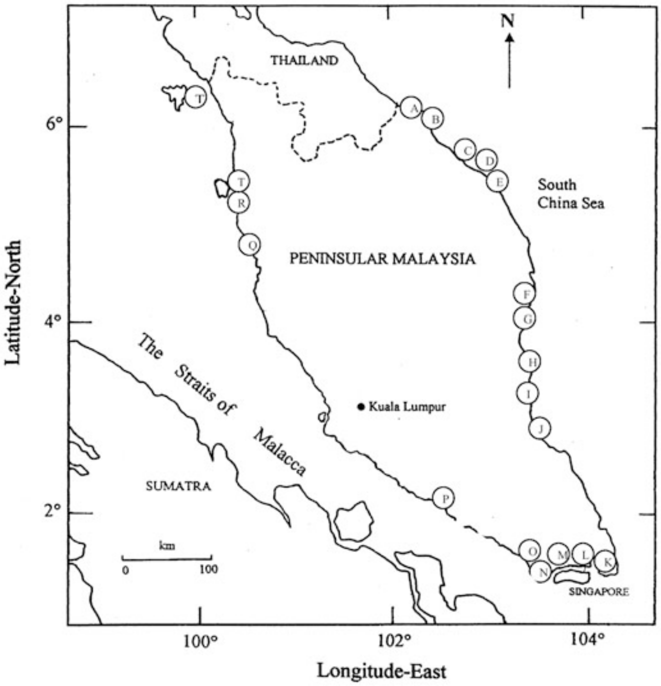

Fig. 1: Sampling sites along the coastal area of Peninsular Malaysia. Names of sampling sites represented by alphabets follow those in Table 1.

Table 1: Sampling dates, sediment types and descriptions of sampling sites for the intertidal sediment collected from the west coast of Peninsular Malaysia

	Sampling sites	*Dates of sampling*	*Site descriptions*
A	Pantai Sri Tujuh, Tumpat	6 April 2004	Fish aquacultural sites
B	Tok Bali	7 April 2004	Beach
C	Jetty to Pulau Redang	7 April 2004	Jetty
D	Kertih	7 April 2004	Fishing area
E	Jetty Tanjung Api	8 April 2004	Fishing area
F	Sg. Pahang	8 April 2004	Pristine area
G	Kampung Tanjung Batu	8 April 2004	Pristine area
H	Kuala Nenasi	8 April 2004	Pristine open sea
I	Jetty Kuala Pontian	8 April 2004	Mussel cultured site
J	Pantai Mersing	8 April 2004	Fishing area
K	Kuala Belungkor	18 April 2002	Pristine area
L	Kampung Pasir Puteh	18 April 2002	Industrial, mooring activities and urban area
M	Pantai Lido	18 April 2002	Urban area and jetty
N	Tanjung Piai	17 April 2002	A Ramsar site
O	Jetty Kukup	17 April 2002	Jetty and boating activity
P	Sebatu	17 April 2002	Mussel cultured site
Q	Kuala Kurau	9 April 2002	Fishing village
R	Bukit Tambun	9 April 2002	Receiving domestic wastes
S	Kuala Juru	9 April 2002	Receiving industrial effluents
T	Teluk Ewa, Langkawi	10 April 2002	Cement factory in the nearby

Speciation of Cu and Zn of Sediment Samples

Geochemical fractions of Cu and Zn in the sediments were obtained by using the modified SET (Badri and Aston, 1983; Yap et al., 2002). The four fractions considered were: 1. Easy, freely, leachable or exchangeable (EFLE), 2. 'Acid-reducible', 3. 'Oxidisable-organic' and 4. Resistant. The extraction solutions and the conditions employed for each fraction used in this study followed those reported by Yap et al. (2002).

The prepared samples were determined for Cu and Zn by an air-acetylene flame atomic absorption spectrophotometer (AAS) Perkin-Elmer Model AAnalyst 800. The data were presented in μg/g dry weight basis.

Quality Control

To avoid possible contamination, all glassware and equipment used were acid-washed. A quality control sample was routinely run through during the period of metal analysis. Percentages of recoveries were 95% for Cu and 110% for Zn.

The quality of the method used was checked with a Certified Reference Material (CRM) for Soil (International Atomic Energy Agency, Soil-5, Vienna, Austria). The agreement between the Cu and Zn analytical results for the reference material and their certified values for the metals were satisfactory (certified Cu: 77.1 ± 4.7 µg/g, measured Cu: 80.0 ± 5.0 µg/g; certified Zn: 368 µg/g, measured Zn: 389 µg/g).

Statistical Analysis

Based on the geographical factor, the sampling sites in the coastal sediments of Peninsular Malaysia were divided into west (five sites), south (five sites) and east (10 sites) coasts. The Pearson's product moment correlation coefficient on the $\log_{10}$ (mean + 1) transformed data (Zar, 1996) was applied, by using the Statistical Analysis System (SAS) for Windows (Release 6.12 software), to determine the strength and levels of significance of the relationships.

RESULTS AND DISCUSSION

The total concentrations of Cu and Zn of all sampling sites are presented in Fig. 2. Total Cu concentrations by using direct aqua-regia method ranged from 3.80 to 117 µg/g dry weight with south coast recording the highest mean concentration (38.8 µg/g dry weight) (the highest Cu concentration at Kg. Pasir Puteh with 117 µg/g dry weight). This is followed by west (31.13 µg/g dry weight) and east coasts (12.96 µg/g dry weight). Total Zn concentrations ranged from 36.6 to 395 µg/g dry weight with west coast recording the highest mean concentration (137 µg/g dry weight) (the highest Zn concentration at Kuala Juru with 395 µg/g dry weight). This is followed by south (111 µg/g dry weight) and east coasts (73.8 µg/g dry weight).

Concentrations of Cu and Zn in each fraction of EFLE, acid-reducible and oxidisable-organic are compared among all the sampling sites, as shown in Figs 3, 4 and 5. For EFLE Cu and Zn (Fig. 3), three sites from K. Juru, Kg. Pasir Puteh and Bukit Tambun were found to be significantly elevated, followed by the rest of the sampling sites. For acid-reducible Zn (Fig. 4), K. Juru was found to be significantly elevated, followed by Bukit Tambun and the rest of the sampling sites but for acid-reducible Cu (Fig. 4), no consistent pattern with known polluted sites are identified. For oxidisable-organic Cu (Fig. 5), Kg. Pasir Puteh was found to be significantly elevated, followed by Bukit Tambun and the rest of the sampling sites while for oxidisable-organic Zn, K. Juru, Kg. Pasir Puteh, Bukit Tambun and P. Lido were found to be significantly elevated, followed by the rest of the sampling sites (Fig. 5).

Spearman's rank correlation coefficients among EFLE, acid-reducible, oxidisable-organic, resistant and nonresistant fractions based on all the sediment data are presented in Table 2. All pairwise are significantly correlated (R = 0.46-0.96; at least $P < 0.05$) except for 'acid-reducible'-resistant fractions of Cu and Zn. Similar results (low R values with acid-reducible fractions)

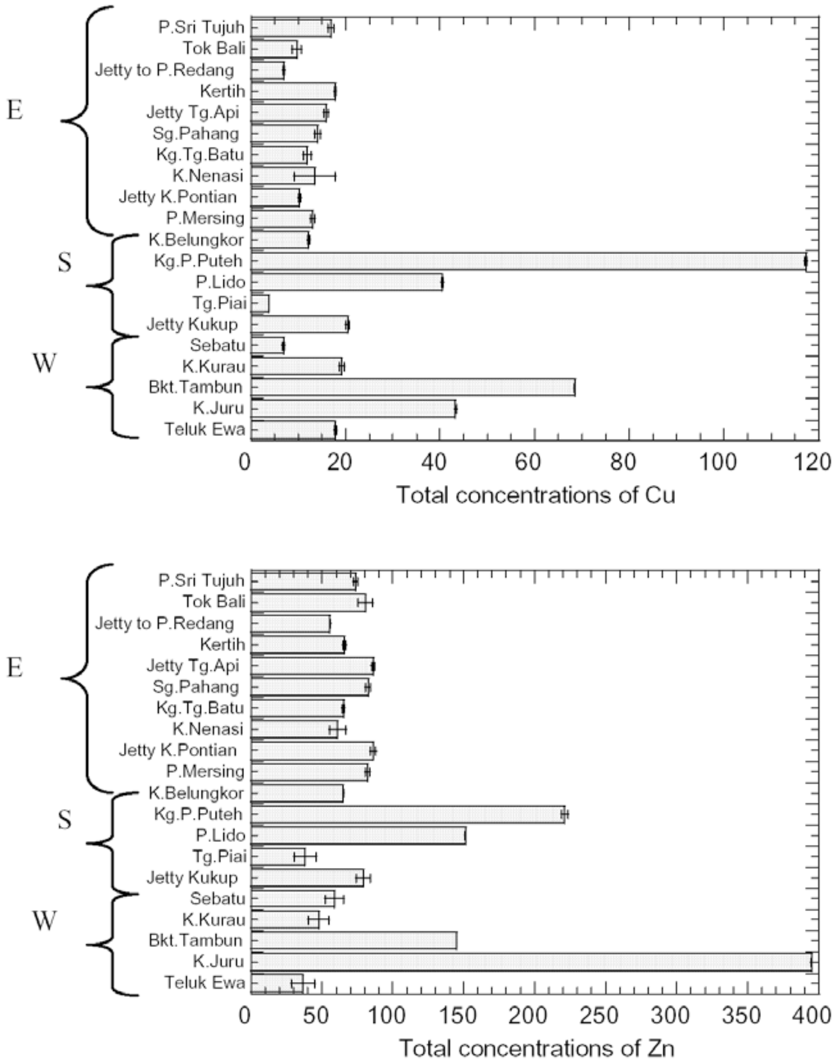

Fig. 2: Total concentrations (mean µg/g dry weight ± standard error) of Cu and Zn, based on aqua-regia method, of the surface sediment collected from the west (W), east (E) and south (S) coasts of Peninsular Malaysia.

are generated based on Zn concentration collected in offshore and intertidal sediments of west coast of Peninsular Malaysia, collected during 1999-2001, as reported by Yap et al. (2005).

Two interesting patterns can be concluded from the correlation coefficients based on correlation analysis in Table 2. First, total concentration of Cu is highly correlated with resistant Cu indicating that when the total concentration was high, high concentration of naturally occurring Cu would be high too

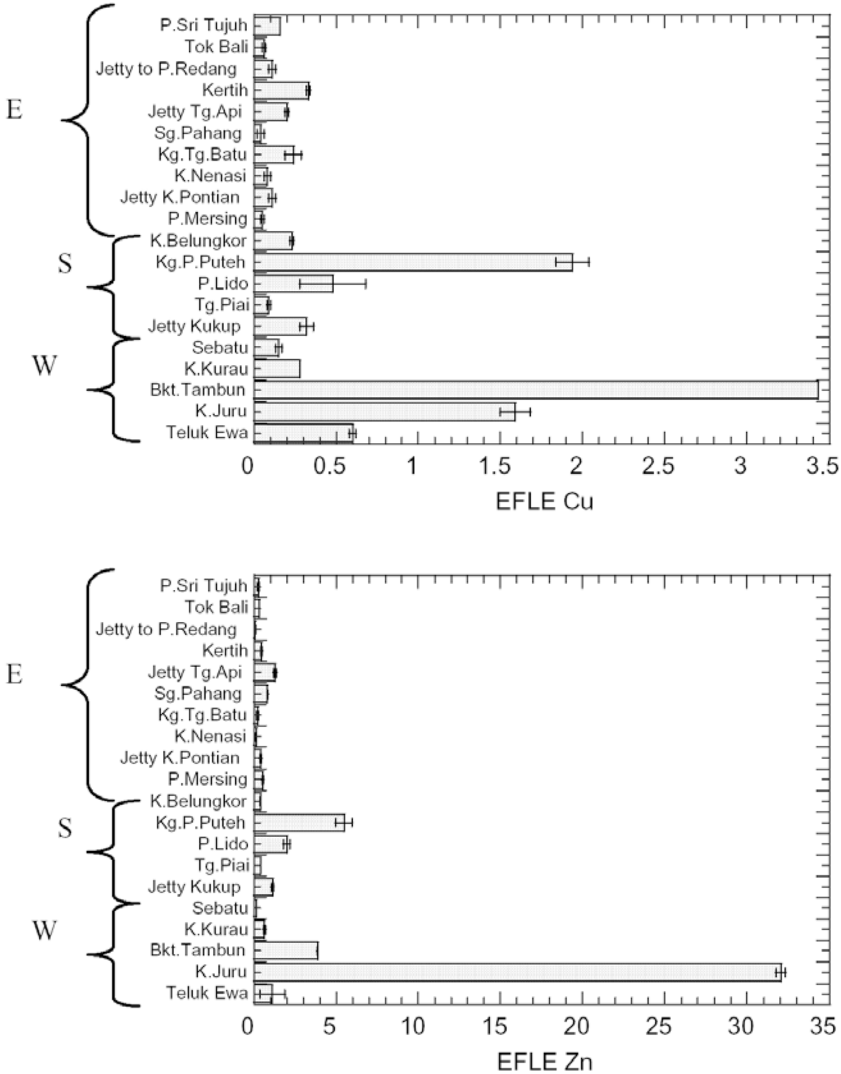

Fig. 3: Concentrations (mean µg/g dry weight ± standard error) of easily, freely or leachable (EFLE) fraction of Cu and Zn in the surface sediment collected from the west (W), south (S) and east (E) coasts of Peninsular Malaysia.

(with $R = 0.96$; $P < 0.001$ in Table 2). This indicated that the Cu polluted sites do not exhibit high percentages of nonresistant Cu. Second, in contrast to Cu, total Zn concentration is not significantly ($P < 0.05$) correlated with resistant Zn. This indicated that the supposedly high Zn polluted sites were also recorded to have low percentage of nonresistant Zn.

A comparison of the west, south and east regions was made and this is presented in Table 3. Summation of all geochemical fractions of Cu and Zn

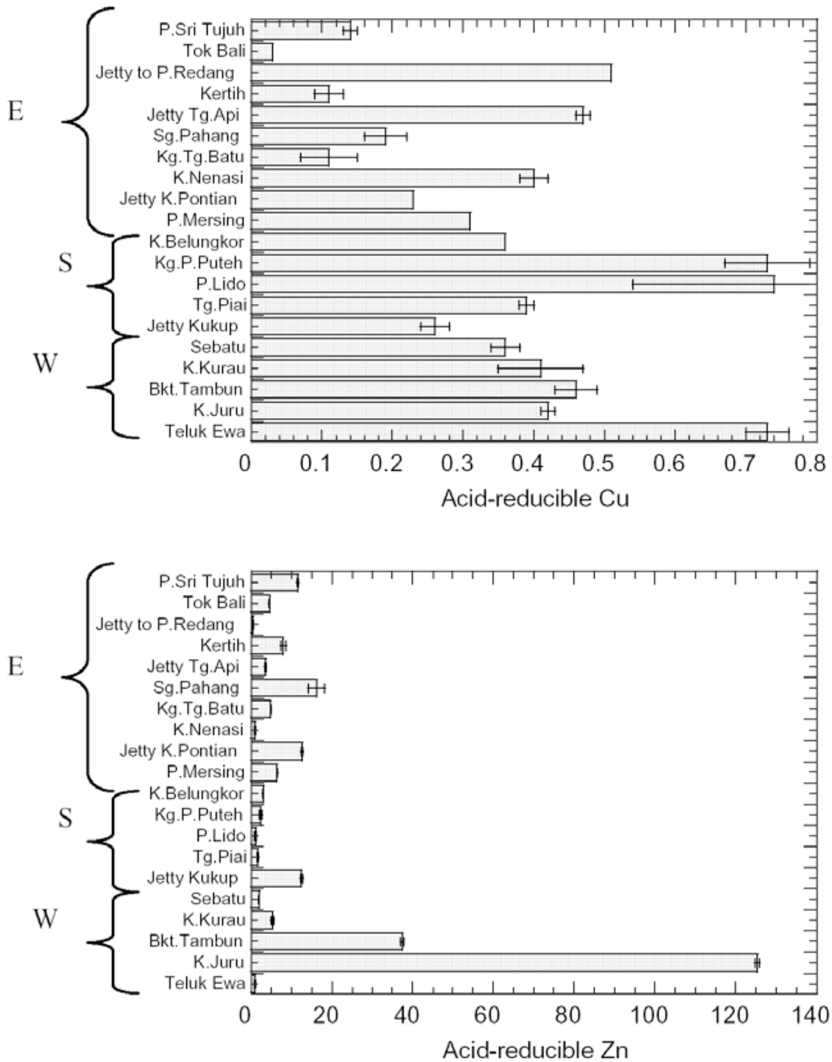

Fig. 4: Concentrations (mean µg/g dry weight ± standard error) of acid-reducible fraction of Cu and Zn in the surface sediment collected from the west (W), south (S) and east (E) coasts of Peninsular Malaysia.

concentrations in the west coastal sediments also showed the highest levels of Cu and Zn when compared to south and east regions.

When compared to background levels and established sediment quality criteria of Cu and Zn (Table 4), concentrations of Cu and Zn in the east coast sediments are all below the levels of sediment quality criteria and close to or below background levels reported from China and Hong Kong. However, some sites recorded elevated concentrations of Cu and Zn which were higher than

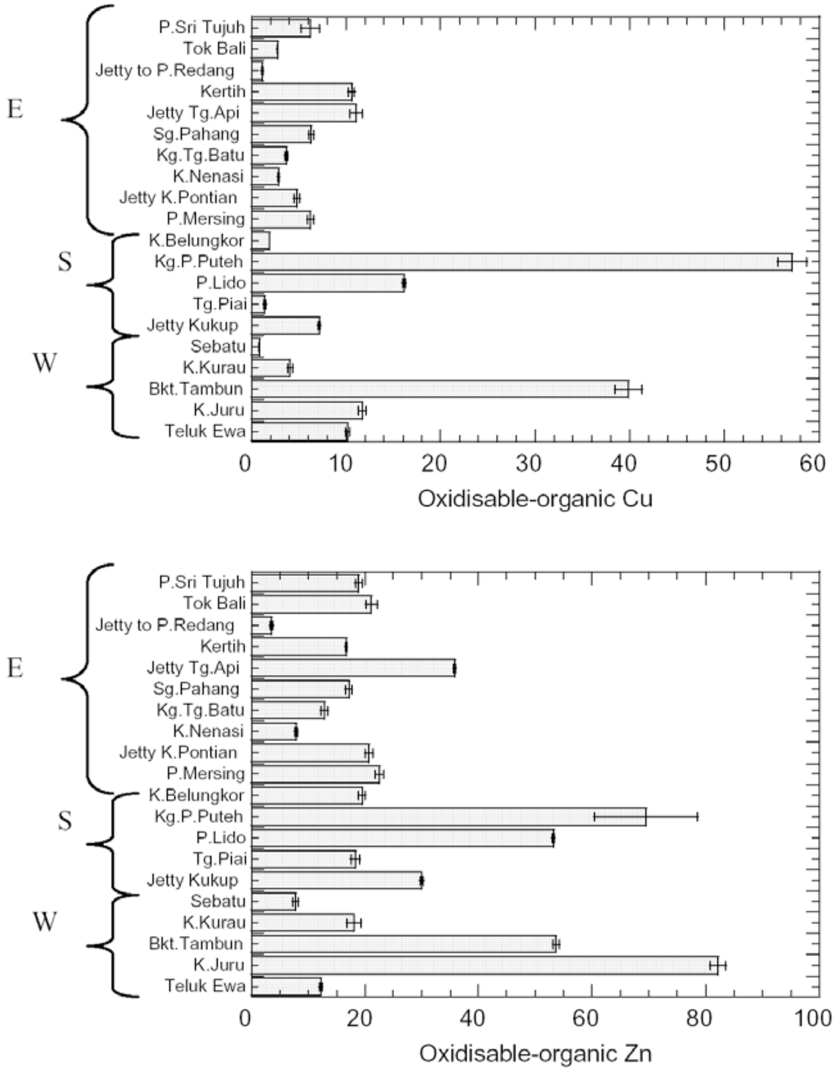

Fig. 5: Concentrations (mean µg/g dry weight ± standard error) of oxidisable-organic fraction of Cu and Zn in the surface sediment collected from the west (W), south (S) and east (E) coasts of Peninsular Malaysia.

the Action Levels of these metals established by the Hong Kong Sediment Quality Criteria (Lau Wong and Rootham, 1993) and the Interim Sediment Quality Values-low (ISQVs-high) for Hong Kong (Chapman et al., 1999). The highest concentrations of Cu and Zn were all below the Interim Sediment Quality Values-high (ISQVs-high) for Hong Kong (Chapman et al., 1999).

For the west coast sediments, only sites at Kg. Pasir Puteh, Kuala Juru and Bukit Tambun fell in the ranges for Action Level of Hong Kong Sediment

Table 2: Spearman's correlation coefficients of intertidal sediments based on 20 sampling sites along the coastal area of Peninsular Malaysia

	TOTCu	*Cu1*	*Cu 2*	*Cu3*	*Cu4*	*TOTZn*	*Zn1*	*Zn2*	*Zn3*	*Zn4*
TOTCu	1.00	0.78***	0.43 ^{ns}	0.89***	0.96***	0.53*	0.82***	0.35 ^{ns}	0.60**	0.28 ^{ns}
Cu1		1.00	0.48*	0.67***	0.84***	0.28 ^{ns}	0.64**	0.13 ^{ns}	0.42 ^{ns}	0.49*
Cu2			1.00	0.37^{ns}	0.37 ^{ns}	0.10 ^{ns}	0.46*	-0.46*	0.23 ^{ns}	0.50*
Cu3				1.00	0.83***	0.72***	0.89***	0.39 ^{ns}	0.69***	0.25 ^{ns}
Cu4					1.00	0.49*	0.79***	0.32 ^{ns}	0.61**	0.33 ^{ns}
TOTZn						1.00	0.66***	0.54**	0.83***	0.21 ^{ns}
Zn1							1.00	0.41 ^{ns}	0.79***	0.37 ^{ns}
Zn2								1.00	0.47*	-0.13 ^{ns}
Zn3									1.00	0.33 ^{ns}
Zn4										1.00

Note: 1 = EFLE, 2 = acid-reducible, 3 = oxidisable-organic and 4 = resistant.
Based on 30 stations in the offshore. Levels of significance: *$P< 0.05$; **$P< 0.01$; ***$P< 0.001$; $^{ns}P> 0.05$.

Table 3: Mean concentrations (µg/g dry weight) of total based on aqua-regia method and four geochemical fractions based on sequential extraction technique, of Cu and Zn in the surface sediments along the intertidal area of Peninsular Malaysia, separated into west, south and east coasts sediments

	Cu				*Zn*			
Region	*Min*	*Max*	*Mean*	*SE*	*Min*	*Max*	*Mean*	*SE*
East coast (10 sites)								
Total concentration-based aqua-regia methods	6.90	17.79	12.96	1.08	55.55	86.13	73.83	3.55
EFLE 0.04	0.33	0.14	0.03	0.08	1.28	0.45	0.11	
Acid-R	0.03	0.51	0.25	0.05	0.48	16.17	6.89	1.63
Ox-Organic	1.15	11.07	5.56	1.03	3.54	35.82	17.71	2.78
Resistant	8.63	17.43	12.73	0.80	41.67	60.91	48.59	1.90
South coast (five sites)								
Total concentration-based aqua-regia methods	3.80	117.34	38.82	20.55	38.05	221.2	110.91	33.35
EFLE 0.09	1.94	0.61	0.34	0.40	5.48	1.88	0.95	
Acid-R	0.26	0.74	0.50	0.10	1.04	12.47	4.07	2.13
Ox-Organic	1.40	57.15	16.74	10.44	18.27	69.51	38.09	10.05
Resistant	6.79	116.63	40.56	20.11	44.05	156.9	75.87	20.62
West coast (five sites)								
Total concentration-based aqua-regia methods	6.87	68.51	31.13	11.08	36.57	394.9	136.59	67.38
EFLE 0.15	3.43	1.21	0.61	0.16	32.05	7.57	6.15	
Acid-R	0.36	0.73	0.48	0.07	0.93	125.2	34.14	23.75
Ox-Organic	0.84	39.86	13.33	6.92	7.74	82.15	34.75	14.36
Resistant	10.16	62.58	29.75	9.34	44.76	188.23	106.38	27.80

Table 4: Comparison of the concentrations of Cu and Zn obtained in this study with some background levels and actions levels of sediment quality criteria

Description	*Cu*	*Zn*	*Reference*
Background values of Chinese coastal areas	30	80	Zheng et al. (1992)
Background values of the marine sediments in Hong Kong	15	94	Tanner et al. (2000)
Background values of the estuary sediment in Hong Kong	10	70	Tanner et al. (2000)
Action level of Hong Kong Sediment Quality Criteria	65	200	Lau Wong and Rootham (1993)
Interim ISQV- Low sediment quality values	65	200	Chapman et al. (1999).
Interim ISQV-High sediment quality values	270	410	Chapman et al. (1999).
East coast of Peninsular Malaysia (10 sites)	12.9 (6.90-17.8)	73.8 (55.6-86.1)	This study
South coast of Peninsular Malaysia (five sites)	38.8 (3.80-117)	111 (38.1-221)	This study
West coast of Peninsular Malaysia (five sites)	31.1 (6.87-68.5)	137 (36.6-395)	This study

Quality Criteria. Also, generally, the mean concentration of Zn was higher than the Zn background levels of Chinese and Hong Kong coastal waters. Therefore, the above sites are regarded as 'hotspot' sites in Peninsular Malaysia.

Three patterns can be seen from the present data based on the aqua-regia and sequential extraction of surface sediments collected from the intertidal area of Peninsular Malaysia. First, the trend of Cu and Zn pollution in the west coast of Peninsular Malaysia are similar and consistent with those previously reported by Yap et al. (2002, 2003a) viz., localized and elevated concentrations of metals were also found at sites close to urban and industrial areas. Second, the west coast of Peninsular Malaysia has more anthropogenic inputs of Cu and Zn when compared to the east coast. Third, the present results indicated that proper management and control measures are needed to mitigate the anthropogenic inputs of Cu and Zn in these 'hotspot' sites in Peninsular Malaysia.

Finally, the 'So what?' question can be asked after the presentation of the present data. Two points can be given: first, these data are important for future reference and second, the present work sets important milestones to be followed for future endeavours or for similar monitoring work in this region.

CONCLUSION

The geochemical partitioning of Cu and Zn provides us with a better understanding of the dominance of Cu and Zn concentrations found in the intertidal sediments of Peninsular Malaysia. The higher concentrations of Cu and Zn in the intertidal sediments collected from the west and south coasts of Peninsular Malaysia indicated contamination of both metals due to anthropogenic inputs. The present data supported our earlier assumption that the west and south coasts of Peninsular Malaysia, having more industries and urban areas, showed higher metal contamination when compared to the east coast. This also indicated that observation of the sampling sites for any possible sources of anthropogenic sources are important in the interpretation of heavy metal concentrations found in the sediments.

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10

Bioaccumulation of Heavy Metals in Aquatic Animals Collected from Coastal Waters of Gresik, Indonesia

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Abstract: A survey of the presence of metals in aquatic animals caught from Gresik coastal waters, Indonesia, has been conducted. The results show that all animals contained Zn levels higher than the level of other metals (As, Cd, Cr, Ni, Cu, Se and Pb) in the same species. The copper level recorded in tissue of banana shrimp showed higher copper concentration than that in other fishes. The concentration of Zn in whole body of animals (ponyfish and anchovy) was relatively higher than those recorded in muscle tissues (banana shrimp, drum, mullet and sea catfish). It was also found that the level of metals in all samples collected from this area contained metals in their tissue within acceptable range for consumption. These data provide useful information for future reference.

Key words: Metals, shrimp, fish, bioaccumulation, coastal waters.

INTRODUCTION

Heavy metals naturally occur in seawater in very low concentrations, but their concentration levels have increased due to anthropogenic pollutants over time (Kargin et al., 2001). Industrial activities as well as agriculture and mining

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create a potential source of heavy metals pollution in aquatic environment (Unlu et al., 1996). Pollution of aquatic ecosystems by heavy metals is an important environmental problem, as heavy metals constitute some of the most dangerous toxicants that can bioaccumulate (Soegianto et al., 1999a; Benson et al., 2007). Metals that are deposited in the aquatic environment may accumulate in the food chain and cause ecological damage also posing a threat to human health due to biomagnification over time (Yilmaz and Yilmaz, 2007). Aquatic organisms have been reported to accumulate heavy metals in their tissues several times above ambient levels (Canli and Atli, 2003). These metal levels in aquatic animals should be monitored regularly to check animal health and in view of the quality of public food supplies.

Gresik is one of the big industrial cities in Indonesia. Industrialization and urbanization have proceeded rapidly during past two decades in this city, including the development of large harbours and heavy industries, resulting in the deterioration of neighbouring marine environment. The coastal waters of Gresik is believed to receive wastewater discharges from number of wastewater treatment facilities of industries located along Gresik coastal zone. The potential industries which contribute to the level of metals in these coastal waters are a superphosphate plant, an asphalt plant, a coal-fired electric power plant, metal smelters and refineries, natural gas processing plants, etc. These waters represent also the habitat of some edible organisms caught by local fishermen. Many people still use the coastal waters as their fishing ground. This study was undertaken to measure the heavy metal contamination in the tissues of aquatic animals collected from Gresik coastal waters of East Java. The data are then compared with the standard for maximum limits of metals in the tissue of marine biota.

MATERIAL AND METHODS

Five species of fishes, ponyfish (*Leiognathus equlus*), anchovy (*Coilia dusumieri*), drum (*Johnius belengeri*), mullet (*Mugil vaigiensis*) and sea catfish (*Arius leptonotacanthus*), and one species of shrimp (*Penaeus merguensis*), were chosen as samples for metal analyses. The species selected for metal analyses was based on general abundance in the area, similarity of their size and their potential to be consumed by local people. The animals were collected by gillnets in Gresik coastal waters in June 2005 (Fig. 1).

Depending on availability, a number of animals of each species were processed for metal analysis. The samples were homogenized prior to metal analysis. Fish species where entire body is consumed such as anchovy and ponyfish, samples of the whole body were homogenized, and prepared for metals detection. For other fishes and shrimp, only edible part or flesh were used for metal detection. Before filleted, external water of each individual sample was absorbed using tissue papers. The flesh then weighed to the nearest 0.1 g on an analytical balance, minced by knife and added to a known amount

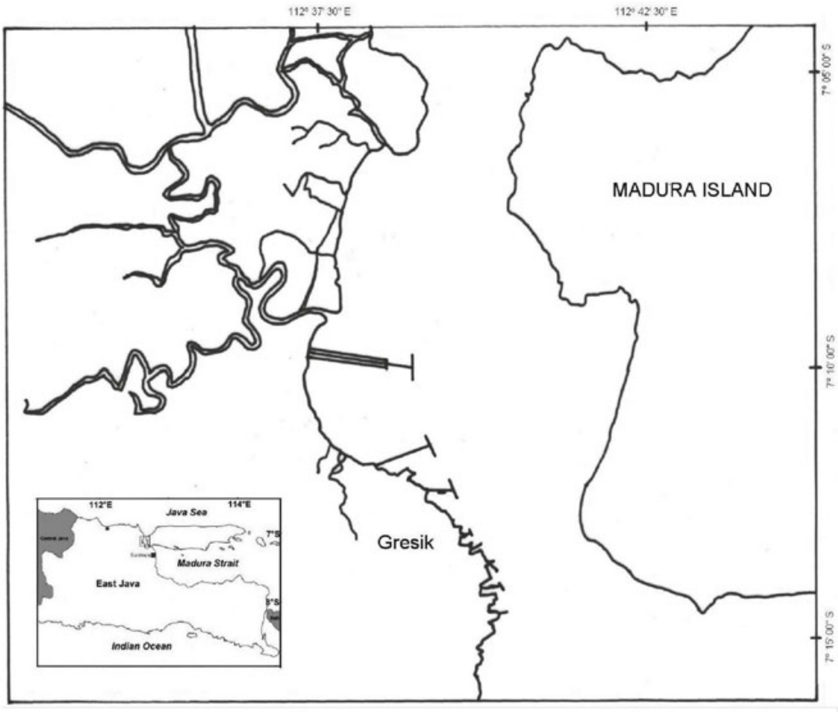

Fig. 1. Sampling location of aquatic animals.

of double de-ionized water, then pureed using a multi-speed blender. The anchovy and ponyfish were also undergoing the same process as well as other species. Each sample then was put into special flask separately, weighed, then frozen at –20°C for a period not less than eight hours. The frozen sample was then placed under vacuum on a freeze-dryer unit (Labconco) until sample was completely dried. Dried sample was weighed and approximately 1 g of each was digested in 5 ml of high purity HNO_3 and 5 ml of high purity HCl using Microwave Digester (Ethos D) for approximately 25 minutes. Digests are filtered through Whatman 44 ashless filter paper and made up to 50 ml with double de-ionized water.

Inductively-coupled plasma emission spectroscopy (Thermo Jarrell Ash Type: IRIS Advantage) was used for determination of arsenic (As), cadmium (Cd), copper (Cu), zinc (Zn), lead (Pb), chromium (Cr) and nickel (Ni). Analytical blanks were run in the same way as the samples and concentrations were determined using standard solutions prepared in the same acid matrix. Accuracy and precision of the results were checked and compared with standard reference material (dogfish muscle reference materials, DORM-2). The standard reference material digests were found to conform with the documented values for certified trace metal concentrations. All metal concentrations were quoted as $mg.kg^{-1}$ dry weight.

RESULTS

The concentration of metals in aquatic animals is presented in Table 1. The data show that all animals caught from Gresik coastal waters, Indonesia, contained Zn levels higher than the level of other metals (As, Cd, Cr, Ni, Cu, Se and Pb) in the same species. The copper level recorded in tissues of banana shrimp showed higher copper concentration than that in other fishes. Our findings also showed that the concentration of Zn in whole body of animals (ponyfish and anchovy) were relatively higher than that recorded in muscle tissues (banana shrimp, drum, mullet and sea catfish).

DISCUSSION

A wide range of values for various metals was found in different species of marine biota, as well as in flesh and whole body samples. The concentration of zinc in both fishes and shrimp were relatively higher compared to concentration of other metals in the same animals. The similar findings were also recorded in fishes (Parsons, 1999; Miramand et al., 2001; Zehra et al., 2003; Tyrrell et al., 2005) and crustaceans (Ridout et al., 1985; Swaileh and Adelung, 1995; Parsons, 1998; Hossain and Khan, 2001; Miramand et al., 2001; Tyrrell et al., 2005) caught from other waters of the world. The copper level recorded in tissue of shrimp samples (*Penaeus merguensis*) showed elevated copper concentration than that in other fishes. This level is presumably influenced by the copper contained in the haemolymph of crustaceans. Both copper and zinc are essential elements and their concentrations are usually regulated by marine fishes (Thompson, 1990) and crustaceans (White and Rainbow, 1982; Rainbow, 1995; Soegianto et al., 1999b).

Almost all metals measured in this study are relatively lower than the values recorded in aquatic animals from other regions of the world. The findings of other studies are summarized in Table 2, and are compared with the concentrations reported in this study and elsewhere in the world.

The levels of heavy metal in aquatic animals vary in various species and different aquatic environments (Canli and Atli, 2003). As reported in our study, trace element concentrations varied markedly among species. These variations are presumably due to individual samples being of different size categories, from different ecological niches, and from different trophic levels. Possibly, species also have different metabolic requirements for specific trace element. Bottom-dwelling and demersal species usually had higher concentrations than more pelagic species, which may be related to greater exposure to contaminated sediments (Trucco et al., 1990; Parsons, 1999). Kargin (1996) stated that due to variations in feeding habits, habitat and behaviour of species, the level of metals found in tissues of the demersal species were always higher than those found in pelagic species. The results presented in this study showed that concentration of some metals (Zn, Cd, Cr and Se) in catfish (demersal species)

Table 1: Heavy metal concentrations measured in tissue samples (mg kg^{-1} dry weight) of aquatic animals collected from coastal waters of Gresik in June 2005

Contaminant	*Species*											
	Banana shrimp		*Ponyfish*		*Anchovy*		*Mullet*		*Sea Catfish*		*Drum*	
	N = 26		*N = 20*		*N = 18*		*N = 4*		*N = 5*		*N = 6*	
	W = 9.8 ± 1.1		*W = 10.7± 1.3*		*W = 6.4 ± 0.8*		*W = 19.3 ± 2.4*		*W = 19.8 ± 2.7*		*W = 13.8 ± 2.0*	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Copper	1.166	0.162	0.205	0.085	0.049	0.027	0.108	0.032	0.098	0.011	0.039	0.025
Lead	0.022	0.008	0.039	0.016	0.028	0.013	0.047	0.002	0.040	0.036	0.021	0.013
Zinc	2.132	0.280	2.264	0.898	2.437	0.545	0.435	0.078	1.035	0.038	0.482	0.046
Arsenic	0.084	0.015	0.003	0.001	0.014	0.007	0.013	0.008	0.027	0.021	0.048	0.046
Selenium	0.014	0.014	0.026	0.020	0.018	0.018	<0.001	<0.001	0.020	0.016	0.014	0.008
Cadmium	0.0002	0.0001	0.0012	0.0010	0.0013	0.0010	<0.0001	<0.0001	0.0006	0.0004	0.0004	0.0003
Nickel	0.008	0.005	0.004	0.003	0.027	0.008	0.012	0.010	0.005	0.001	0.007	0.005
Chromium	0.002	0.001	0.016	0.005	0.056	0.019	0.008	0.006	0.009	0.001	0.003	0.002

Note: N = number of animals; W = weight (gram); SD = standard deviation

Table 2: A comparison of heavy metal concentrations (mg kg^{-1} dry weight) in aquatic animals collected from Gresik coastal waters and other regions of the world

Location	*Species*	*As*	*Cd*	*Cr*	*Cu*	*Ni*	*Pb*	*Se*	*Zn*	*References*
Gresik coastal waters, Indonesia	*Penaeus merguensis* (Crustacea, decapod)	0.084 ± 0.015	0.0002 ± 0.0001	0.002 ± 0.001	1.166 ± 0.162	0.008 ± 0.005	0.022 ± 0.008	0.014 ± 0.014	2.132 ± 0.280	Present study
	Leiognathus equulus (Teleostei)	0.003 ± 0.001	0.0012 ± 0.0010	0.016 ± 0.005	0.205 ± 0.085	0.004 ± 0.003	0.039 ± 0.016	0.026 ± 0.020	2.264 ± 0.898	Present study
	Coilia dusumieri (Teleostei)	0.014 ± 0.007	0.0013 ± 0.0010	0.056 ± 0.019	0.049 ± 0.027	0.027 ± 0.008	0.028 ± 0.013	0.018 ± 0.018	2.437 ± 0.545	Present study
	Johnius belengeri (Teleostei)	0.048 ± 0.046	0.0004 ± 0.0003	0.003 ± 0.002	0.039 ± 0.025	0.007 ± 0.005	0.021 ± 0.013	0.014 ± 0.008	0.482 ± 0.046	Present study
	Mugil vaigiensis (Teleostei)	0.013 ± 0.008	<0.0001	0.008 ± 0.006	0.108 ± 0.032	0.012 ± 0.010	0.047 ± 0.002	<0.001	0.435 ± 0.078	Present study
	Arius leptonotacanthus (Teleostei)	0.027 ± 0.021	0.0006 ± 0.0004	0.009 ± 0.001	0.098 ± 0.011	0.005 ± 0.001	0.040 ± 0.036	0.020 ± 0.016	1.035 ± 0.038	Present study
Hongkong	Natantian decapods	-	<0.9-59.29	<0.9-13.95	8.91-113.1	<0.9-65.40	<0.9-248.4	-	9.05-62.77	Parsons (1998)
	Johnius belengeri (Teleostei)	<0.9-96	<0.9-13.5	<0.9-3.5	<0.9-17.2	<0.9-6.6	<0.9-60	<0.9-36.5	10-50	Parsons (1999)
	Leiognathus brevirostris (Teleostei)	<0.9-59.8	<0.9-9.7	<0.9-3.8	<0.9-8.2	<0.9-5	<0.9-102	<0.9-28.1	30.5-63.5	Parsons (1999)
Bengal bay, Bangladesh	*Penaeus monodon* (Crustacea decapod)	-	0.2-0.3	1.7-2.9	12.2-21.3	2.9-5.9	0.8-1.3	-	24.2-35.7	Hossain and Khan (2001)
	Panulirus polyphagus (Crustacea decapod)	-	0.3-0.4	2.5-3.1	25.8-35.7	3.1-7.0	1.0-1.9	-	17.6-64.5	Hossain and Khan (2001)

(*Contd.*)

Table 2: (*Contd.*)

Location	*Species*	*As*	*Cd*	*Cr*	*Cu*	*Ni*	*Pb*	*Se*	*Zn*	*References*
East Atlantic Ocean	*Systellapsis debilis* (Crustacea decapod)	-	4.3-5.7	-	19-176	-	-	-	38-177	Ridout et al. (1985)
Western Baltic	*Diastylis rathkei* (Crustacea: Cumacea)	-	0.17-0.56	-	61.7-172.4	-	2.9-14.8	-	54.3-120.3	Swaileh and Adelung (1995)
Irish Ports	*Nephrophs norvegicus* (Crustacea decapod)	-	0.28	<0.28	17.4	-	<0.24	-	53.2	Tyrrell et al. (2005)
	Scomber scombrus (Teleostei)	-	<0.016	<0.28	2.12	-	<0.24	-	14.96	Tyrrell et al. (2005)
	Pleuronectes platessa (Teleostei)	-	<0.016	<0.28	<0.64	-	<0.24	-	17.28	Tyrrell et al. (2005)
Baluchistan Coast, Pakistan	*Acanthopagurus berda* (Teleostei)	-	0.04-0.11	-	0.30-0.55	-	0.25-0.50	-	3.65-4.32	Zehra et al. (2003)
Seine Estuary	*Dicentrarchus labrax* (Teleostei)	-	0.016-0.035	-	2.7-42	-	0.12-0.26	-	54-79	Miramand et al. (2001)
	Platichthys flesus (Teleostei)	-	0.019-0.052	-	2.8-3.4	-	0.34-0.92	-	72-192	Miramand et al. (2001)
	Crangon crangon (Crustacea decapod)	-	0.08-014	-	48.5-81	-	0.4-0.9	-	57-105	Miramand et al. (2001)
	Palaemon longirostris (Crustacea decapod)	-	0.05-0.23	-	67.5-1007	-	0.3-1.0	-	79-89	Miramand et al. (2001)
Gulf of Cambay, India	*Harpodon nehereus* (Teleostei)	1.74 ± 0.865	0.23 ± 0.029	0.77 ± 0.054	2.37 ± 0.451	ND	1.09 ± 0.071	-	38.24 ± 1.641	Reddy et al. (2007)
	Metopograpsus maculates (Crustacea decapod)	ND	1.6 ± 0.566	2.075 ± 0.389	175.45 ± 2.45	3.15 ± 0.041	2.775 ± 0.177	-	44.22 ± 1.21	Reddy et al. (2007)

Note: ND = nondetectable, - = No data

Table 3: Maximum residue limit and maximum permitted concentration of metals in marine biota muscle (mg kg^{-1} dry weight) from various countries and organizations

No.	*Contaminant*	*U.K.*[1]	*Australia*[2]	*Hong Kong*[1]	*European Regulation 466/2001/EC*[3]	*Indonesia*[4]	*IRPTC*[5]
1	Cadmium	-	0.80	8	0.4	-	-
2	Lead	-	6.0	24	1.6	8	-
3	Chromium	-	-	4	-	-	-
4	Copper	80	-	-	-	80	-
5	Zinc	200	-	-	-	400	-
6	Arsenic	-	4^{+}	-	-	4	-
7	Nickel	-	-	-	-	-	2
8	Selenium	-	4	-	-	-	-

Note: 1. Parsons (1998, 1999); 2. Otway (1992); 3. Tyrrell et al. (2005); 4. Decree of General Director of Food and Drug Supervision No. 03725/B/SK/VII/89 concerning maximum limit of metals in food; 5. IRPTC (1988); + Inorganic arsenic, this study measured total arsenic.

were relatively higher than that recorded in muscle tissues of pelagic fishes (mullet and drum).

The potential toxicological impacts of contaminated seafoods can be evaluated on the basis of concentrations in whole body and flesh samples. Concentrations of trace elements can be 200-400% greater in organs and other tissues than in muscle (Thompson, 1990; Chan, 1995). Thus, one might expect higher concentrations to be recorded in homogenized whole body samples. In our study, the concentrations of certain metals (Zn, Cr and Cd) in whole body of fish (anchovies and ponyfish) were relatively higher than those documented in muscle tissue of mullet, drum and sea catfish. This difference is presumably due to higher concentration of metals in the viscera of animal. Target organs, such as liver, gonads, kidney and gills, have a tendency to accumulate heavy metals in high values (Yilmaz, 2005). It is generally accepted that muscle is not an organ in which metals accumulate (Legorburu et al., 1988). Similar results were reported from a number of fish species showing that muscle is not an active tissue in accumulating heavy metals (Karadede and Unlu, 2000; Kargin and Erdem, 1991).

Comparing the present data with guidelines and limits (Table 3), it can be seen that most of metal concentrations found in the tissues of aquatic animals proved to be below the tolerance levels for human consumption.

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11

Hydrodynamic and Transport Model of the Siak Estuary

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Abstract: The Siak River flows around an industrial area of Riau Province, Sumatra (Indonesia) towards the Malacca Strait. Most of domestic and industrial wastes are transported along this river to the estuary. In this investigation, the HAMburg Shelf Ocean Model (HAMSOM) and an attached dispersion model are employed to simulate the circulation patterns and the dispersion of pollutants, respectively. In this study the pollutants are released only in the front of Siak river mouth. The simulation is performed for the period from January 2001 until May 2006, and the results are validated with available observations and satellite data.

By means of this model study, it is shown that although the wind direction changes with the monsoon, the direction of the surface currents in the Malacca Strait are almost the same over the entire year. Results of the transport model suggest that most of the pollutants are transported through the Bengkalis Strait to the north into the Malacca Strait. Although the general circulation pattern in the Malacca Strait does not show a seasonal reversal, it could be demonstrated that the monsoon cycle influences the transport and dispersion of the pollutants significantly.

Key words: Siak, HAMSOM, Malacca, waste.

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INTRODUCTION

Riau Province is located in the east of Sumatra and has an extended coastal zone including a number of large and small islands along the coast of the Malacca Strait. This province covers an area of 329,867.61 km^2, from which 71% consists of ocean. There are about 15 rivers in the province with four of them being more important and used as waterways, namely, the Siak river with 8-12 m depth and 300 km length, the Rokan river with 6-8 m depth and 400 km length, the Kampar river with about 6 m depth and 400 km length, and the Indragiri river with 6-8 m depth and 500 km length. The headwaters of these rivers are located in the Bukit Barisan Mountain, in the western part of Sumatra. All of these rivers release their water into the Malacca or Karimata Strait.

As one of Indonesia's richest province with oil, gas, agriculture and plantation resources, the development in this province is very fast as well as the population growth. The population in Riau Province amounts to 5,281,000, with more than 50% of them living on the small islands and more than 580, 000 people living in Pakanbaru city (Bureau of Statistics of Riau Province (BPS Riau), 2000).

Pakanbaru is the capital city of Riau Province from where the Siak River flows another 100 km to the northeast before it enters the Bengkalis Strait. There are a number of factories and urban and rural households along the river discharging waste into the river directly which leads to the fact that the Siak River is one of the strongly polluted rivers in Indonesia. Closer to the estuary, the pollutant concentrations increase and the type of the pollutants are getting more diverse. This contamination of the estuary has a negative impact on public health, which used the Siak River water and the chemical and biological system including the biodiversity (Nedi, 1999).

Because of the shallow water depth and the large number of small islands around the Malacca Strait, the energy input from ocean current and waves into the Siak estuary is significantly reduced. By this means the islands and straits around the Siak river estuary also suppress the transport of pollutant from the Siak estuary into the Malacca Strait (Fig. 1). However, the periodicity of tides in combination with the effect of the shallow water depth strongly tends to cause vertically homogeneous conditions in the Riau waters. Fig. 1: (a) Large model area bathymetry of Java Sea and Malacca Strait and (b) detailed model area of Riau Waters.

The depth of the Malacca Strait around the Riau Islands is shallower than 50 metres (see Fig. 1b). The water masses are influenced by the Indian Ocean in the northern part and Java Sea in the south-eastern part. Generally, in the Malacca Strait, the water mass flow is directed towards the Indian Ocean which is strongly related to the sea level gradient in this strait (Wyrtki, 1961).

During the northeast monsoon, the absolute dynamic topography obtained from AVISO Data (2006) in the Andaman Sea, north of the Malacca Strait, is

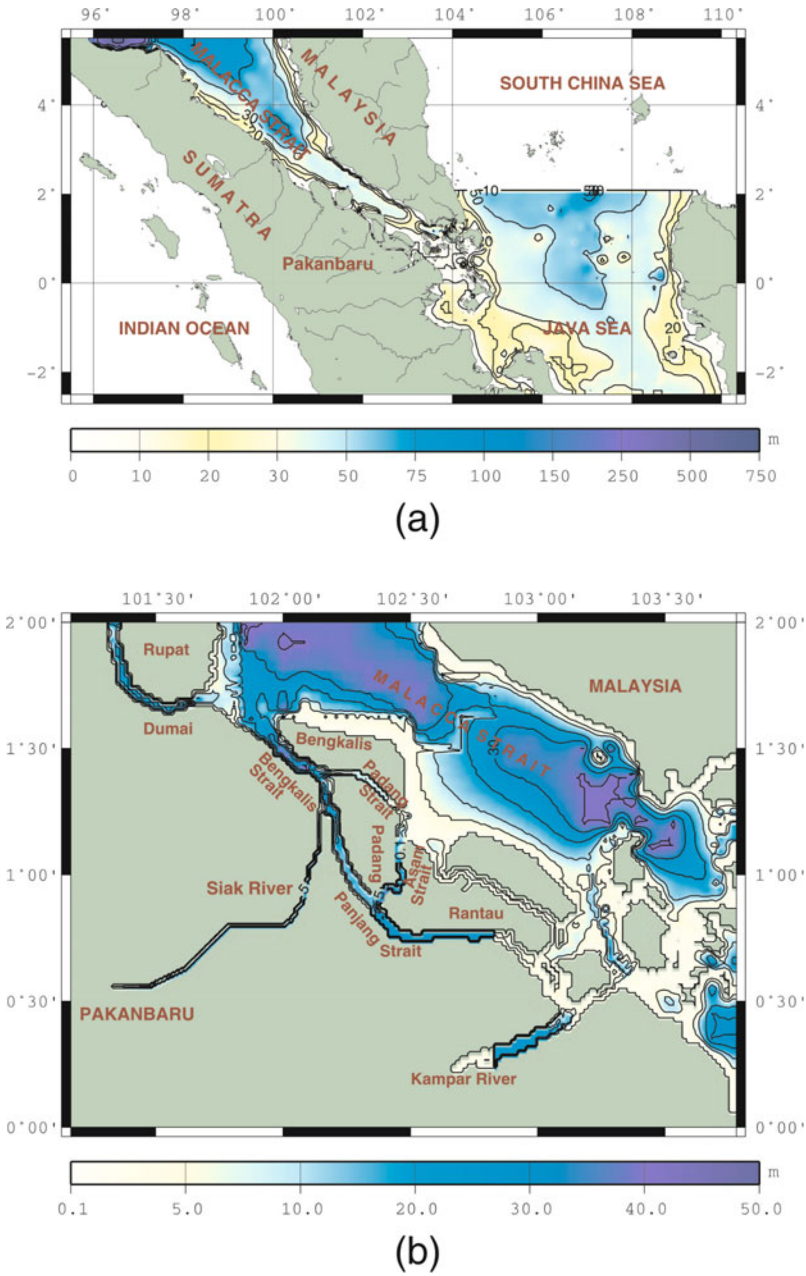

Fig. 1: (a) Large model area bathymetry of Java Sea and Malacca Strait and (b) detailed model area of Riau Waters.

lower than in the Java and South China Seas in the south-eastern part. Therefore, the sea surface currents show the strongest flow towards the Indian Ocean through the Malacca Strait during this season. During the southeast monsoon the dynamic topography is nearly reversed. Nevertheless the sea surface currents still flow towards the Indian Ocean through the Malacca Strait mainly due to the south-easterly surface winds during this monsoon phase.

The geographic and oceanographic conditions around the Siak river estuary are quite complex; therefore to understand the characteristics of the ocean dynamics, a number of numerical simulations have been performed. These simulations should help us to understand in more detail the dynamical processes in this estuary including their impact on the dispersion of matter. In this way, the study can also support decision makers for environmental and land use planning as well as coastal zone management.

MODEL DESCRIPTION

General Description of HAMSOM Circulation Model

The circulation model applied in this study is a modified version of the HAMSOM shelf sea model developed by Backhaus (1985). It is a three-dimensional, baroclinic shallow water equation model. Additionally, the equation of state for sea water (Fofonoff and Millard, 1983) and the transport equations for temperature and salinity are employed. The modifications with respect to Backhaus mainly concern the transport equation for temperature and salinity and the formulation of the vertical eddy viscosity. The latter is parameterized using a method developed by Kochergin (1987). In this turbulence closure scheme the vertical eddy viscosity Av is dependent on the vertical velocity gradient and on the stability of the water column.

$$A_{Iv} = (c_{ML} \cdot h_{ML})^2 \cdot \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2 + \frac{1}{S_M}\frac{g}{\rho}\frac{\partial \rho}{\partial z}} \quad (1)$$

where h_{ML} is the thickness of the mixed layer, c_{ML} a free constant set by Kochergin to $c_{\mathrm{ml}} = 0.05$ and S_{M} is known as the turbulent Schmidt-Prandtl number. The vertical diffusion coefficients A_{Mv} are calculated by: $A_{\mathrm{Mv}} = A_{\mathrm{Iv}}/S_{\mathrm{M}}$. Further details about the implementation into HAMSOM as well as a validation of the turbulence closure scheme can be found in Pohlmann (1996a).

Numerical Scheme

The differential equations are solved on an Arakawa-Cgrid. In order to minimize problems arising from longer time-steps, moreover, a rotational matrix is applied for the Coriolis term, guaranteeing a second order accuracy in time. The most detailed overview about the rotation of the Coriolis term and the other numerical formulations are described in Backhaus (1985). The use of longer timesteps is possible since these terms that limit the timestep most severely are treated implicitly. Investigation of the stability criteria shows that it is necessary to have an implicit formulation for vertical shear stress and diffusion terms as well as for terms determining the surface gravity waves, namely the barotropic pressure and the vertically integrated continuity equation that leads to the prognostic equation for the sea surface elevation. All the other terms are formulated explicitly. This also concerns the advective terms in the momentum equation and in the transport equation for temperature and salinity. Sub-scale processes have been parameterized by a horizontal turbulent exchange coefficient of 250 m2/s as well in the large-scale as in the meso-scale model. This relatively high value is also appropriate also for the mesoscale model since the applied Arakawa J7 algorithm is less diffusive than other second order schemes (Arakawa and Lamb, 1977). Because the free surface waves and the vertical diffusion are treated implicitly, only the explicit formulation of advection can cause limitations of the time-step. But since typical values of the advection velocity are of the order of O (1 m/s) for the spatial scales under consideration the limiting Courant number (Roache, 1985) does not restrict the time step too rigorously.

The high resolution of the model was only possible because the model code was optimized in order to give a good performance on the NEC-SX6 computer of the German Climate Computing Centre (Pohlmann, 2006). This optimization consists of two steps. First, a vectorisation of the model code was performed by loopswitching. Secondly, the parallelisation of the code was done by means of the domain splitting method, where the model domain is divided into a number of subdomains in accordance with the number of available processors. The relevant information is exchanged normally every time-step between these sub-domains in particular along the bordering grid points using the MPI (Message Passing Interface) library (wwwunix. mcs.anl.gov/mpi).

General Forcing and Boundary Conditions

At the closed lateral boundaries a semi-slip and zero flux condition is applied. Contrarily, at the open boundaries the sea surface elevation is prescribed and a zero gradient condition for the transports is used, which together form a stable boundary condition for the hydrodynamical model parameters. At open boundaries under inflow conditions temperature and salinity values are prescribed, while for outflow conditions a Sommerfeld radiation condition is applied (Orlanski, 1976). At closed boundaries river inflow is simulated by introducing temperature and salinity changes at the respective input grid cells.

At the sea bottom the quadratic stress law is applied and at the sea surface fluxes of momentum, heat and fresh water are calculated by means of bulk formulae from meteorological parameters: 10 m wind speed, sea surface pressure, 2 m air temperature, sea surface temperature, 2 m relative humidity, total cloud cover and total precipitation. The bulk formula for incoming solar radiation was taken from the COHERENS model (Luyten et al., 1999) whereas the outgoing long-wave radiation was calculated according to Fung et al. (1984). The sensible and latent heat flux parameterisation were obtained from Kondo

(1975). This set of bulk formulae turned out to give the most reasonable results for the Indonesian waters. It has to be noted that the realistic determination of the latter three fluxes can only be performed in a coupled mode with the help of the hydrodynamical model, since otherwise it is not possible to provide the required actual sea surface temperatures, that influences as well the sensible as the latent heat flux.

Model Setup

As a first step, HAMSOM had been adopted to a larger area reaching from 2.5°S to 5.5°N and 95.5°to 110.5°E, covering the Malacca Strait and the western part of the Java Sea (see insert in Fig. 1a). This area is divided into 361 × 193 grid cells horizontally with a spatial resolution of 2.5 minutes (about 4.625 km); it has 17 layers of increasing thickness in the vertical direction: 5 m in the first 10 layers, and 10, 20, 20, 50, 100, 250, and 300 m for the subsequent layers, respectively. The time step used in this simulation is 30 minutes covering a simulation period of 5.5 years (from January 2001 to May 2006).

The major tidal constituent in Malacca Strait is semidiurnal (Wrytki, 1960 and Chen et al., 2005). Therefore, to analyze the seasonal variation in the Riau seawaters the model uses only the M_2 constituent (Zahel, 2000), seven parameters of 6-hourly atmospheric data, i.e., 2 m air temperature, 10 m surface wind (two components), specific humidity, surface pressure, cloud cover, precipitation, from the National Center Environmental Prediction (NCEP/NCAR) (Kalnay et al., 1996) and temperature and salinity data from the World Ocean Atlas 2001 (Conkright et al., 2002) to force and initialise the model.

A nested model strategy is applied is this study. For this purpose a second small-scale model was set-up, covering the vicinity of the Siak river estuary from 0° to 2°N and 101°10′E to 103°47′E with 315 × 241 grid cells. The horizontal resolution is 0.5′ (approx. 0.93 km) and in the vertical the water body is subdivided into nine layers which have each a thickness of 5 m up to the bottom at 45 m depth. Boundary values are taken from the largescale model, namely the sea surface elevation and temperature as well as salinity data are prescribed along the open boundaries (Fig. 1b).

The forcing and initialisation of the small-scale model was performed analogously to the large-scale model with NCEP/NCAR and World Ocean Atlas data. Additionally, along the first 98 km of the Siak River from Pakanbaru to the estuary the salinity is set to 0.2 psu, whereas for the last 2 km, data observed during an own measuring campaign in 2004 are prescribed. Moreover, in the smallscale model the influence of the freshwater discharge from rivers is considered.

General Description of the Transport Model

In principle it is possible to employ two different types of dispersion models, i.e., Eulerian or Lagrangian models. Both types have their advantages and disadvantages. The Eulerian model is more suitable for the simulation of widespread pollutants, whereas Lagrangian models are mainly used to trace single releases of a more localised character.

In this paper only the results from an Eulerian type dispersion model will be presented. The basis of this model is the three-dimensional transport equation for conservative substances which is formulated on a fixed three-dimension numerical grid. The parameters provided by the circulation model are the three-dimensional circulation pattern to describe the advective transport and the vertical diffusion coefficient which indicate the strength of diffusive processes. Due to scaling arguments horizontal advection could be neglected.

Numerically the advection is solved by an explicit component up-stream scheme, while the vertical diffusion is treated implicitly in order to be able to use a larger time-step. The spatial grid is identical to that one of the circulation model. By this means no information is lost due to an interpolation of the forcing data from the circulation to the transport model. For the transport model a time-step of 30 minutes has been chosen.

Simulation Set-up of the Transport Model

After running the HAMSOM circulation model on the small-scale grid for the Riau Waters a transport model has been applied to perform the following dispersion scenarios:

1. Dispersion simulation of constant and continuous sources for more than five years of simulation time with daily currents taken as forcing. This simulation is used to observe the spreading of pollutants from the Siak River estuary, for which an arbitrary concentration of 100 mg/l was chosen. As an initialisation the concentration of the ambient water was set to 1 mg/l at the beginning of the simulation.
2. Dispersion simulation of an instantaneous release at the first day of each month. These dispersion simulations are performed with daily current fields covering always a one month period. This simulation is conducted for a source at the Siak River mouth, only for the year 2005.

MODEL VALIDATION

In order to validate the hydrodynamical model results the information from Feliatra (2002), Gin et al. (2000) and the satellite AVHRR from NOAA have been employed.

Based on the former measurement on 11 March-7 April 2001 north of Bengkalis (Feliatra, 2002) in the estuary of the Batan Tengah River (1°30′-1°35′N and 102°15′-102°20′E), the temperature and salinity in this location are ranging between 28-30°C and 26-30 psu, respectively. From the simulation results, it can be inferred that the temperature and salinity in the same area on 11 March-7 April 2001 lies between 28-31 °C and 28-30 psu.

Gin et al. (2000) explained the dynamics of the Singapore Strait and wrote that the water temperature and salinity around the Singapore Strait, based on observations in December 1996 until November 1999, are about 28.3-31.2°C and 28.7-32.2 psu, respectively. In agreement with these findings, the simulation results during the year 2001 at the same location show a temperature and salinity of 28-31.5°C and 28-30 psu. Thus it can be concluded that in general the simulation results provide good quantitative agreement with observations.

In order to provide a more detailled view of the model skill the simulation results have also been compared with monthly sea surface temperature (SST) data from the NOAA AVHRR satellite (Fig. 2). In general the average SST from the model simulations is in good agreement with observational data during March and October 2004, and January and August 2005. However, this agreement is larger for the year 2004 compared to 2005. Unfortunately the cloud cover during those periods makes satellite observations impossible for certain locations (indicated by blank areas in Fig. 2). Hence the comparisons can only be performed for selected locations, i.e. in October 2004 the SST from simulation is similar to the satellite data around Riau seawaters and north Malacca Strait, respectively 30°C and 29.2°C.

From the simulation it can be shown that the mean SST during January 2005 (figure not shown) is less than 28.5°C, lower than the mean SST in August (with more than 30°C) at the same year. From the NOAA AVHRR data it can be concluded that the SST lower than 27.5°C is transported into the Java Sea from the South China Sea during the northeast monsoon. Altogether it can be concluded that observed and simulated pattern are in a reasonable agreement. This is also true for the absolute values. Maximum differences in general do not exceed 1°C, which is acceptable taking into account the coarse resolution of the atmospheric forcing data.

Dynamical Conditions of the Southern Malacca Strait

Riau is located in the Malacca Strait, between the Indian Ocean in the north-northwest and the Java Sea in the southeast. Based on its location, the dynamical conditions of Riau waters are influenced by both seas.

In January, representing the northeast monsoon, the surface current from the South China Sea flows in southeastward direction into the Java Sea (Fig. 3a). Part of these water masses turn to the northwest entering the Malacca Strait because the sea level in the Java Sea is higher than in the Indian Ocean, as indicated by the anomalies described in the introduction. By this mechanism the warm and low saline water from the Java Sea is transported into the Malacca Strait.

During the southeast monsoon, represented by August 2005, the gradient of the sea level anomaly is reversed. It is now slightly higher in the Malacca Strait compared to the Java Sea. Nevertheless, the sea surface currents still flow into the Malacca Strait from the Java Sea (Fig. 3b). The main reason is

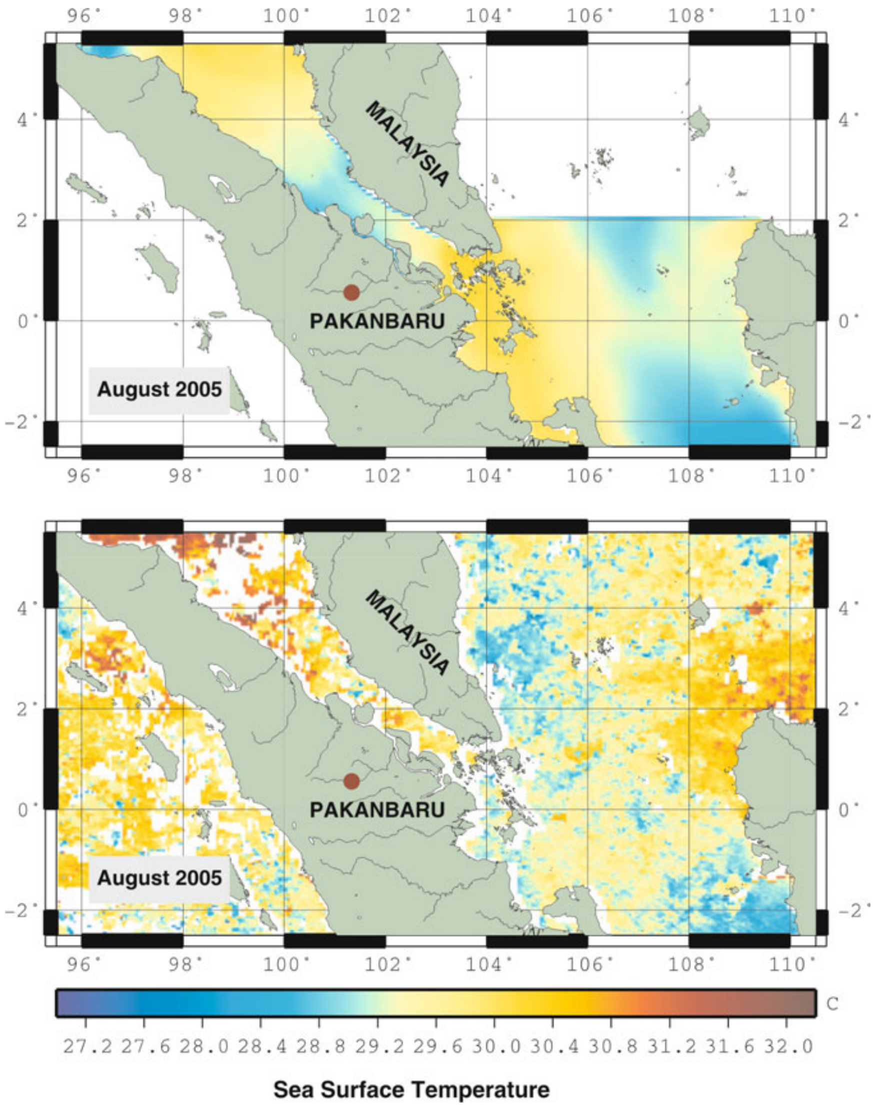

Fig. 2: Sea Surface Temperature in the Malacca Strait in August 2005 from HAMSOM Result (upper) and NOAA AVHRR (bottom).

the monsoonal winds, which predominantly blow from the southeast during this monsoon phase.

Dynamic Conditions of the Riau Waters

The small-scale distribution of the sea surface currents as well as the temperature and salinity of the Riau waters in August 2005 are presented in Figs 4 and 5. Warm and low saline water masses (Fig. 5) from the Java Sea are transported

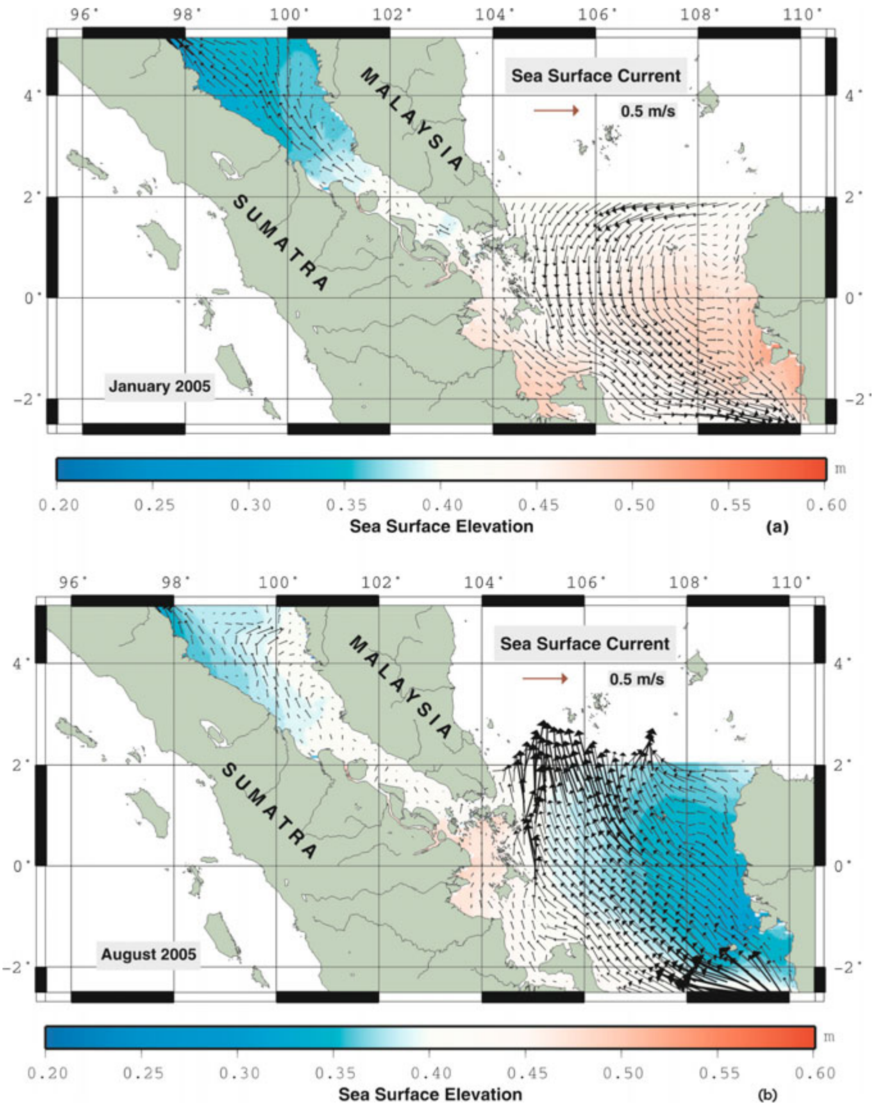

Fig. 3: Mean Sea Surface Current of the Malacca Strait (a) in January 2005 and (b) in August 2005.

northward to the Malacca Strait with the transport in August (during the southeast monsoon) being stronger than in January (during the northeast monsoon). In January in the centre of the Malacca Strait, water masses from the Java Sea flow predominantly northward but also are showing a loop current in the vicinity of the Singapore Strait.

As shown in Fig. 4, at the Siak river mouth the water is transported dominantly northward almost constantly over the entire years. During the northeast monsoon a rainy season exists and therefore the discharge from the

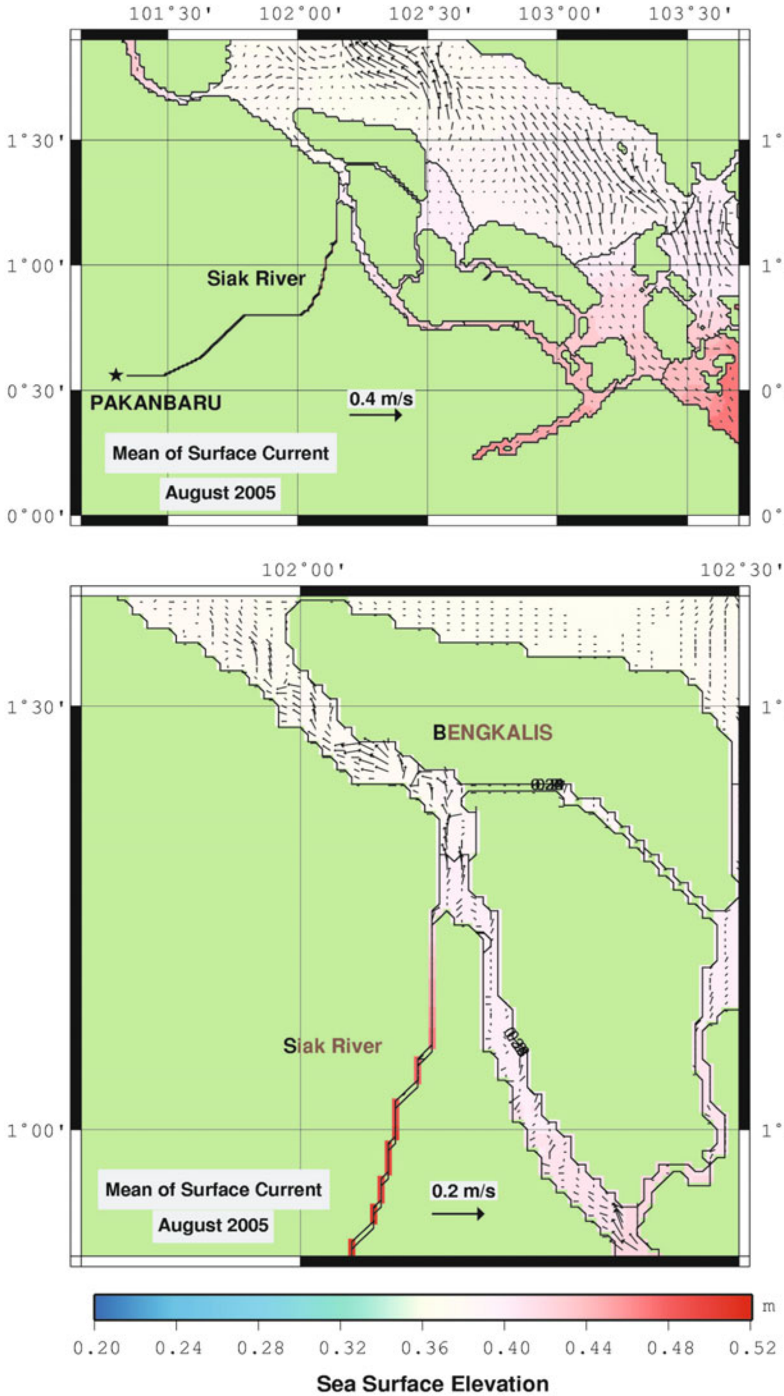

Fig. 4: Mean Sea Surface Currents in the Riau waters in August 2005.

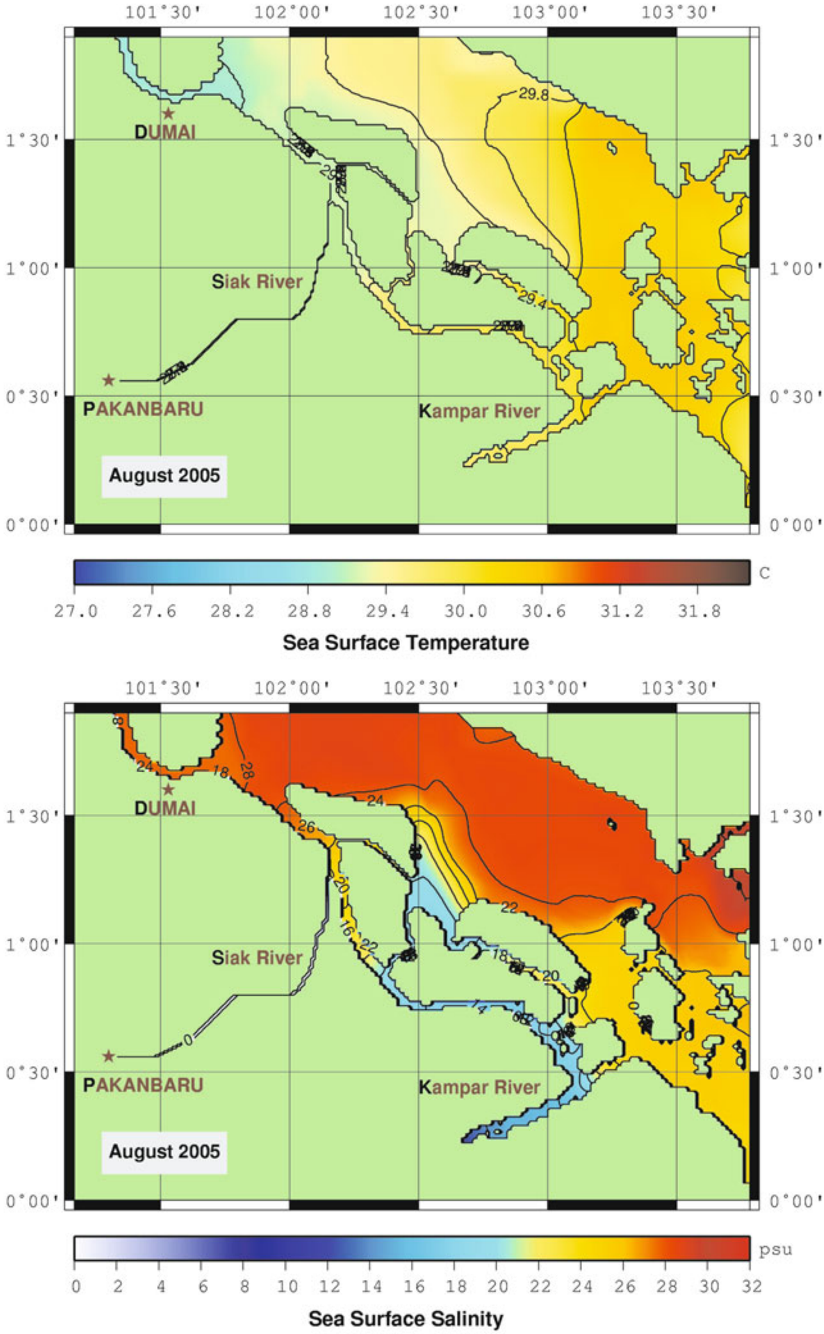

Fig. 5: Mean Sea Surface Temperature (top) and Salinity (bottom) in the Riau waters and the adjacent Malacca Strait in August 2005.

rivers is strong enough and influences the surface currents, whereas the southeast current originating from the Java Sea is as well strong enough. However due to the south-easterly surface winds during this monsoon phase, the sea surface current flow still northward, although the discharge from rivers is small during the southeast monsoon.

The monthly SST in the Malacca Strait is about 27.5-29°C in January and increases to 29-30°C in August in the south-eastern part (Fig. 5, top). The increase of the SST during the southeast monsoon in August is caused by the influence of warm water from the Java Sea which flows to the Malacca Strait, while the influence of cold water from the Indian Ocean to the Malacca Strait is not dominant. Nevertheless, the Indian Ocean water mass with higher salinities (more than 29 psu) reaches the north of Bengkalis Island. Around the Padang and Rantau Islands, the water masses show significantly lower salinities of 24 to 26 psu.

DISTRIBUTION OF POLLUTANTS

Continuously Source

At first, a continuously pollutant source at the mouth of the Siak River (100 mg/l) is simulated. Arbitrarily 100 mg/l is assumed to make up 100% of pollutant concentration which is released from 1 January 2001 until 31 May 2006 and transported by daily current provided by the circulation model. After one year of simulation, most of the pollutants have been transported northward to the Malacca Strait. In general the pollutants are transported and dispersed northward. This can be explained by dominantly northward currents as already discussed in an earlier section.

Parts of the pollutants, which move northward towards the Malacca Strait, are transported through the Bengkalis Strait. Moreover, the simulation results show that pollutants can also be transported further south but brought back to the Bengkalis Strait due to the dominant northward current.

During the northeast monsoon, i.e., the rainy season, pollutants are transported to the Malacca Strait only showing relatively low concentrations. High concentrations are only found in the Siak river estuary and along the Bengkalis Strait (see Figs 6a and 6b for conditions in January and March, respectively). At the end of this monsoon phase, in May, the pollutants are transported to the northern entrance of the Bengkalis Strait and still showing high concentrations along the Bengkalis Strait. Meanwhile, during the transition from the southeast to the northeast monsoon in September and October, the weaker northward surface current causes the pollutants to concentrate north and east Bengkalis Island. However, the highest concentrations are found along the Bengkalis Strait in November (beginning of the rainy season).

Results from the transport model show that the spreading of the plume from the Siak river mouth is in good agreement with data from satellite (see Figs 7a and 7b). In analogy to the observed plume from the estuary of the Siak

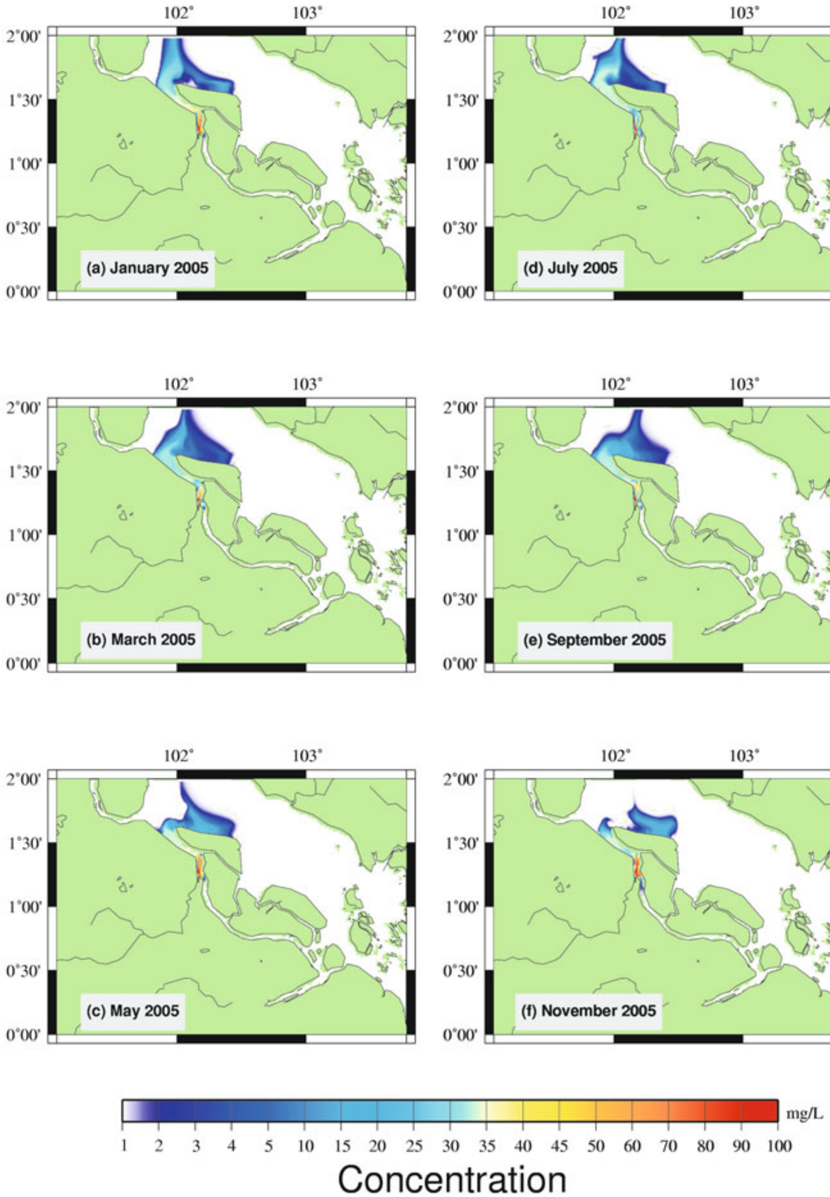

Fig. 6: Pollutant concentration from January to November 2005 released continuously from a source at the Siak river mouth starting at 1 January 2001 (a) January, (b) March, (c) May, (d) July, (e) September, and (f) November.

River also the simulated plume is transported to the north through the Bengkalis Strait. However, in both seasons observations show that a minor part of the plume enters the Malacca Strait through the smaller Padang Strait south of Bengkalis Island. The same phenomenon could also be reproduced by the transport simulation. Some discrepancies between model results and observations like the high plume concentrations in the Rupat Channel can be explained by the effect of additional sources which have not been considered in the transport simulation. Also observed high plume concentration south of the Siak River mouth must be attributed to the impact of the Kampar River, which has a much stronger load of sediments than the Siak River.

Non-Continuously Source

Secondly, a non-continuous source was simulated. In this case an arbitrary pollutant with concentration of 100 mg/l was released at each first day of the month in the mouth of Siak River. The resulting distribution at the end of the specific month is analysed in order to discuss the influence of monsoon and its variability on the pollutant transport. The simulations were performed for every month from January to December 2005.

The simulation results show that the distributions after one month of dispersion are almost similar for every year. In January, representing the peak of the northeast monsoon, maximum concentrations after one month are less than 2 mg/l or equal to 2% of the input pollutant concentration. Moreover,

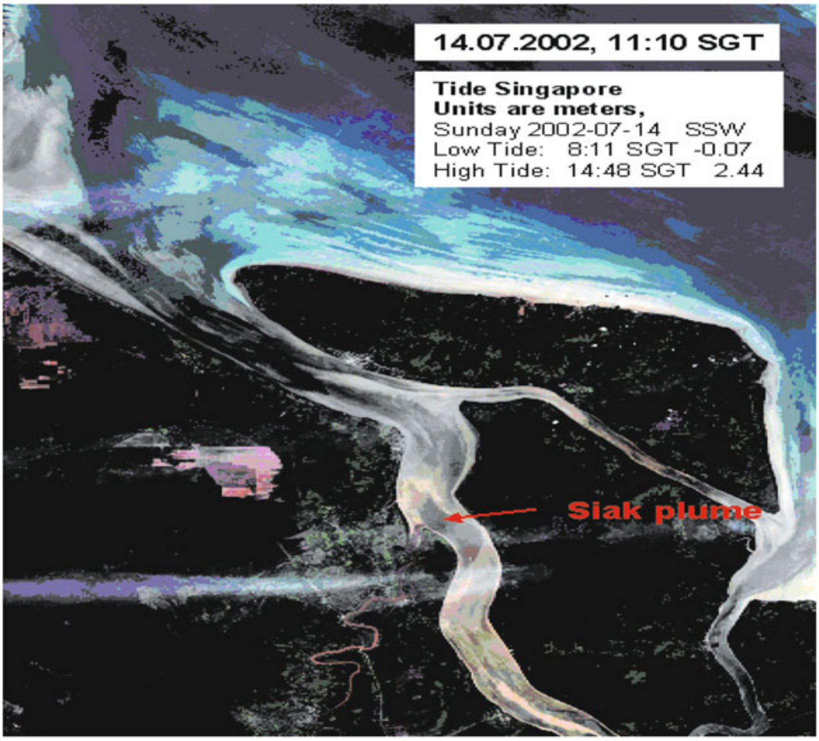

Fig. 7(a): Landsat 7 ETM+ scene acquired on 14 July 2002 11:10 SGT showing the Siak River plume during flood tide.

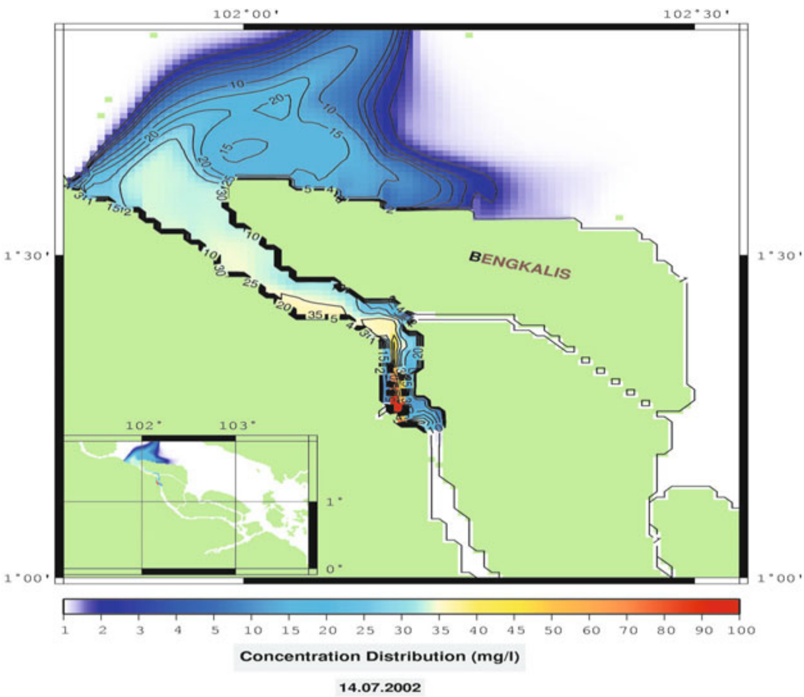

Fig. 7 (b): Simulation Results on 14 July 2002 after 1.5 years of continuous release at the Siak river mouth.

from January until May the pollutant has reached the central Malacca Strait through the Bengkalis Strait. The maximum concentration becomes higher, about 7 mg/l or 7% of the pollutant input concentration, during the southwest monsoon. The tip of the plume during this time is located around the northern entrance of the Bengkalis Strait. Because of the lower river discharge during the dry season until the beginning of northeast monsoon (July until November), the pollutant accumulates near the mouth of Siak River estuary. In contrast, during the northeast monsoon, when the river discharge peaks, the pollutant is transported further to the north reaching the central Malacca Strait as in January.

CONCLUSION

Several conclusions could be drawn from the above investigations. Firstly, it could be demonstrated that the HAMSOM circulation model is able to reproduce the hydrodynamical conditions in the Riau waters reasonably well. The same is true for the dispersion model. The resulting concentration patterns of substances released at the Siak river mouth are in good agreement with satellite observations.

Secondly, the hydrodynamical simulations prove that the sea level difference between the Java Sea and Indian Ocean causes a predominantly northward flow in the Malacca Strait. Therefore the seawater properties of Java Sea with low salinity are dominating in the southeastern part of the Malacca Strait.

Thirdly, the transport model simulation shows that substances released at the Siak river mouth in general is transported to the north through the Bengkalis into the Malacca Strait. However, a minor part of the Siak river water is transported through the Padang Strait south of Bengkalis Island.

Finally, this dispersion simulation indicates that the longest residence times for substances released at the Siak River mouth occur during the northeast monsoon (in January). After one month of dispersion the maximum concentration found in the Bengkalis Strait still exhibits up to 6-7% of the initial concentration released at the starting day.

ACKNOWLEDGEMENT

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12

Net Phytoplankton Community Structure and Its Biomass Dynamics in the Brantas River Estuary, Java, Indonesia

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Abstract: Research on estuarine phytoplankton ecology was conducted from March 2006 till March 2008 in two Brantas river mouths : Wonokromo and Porong, Indonesia, which was aimed to evaluate the phytoplankton ecology and its related environmental condition dynamics. Under water light measured as Secchi depth profiles show a strong influence of rainy season in reducing light availability due to high turbidity derived from the incoming rivers at both estuaries. Nutrient concentration dynamics were observed, showing higher values in the river mouth stations and lower values in the offshore stations. In Porong estuary, lowest nitrate concentrations were found in offshore waters (ranging from 0.72 to 1.21 μM NO_3-N), while maximum values prevailed at river mouth stations (ranging from 2.62 to 2.71 μM NO_3-N). Typical difference of the two monsoonal seasons on phytoplankton biomass is obviously observed, showing a low average phytoplankton biomass during the rainy season. Annual average of phytoplankton biomass in Porong and Wonokromo estuaries accounted for 4.75 μg Chl *a* l^{-1} and 2.51 μg Chl *a* l^{-1}, respectively (ranging from 0.21 μg Chl *a* l^{-1} to 22.23 μg Chl *a* l^{-1}). Low average of phytoplankton biomass in rainy season is likely due to light inhibition during the very turbid water of rainy period and inversely during the dry season. Phytoplankton biomas dynamics is correlated with that of nutrient concentration.

Key words: Brantas – Madura, Porong, Wonokromo, nutrients, phytoplankton, phytoplankton biomass, tropical monsoon.

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INTRODUCTION

Brantas river is the largest river in East Java Province, Indonesia, with 350 km length and of around 12,000 km^2 catchment area (Handayani et al., 2001) and one of the priority river catchment management of Indonesian government. Source of this river is at Mt. Arjuno while its mouth is in Madura Strait, splitting into three river mouths: Porong, Wonokromo and Kali Mas. Its major branches, the Porong and Wonokromo are the major sources of freshwater, dissolved and particulate substances for the coastal waters, as well as the source for nutrients for the recipient and adjacent sea waters. Jennerjahn et al. (2004) stated that Brantas estuary is a shallow and rich nutrient estuary due to its continuous supply of nutrients from the river. Average concentrations of nitrogen in this area are of around 120 μM (Porong mouth) and 105 μM (Wonokromo mouth).

Study on the relationship between nutrient concentration and its phytoplankton community in tropical coastal waters is not done as extensive as in the temperate areas (Cloern, 2001; Berdalet et al., 1996; Foy, 1993; Olli et al., 1996; Hessen et al., 1995; Muscatine et al., 1989). In Indonesian estuaries, studies on nutrient enrichment and its relation to phytoplankton ecology are very limited (Kaswadji et al., 1993; Damar, 2003). The monsoonal temporal influence on the dynamics of nutrient concentration and phytoplankton community is also rarely done in Indonesian coastal waters (Damar, 2003). In fact, the typical tropical monsoonal system and its effects in Indonesian coastal waters phytoplankton community dynamics is among the most interesting aspects to be more explored. In tropical region, there is no significant temporal variation in temperature and light while in temperate region it is vice versa (Damar, 2003). This difference then creates a specific character of tropical phytoplankton community dynamics. In general, the load of nutrients from the incoming river increases during the rainy season, and decreases during the dry season, following the river discharge variability (Damar, 2003). However, during the rainy period, higher nutrient concentration is counteracted by higher turbidity, resulting in obstacles in phytoplankton development (Damar, 2003).

This research is aimed to study phytoplankton ecology in tropical estuary especially on the dynamics of nutrient concentration and its effect on phytoplankton community in Brantas estuaries throughout the monsoonal variability. The information resulted from this research will be among the first scientific information available that can be used as a basic information for the environmental management in the area.

MATERIALS AND METHODS

Measurement campaigns were performed in the study area over a 24-month period (March 2006 – March 2008), encompassing the four different tropical monsoonal seasons, namely dry, transitional period of dry to rainy season, rainy season and transitional period of rainy to dry season. Water samples were taken at each sampling station, with a frequency of approximately every four months. Sampling stations were defined in order to have sufficient spatial salinity gradient coverage of the area (starting salinity = 0 PSU up to marine waters approx. 35 PSU) (Fig. 1). Measurement on nutrient concentration, i.e. nitrate, ammonium, ortho-phosphate and silicate, were performed according to the method of Grashoff et al. (1983). Surface water samples (depth of 0 to 1.5 m) were collected by means of 5-litre PVC Van Dorn bottle. Net plankton samples were collected by using a 25-µm net, to enable phytoplankton species identification. Besides taking a water sample, in situ measurements were also

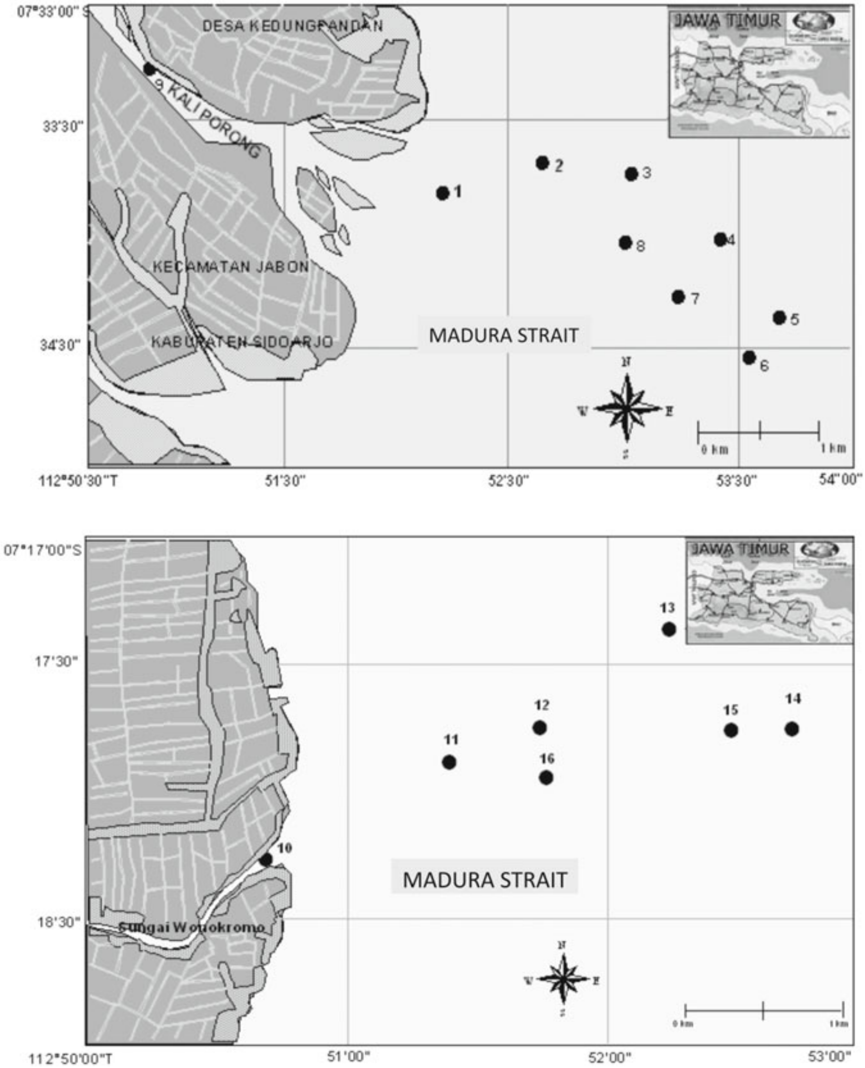


Fig. 1: Sampling sites at Porong Estuary (upper graph) and Wonokromo Estuary (lower graph).

conducted for salinity and Secchi depth. Phytoplankton cell counts were performed according to the settling method developed by Utermöhl (1958). Chlorophyll *a* as phytoplankton biomass determination were conducted according to Lorenzen (1967) method.

RESULTS

Physical Environmental Features

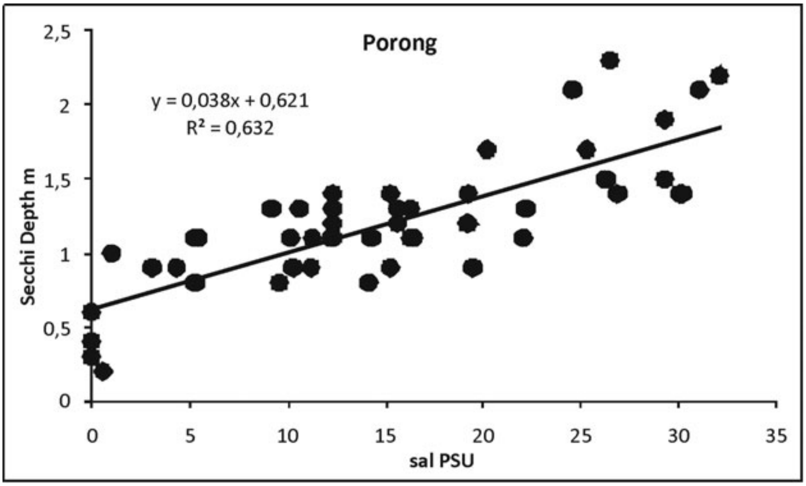
Distinct spatial gradients in salinity was found at each seasonal survey, reflecting the importance of freshwater inflow from the incoming rivers. There was difference in salinity value between seasons and sites (ANOVA, $p < 0.05$). The lowest annual average of salinity was observed at station 9 Porong (river site) and 10 Wonokromo (river mouth), 1.0 PSU and 3.5 PSU, respectively. The highest were observed at stations 5 and 14 for Porong and Wonokromo, 32.5 PSU and 30.5 PSU, respectively. The highest salinity values were observed during dry period both for Porong and Wonokromo, July 2006 and August 2007, respectively. An LSD-Test (Least Significant Difference) showed that spatial differences were due to stations of river site (stations 9 Porong and 10 Wonokromo), while in the temporal form, the difference was due to the measurement of July 2006 and August 2007. It is obvious that the incoming rivers, the Porong and Wonokromo, are the main sources of fresh water for the estuaries studied, which are detected further to the more offshore stations.

Secchi depth values were significantly different between sites and seasons ($p < 0.01$). Secchi disk readings were significantly positively correlated with salinity ($p < 0.001$; Pearson's $r = 0.55$, respectively), indicating a prominent role of river inflow for this parameter both for Porong and Wonokromo (Fig. 2). Secchi depth values at 0 PSU and river mouth stations both Porong and Wonokromo were always low, showing values below 1.0 m and 1.5 m, at Porong and Wonokromo respectively.

Dissolved Inorganic Nutrients

All nutrient species showed significant spatial differences in nutrient concentrations (ANOVA, $p < 0.001$), where distinct spatial gradients were observed along with increasing salinity. At temporal scale, from the four major nutrient species, nitrate, ammonium and silicate concentrations were significantly different (ANOVA, $p < 0.001$).

In spatial term, high values prevailed in the vicinity of freshwater inputs, which is in line with generally high nutrient concentrations of the rivers. Minimum values of phosphate was observed at station 1 (0.20 μM) and station 15 (0.04 μM) for Porong and Wonokromo, respectively. Almost in all seasonal surveys, phosphate was mostly concentrated in the area close to river mouth of Porong river (stations 2 and 3) and Wonokromo river mouth (station 11). For Porong



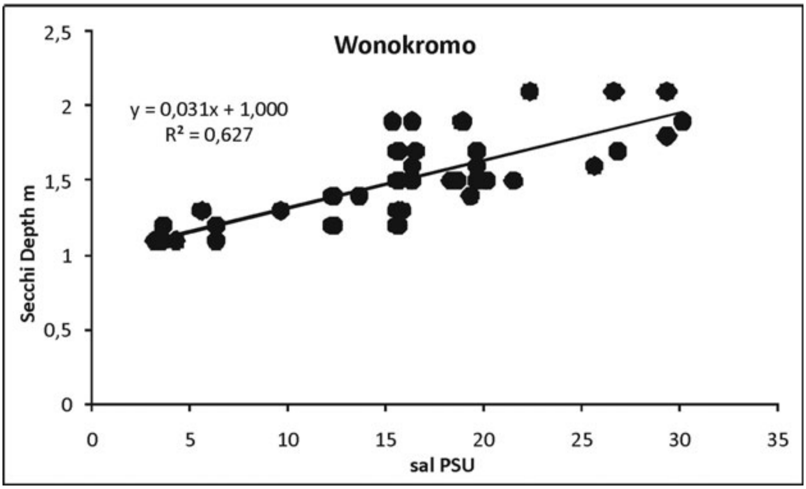


Fig. 2: Linear regression between salinity and Secchi depth readings at Porong estuary (upper graph) and Wonokromo (lower graph).

estuary, stations 2 and 3 were always higher than that of stations 1 and 9. This indicates that the main source of phosphate is not only from the incoming Porong river, but also from the sea. It seems that rivers in the north side of the study area play significant role in contributing the nutrient elevation in the estuary of Porong river. It is similar in Wonokromo, where a clear pattern of decreasing phosphate content is not observed. The pattern of phosphate gradients in the estuaries studied were not clearly observed as indicated by a weak correlation between salinity and phosphate both for Porong and Wonokromo. This indicates that the incoming rivers of Porong and Wonokromo are not the main sources for phosphate in the estuaries. Temporal variations show a more clear pattern of phosphate concentration, showing an elevated value during rainy period. (Pearson's $r = -0.62$, $p < 0.01$).

Significant differences in nitrate concentration were observed both on spatial (ANOVA, $p < 0.001$) and temporal scales (ANOVA, $p < 0.05$). In Porong, the lowest nitrate concentrations were found in offshore waters (ranging from 0.72 to 1.21 μM), while maximum values prevailed at stations 2 and 3 (ranging from 2.62 to 2.71 μM). The river site station (station 9) too, always exhibited elevated nitrate concentrations, ranging from 0.92 to 2.66 μM. For Wonokromo, the highest was observed at station 10 and gradually decreased in the more offshore stations. Statistically significant seasonal fluctuation in nitrate concentration was also observed at Porong and Wonokromo. In Porong, a maximum temporal mean of nitrate prevailed in August 2007 (3.51 μM), while a minimum occurred in December 2006 (0.75 μM). For Wonokromo, the mean maxima was observed in July 2006 while the minima was observed in March 2008. High temporal mean in August 2007 in Porong and July 2006 in Wonokromo was during the low input of riverine discharge of dry season. It seems that the internal process of estuary is able to accommodate the internal turn over of nitrate from the sediment during the dry period. In general, the influence of fresh water is not significant in influencing the elevated nitrate values.

Ammonium exhibited a steep gradient in the riverine-coastal transitional zone, indicating high loads of ammonium from the incoming rivers. The highest annual mean was observed at station 3 (Porong) and station 11 (Wonokromo), 3.1 μM and 3.4 μM, respectively. The pattern was in the medium level in the river mouth, then increased seawards and then decreased again in the more offshore waters. Both in Porong and Wonokromo, it is seen that the highest level of ammonium were not observed in the river mouths, but they were high in the stations just outside the river mouths. It is an indication that in the estuary studied, the river is not the only source of ammonium. Significant differences were found on the spatial ($p < 0.001$) and temporal scales ($p < 0.05$).

In seasonal pattern, the mean maxima of ammonium prevailed in the dry season which were in July 2006 - 3.5 μM (Porong) and August 2007 - 3.1 μM (Wonokromo). Other secondary maxima were also observed during the dry season, i.e. August 2007 - 2.8 μM (Porong) and July 2006 - 2.3 μM (Wonokromo). The minima of ammonium were observed during the rainy season for both of the estuaries. The ammonium minima in Porong was observed in March 2006 (0.3 μM) while in Wonokromo was observed in March 2007 (1.05 μM). Both phenomena might be caused by the influence of waste water from the shrimp pond culture along the northern and southern parts of the estuaries studied. However, river discharge seems to be the main factor determining the ammonium distribution. An inversely but strong correlation ($p < 0.001$; Pearson's $r = -0.61$) was observed between salinity and ammonium all over the research period.

There were significant differences in silicate concentration, both between sites and seasonal surveys (ANOVA, $p < 0.001$). General spatial pattern shows that silicate was high in the inner part of the estuaries, and then decreased in the more offshore waters. On temporal scale, the maximum average of silicate at Porong estuary occurred during rainy season of December 2006 (around 12 µM), while the minimum was observed during dry season of July 2006 (around 4 µM). In Wonokromo estuary, the mean maxima of silicate was observed during rainy season of March 2008 (around 6.5 µM) while the minima of silicate was observed in the dry period of August 2007 (around 3.2 µM). It shows that Porong and Wonokromo rivers are the main source of silicate in the estuaries studied. Freshwater discharge is held to be the prominent factor for silicate distribution in the estuaries ($p < 0.001$, Pearson's $r = -0.65$, for salinity).

Figures 3 and 4 show correlation between salinity and each nutrient species both for Porong and Wonokromo estuaries. Results for Porong revealed a significant correlation between salinity and ammonium and silicate ($R^2 = 0.331$ and 0.531 for ammonium and silicate, respectively) while with other nutrient species shows weak correlation ($R^2 = 0.09$, 0.057 and 0.002 for nitrate, nitrite and phosphate, respectively). This shows that only ammonium and silicate are contributed by the incoming river of Porong. Results for Wonokromo revealed non-significant correlation between salinity and almost all nutrient species except with silicate ($R^2 = 0.418$). This shows that only silicate is significantly contributed by Wonokromo river, while other nutrients are not.

Phytoplankton Biomass and Species Composition

Phytoplankton biomass is represented by the content of chlorophyll *a*. A clear spatial pattern of mean chlorophyll *a* at each temporal survey is observed (ANOVA, $p < 0.001$). There is difference in the spatial pattern of chlorophyll *a* distribution for both estuaries. In Porong, chlorophyll *a* was low in the river site and river mouth, then increased in the middle part of estuary and steeply declined in the offshore stations. In Wonokromo, chlorophyll *a* was low in river site, river mouth and some stations seaward but then increased again in offshore stations.

For Porong estuary, throughout the year, river site and river mouth (stations 9 and 1, respectively) were always low in annual mean of chlorophyll *a* content, i.e. around 0.1 µg Chl *a* $l^{-1}$and 2.8 µg Chl *a* l^{-1}. The mean maxima was observed in station 3 (10.1 µg Chl *a* l^{-1}). For Wonokromo, the lowest value of chlorophyll *a* was at station 10-river mouth (1.1 µg Chl *a* l^{-1}) and the highest was observed at station 15 (3.4 µg Chl *a* l^{-1}). In the transect from inner to outer part of estuary, the content of Chlorophyll *a* was increased and then decreased at the outermost of the estuary (station 16).

Statistically significant temporal variation in chlorophyll *a* was observed in Porong estuary, with August 2007 as the highest (temporal average 8.3 µg Chl *a* l^{-1}), whereas December 2006 as the lowest concentration (temporal average 1.9 µg Chl *a* l^{-1}). Similar pattern was also observed at Wonokromo

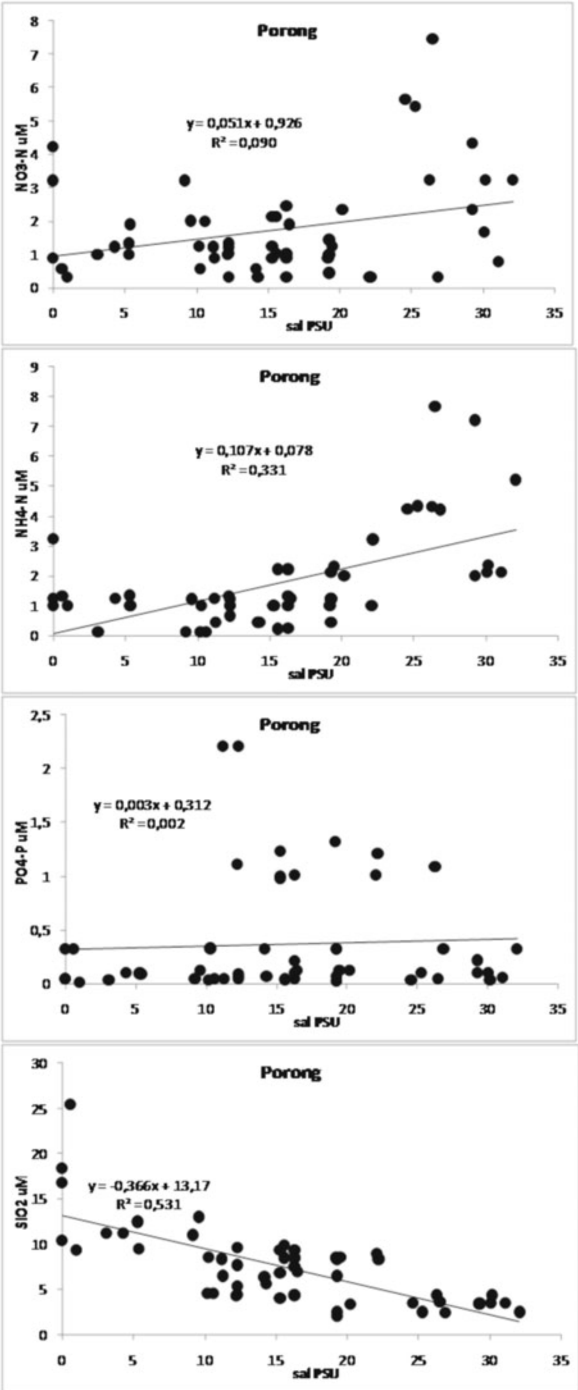


Fig. 3: Linear regressions between salinity and nutrients (nitrate, ammonium, phosphate and silicate) in Porong Estuary. $N = 63$.

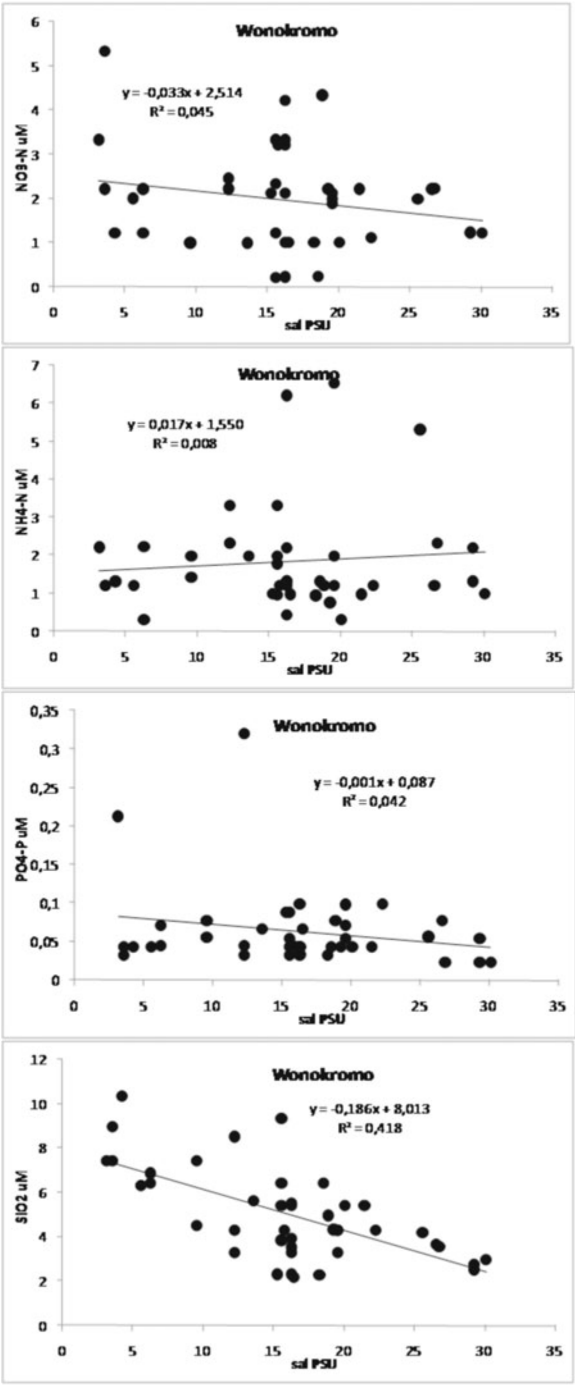


Fig. 4: Linear regressions between salinity and nutrients (nitrate, ammonium, phosphate and silicate) in Wonokromo Estuary. $N = 42$.

estuary, showing the highest peak in August 2007 (4.8 μg Chl *a* l^{-1}) and the lowest was observed in March 2007 (1.1 μg Chl *a* l^{-1}).

An inverse exponential significant correlation was observed between salinity and chlorophyll *a* ($p < 0.01$; $R^2 = 0.41$), supporting the role of the riverine nutrients on phytoplankton biomass. Only nitrate and ammonium are strongly correlated with phytoplankton biomass in Porong estuary, while other nutrient species are weakly correlated. For Wonokromo river, only silicate is strongly correlated with chlorophyll *a*, while other species are not. This shows that phytoplankton biomass increases in direct proportion to the increased content of nitrate, ammonium and silicate.

In both estuaries studied, diatoms (*Skeletonema costatum, Chaetoceros* spp., *Coscinodiscus* and *Pseudonitzschia* spp.) dominated phytoplankton community, especially in the more offshore stations. At the inshore stations, including river mouths, dinoflagellates (*Ceratium* spp. and *Gymnodinium* sp.) was more prevalent.

There were significant differences in phytoplankton abundances between temporal surveys and sites (ANOVA; $p < 0.001$). In Porong, on each temporal survey, high phytoplankton abundance was observed at stations 2 and 3, where located outside the river mouth (around 1.4×10^6 cells l^{-1}). The abundance was then steeply decreased in the more offshore stations and down to around 150,000 cells l^{-1} at stations 6 and 8 (the outermost stations). At temporal scale, significant difference was observed, showing high abundance during the dry season of July 2006 and August 2007 (around 1.4×10^6 cells l^{-1}). For other sampling periods, the abundance were low and decreased down below 100,000 cells l^{-1}.

Wonokromo's phytoplankton abundance shows a slight different pattern to that of Porong. The pattern was low at the river mouth, then gradually increased seaward but it decreased again in the outermost of the estuary. The lowest was around 100,000 cells l^{-1} while the highest was around 400,000 cells l^{-1}.

At a temporal scale, Wonokromo was characterised by high phytoplankton abundance in the dry seasons (July 2006 and August 2007), and low during the rainy seasons of March 2006, December 2006 and March 2008. It also commensurates with the chlorophyll *a* pattern, which reached a maximum in the dry seasons. Pearson's correlation showed a strong and positive correlation between phytoplankton abundance and chlorophyll *a* concentration ($p < 0.001$; $r = 0.75$). This high correlation also indicates a low variation on phytoplankton species composition in the study area.

DISCUSSION

Comparison between light resource relative to nutrient resource (DIN) shows that phytoplankton communities in the river mouths and inner estuaries stations of both Porong and Wonokromo estuaries are potentially limited by light resource rather than nutrient resource. In these sites, the incoming rivers increase water turbidity, reducing light penetration into water column, as indicated by extremely low of Secchi depth readings (below 1.5 m). In the more offshore stations, the water clarity increases as indicated by the increase of Secchi depth values, either in Porong or Wonokromo estuaries. It is proved by significantly positive correlation between salinity and Secchi depth readings at both estuaries studied. This result is in concomitant to other tropical estuaries, such as Jakarta Bay, Lampung Bay and Semangka Bay (Damar, 2003; Koropitan et al., 2009). It seems that phytoplankton and planktonic production system in the inner part of the estuary and area close to the river mouth are limited by lack of underwater irradiance rather than nutrient. Inversely, in the more offshore station, where the turbidity is reduced, causing better light penetration, the availability of nutrients plays important role in regulating the development of phytoplankton (Cloern, 1999; Kocum et al., 2002; Tillmann et al., 2000; Damar, 2003, Koropitan, 2009). Porong and Wonokromo estuaries are relatively shallow waters with average depth of 1.6 m. With this low water depth, the posibility of phytoplankton cell to be always in the illuminated layer is high. However, since the water is highly loaded by the turbid incoming water, it is hampered by lack of light for phytoplankton growth.

In Porong estuary, spatial distribution of the five nutrient species investigated are varied. However, at Porong estuaries, except silicate, elevated concentrations of nutrients always prevail at stations 2 and 3 located in the north part of the estuary. These sites are not directly the main passage of Porong riverine flow in the estuary, but much more influenced by the water mass coming from outside estuary northward. Porong river mouth is not the only one riverine input in the study area. In the north side of the estuary studied, there are several small river mouths facilitating transports of nutrient from the land and also shrimp ponds. The spatial patterns of dissolved inorganic nitrogen and phosphate were relatively low in the river side and river mouth (stations 9 and 1) but increased in stations 2 and 3 and then decreased again in the more offshore stations (the rest of the stations). The pattern of silicate is not similar to that of other nutrient species, showing a strong influence of Porong river watermass for the increase of silicate contents in the estuary. This pattern was also observed in other tropical estuaries such as in Jakarta Bay, Lampung Bay and Semangka Bay.

The temporal pattern of nutrient distribution is somehow correlated with the monsoonal regime of the study area. Elevated values always prevailed during the rainy period and inversely reduced concentrations during the dry period. Elevated river discharge seems to be the main cause for the increase of nutrient concentration during rainy period. High erosion rate in the upland along the river is the main cause of the increase of nutrient during rainy period.

Nutrient concentrations in Wonokromo were significantly negatively correlated with salinity, showing the prominent role of the incoming riverine watermass as main source of nutrient for the adjacent estuary area. The temporal pattern of nutrient concentration in Wonokromo estuary is also related to that

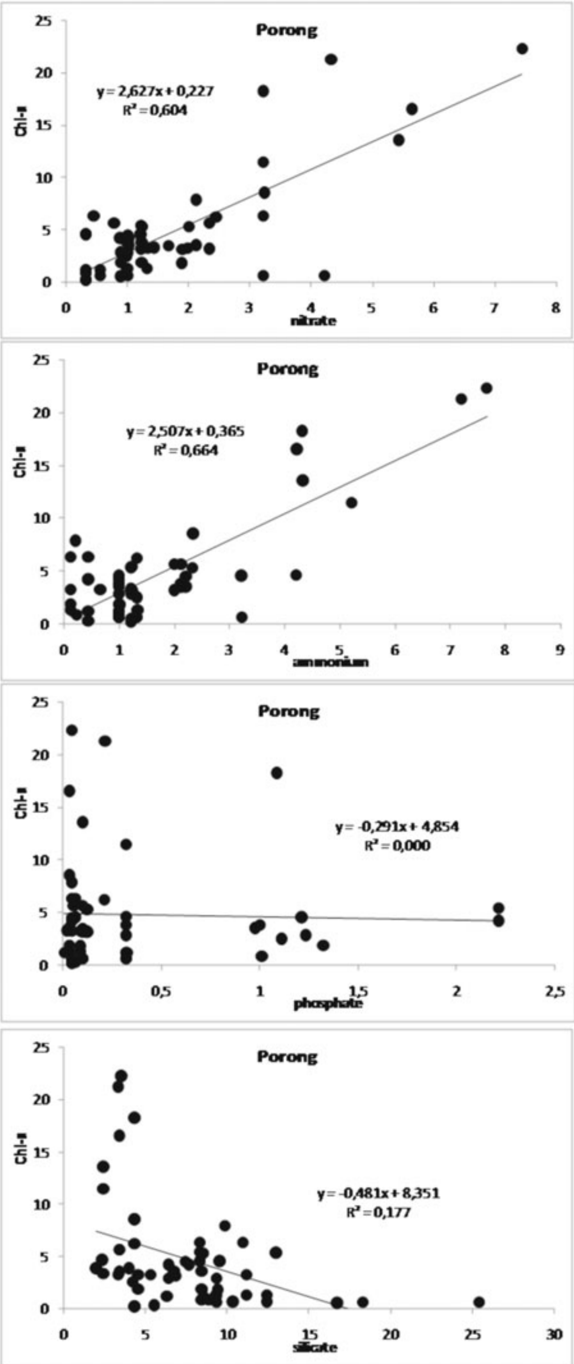


Fig. 5. Linear regression between concentrations of nitrate, ammonium, phosphate and silicate to chlorophyll *a* in Porong Estuary.

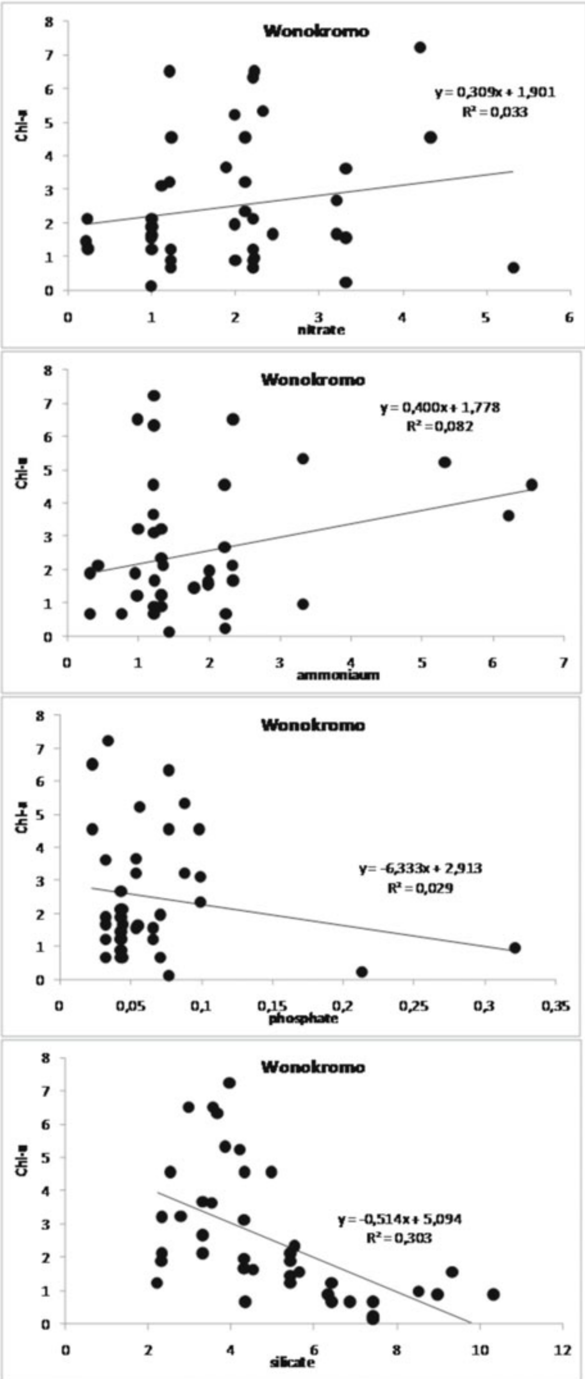


Fig. 6. Linear regression between concentrations of nitrate, ammonium, nitrite, phosphate and silicate to chlorophyll *a* in Wonokromo Estuary.

of climate variability, showing elevated values during rainy period and low values during the dry season.

Comparison among Porong and Wonokromo, show that there are no significant differences in the concentration of each nutrient species. However, a slight difference is observed, showing higher total average of nitrate and ammonium of Wonokromo compared to that of Porong (1.98 μM to 1.72 μM for nitrate and 1.84 μM to 1.75 μM for ammonium). Different pattern is observed for phosphate and silicate where Porong shows higher total average than Wonokromo (0.36 μM to 0.06 μM for phosphate and 7.48 μM to 5.02 μM for silicate). If these values are compared with other tropical estuaries such as Jakarta Bay, the values of nutrient concentration in the study area are lower. Damar (2003) resulted in annual mean of phosphate and silicate in Jakarta Bay as much as 5.1 μM PO_4-P, and 44.8 μM Si, respectively. Comparing with the Johor Strait, Singapore (Gin et al., 2000), these study results are slightly lower. In Johor Strait, the annual average of phosphate and DIN were 1.4 μM PO_4-P and 17.4 μM DIN, respectively.

In general, concentrations of dissolved inorganic nutrients show strong spatial and seasonal variations. High values of nutrients always prevail at river mouths and surrounding sites, while in the more offshore waters, the nutrient concentrations rapidly decline. A steep gradient of nutrient concentrations occurs in the riverine-marine transitional zone. This steep gradient is a common phenomenon in estuaries due to dilution with low nutrients water, as shown at some estuaries such as in Rhone estuary and Jakarta Bay. In the Rhone estuary, nitrate was 110 μM at the river mouth and went down to 2 μM at the sea sites (Bianchi et al., 1994). In the offshore waters of Jakarta Bay (Damar, 2003), nutrients sharply decreased, which could be caused by dilution with low nutrient waters, but also be due to a rapid uptake by phytoplankton.

On a seasonal basis, strong fluctuation in nutrient concentrations is also observed at both estuaries, showing a high peak in rainy season and the low peak in dry season, especially for nitrate, ammonium and silicate. This seasonal variation pattern is a common phenomena for tropical estuaries such as being observed by Damar (2003) in Jakarta Bay which was also previously observed by Praseno and Kastoro (1980) and Suyarso (1995), who showed higher values of nutrients during the rainy season compared to the dry season, mostly due to increase of nutrient loads from the rivers.

Annual average of phytoplankton biomass in Porong and Wonokromo estuaries accounted for 4.75 μg Chl *a* l^{-1} and 2.51 μg Chl *a* l^{-1}, respectively (ranging from 0.21 μg Chl *a* l^{-1} to 22.23 μg Chl *a* l^{-1}), which makes this area to be classified as a oligo to mesotrophic area, especially in the inshore waters (e.g. according to Nixon, 1995). Comparing with other tropical embayments such as Jakarta Bay, Lampung Bay and Semangka Bay (Damar, 2003), phytoplankton biomass of this study in Porong and Wonokromo is lower. Investigation done by Kaswadji et al. (1993) in Jakarta Bay showed that chlorophyll *a* around Marunda River mouth and eastern part of the bay ranged from 5.24 μg Chl *a* l^{-1} to 17.50 μg Chl *a* l^{-1} which are still higher than values obtained in this study. However, other studies also showed similar spatial and seasonal patterns, showing that during the rainy season, chlorophyll *a* content was higher than that during the dry season, with maxima of 7.5 μg Chl *a* l^{-1} in Jakarta Bay. A seasonal increase in phytoplankton biomass occurred during the rainy season. This is in accordance with the increase of nutrients in the estuaries during the rainy season, due to the increase of nutrient loads. This conforms with Gin et al. (2000), who stated that a seasonal variation of phytoplankton biomass in the tropical Singaporean waters was mostly due to the increase of nutrient discharges during the rainy season.

Steep spatial gradients of phytoplankton biomass occurred in both estuaries with a mean annual value for Porong in the river mouths of 3 μg Chl *a* l^{-1}, increased to around 10 μg Chl *a* l^{-1}, and decreased again down to around 3 μg Chl *a* l^{-1} in the outer layer of estuary. For Wonokromo, the spatial patterns are in the river mouths of 1 μg Chl *a* l^{-1}, increased to around 3.5 μg Chl *a* l^{-1} in the middle of estuary and decreased again down to around 2 μg Chl *a* l^{-1} in the outer layer of estuary. In the inner part sites of estuaries studied, high nutrient concentrations is counteracted by low light availability condition due to high water turbidity condition, resulting in unfavourable condition for accumulation of phytoplankton biomass. In the middle and more offshore waters, even though nutrients are decreased, increase in underwater light availability is able to promote better environment for phytoplankton growth.

Net phytoplankton communities in the study area are mainly dominated by diatoms (*Skeletonema costatum* and *Pseudonitzschia* spp.), followed by dinoflagellates (*Ceratium* spp. and *Dinophysis* spp.), cyanophyceae (*Trichodesmium* spp.) and chlorophyceae (*Scenedesmus* spp.). This distribution pattern conforms with previous studies done by Damar (2003), Arinardi (1995), Kaswadji et al. (1993) and Adnan (1994) in other Indonesian tropical estuaries. Comparison with Singaporean tropical waters gives a similar pattern, showing a domination of diatoms in the more offshore waters (Gin et al., 2000).

Finally, it is clearly seen that the variation of phytoplankton biomass and abundance in Porong and Wonokromo estuaries was regulated by combination factors of nutrient concentrations and underwater light availability, resulting in high values in the more offshore waters during the dry season and low values in the inshore waters during the rainy season. This also reveals that the influence of tropical monsoonal variability has tremendous effect on the dynamics of phytoplankton ecology in the tropical estuary, which works in different mechanism to those observed in temperate estuaries.

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13

Valuing Rural Piped Water Services in the Mekong Delta, Vietnam: Case Study at Phuoc Vinh Dong Commune

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Abstract: Over 42 million people of Vietnam do not have access to safe water. To address the problem efficiently, we need an appropriate method to estimate people's demands for safe water supply and factors affecting their demands. This paper presents a case study of the use of the contingent valuation method (CVM), as a solution to the problem. The CVM has been considered an important method to value environmental goods, and it has been increasingly applied in developing countries since the 1980s to value water supply services and other important environmental goods.

In Vietnam, however, CVM has not been officially applied for valuing water supply services. This study is the first to employ the double-bounded CVM to value rural piped water supply services in the Vietnam context. A sample of 217 households was selected using a two-stage stratified random sample method for in-person interviews. Findings of this study suggest that when designing water supply projects; policymakers, donors or private sectors in Vietnam should pay attention to the factors that affect household's willingness to pay (WTP). Another policy implication is that cost-benefit analysis based on CVM estimation can be used to design suitable program for water supply services.

Key words: Mekong Delta, rural water supply, double-bounded dichotomous choice, contingent valuation.

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INTRODUCTION

According to WHO/UNICEF (2000), 2.2 million people in developing countries die every year due to the diseases associated with lack of safe drinking water, inadequate sanitation and poor hygiene. Global efforts have been done to improve people's access to improve water supply and sanitation. Surprisingly, there was still 884 million people and most of them from developing countries without access to improved drinking water sources (WHO/UNICEF, 2010). In Vietnam, for example, there are large number of population facing water supply problem, especially rural developers. In 2009, nearly 65 million people accounting for 70.26% of Vietnam's population were dwelling in rural areas (GSO, 2010). By the end of the year 2005, however, only about 30% of the rural population had access to a water supply that met the national quality standards (MARD, 2005b). Therefore, serious water-related diseases are reported every year, with only five out of the 20 common water-related/borne diseases accounting for 1.5 million cases per year (MOH, 2002). Thus, the National Rural Water Supply and Sanitation (RWSS) Strategy up to 2020 was issued in the year 2000. This Strategy adopts Dublin statements to supply clean and safe water for people at affordable prices based on a demand response approach (MARD, 2000). Nevertheless, it is difficult to implement this principle in Vietnam. One of the main reasons is that the appropriate method used to value people's demands and their willingness to pay (WTP) for water supply in Vietnam has not been well developed. Many other parts of the developing world also have problem in supplying clean and safe water at affordable prices for their citizens depending on demand response approach.

The CVM (contingent valuation method), first suggested in 1947, has been increasingly applied in developing countries after the 1980s to value water supply (Briscoe et al., 1990; Griffin et al., 1995; WB, 1993; Venkatachalam, 2006; Whittington et al., 1990, 2002). The results of these studies provide growing evidences that people in developing countries are willing to pay (WTP) for water supply services and that the CV (Contingent Valuation) studies can provide useful information for policy-makers in this field to plan suitable projects. Moreover, since site-specific factors were found to affect households' WTP for improved water supply services (Griffin et al., 1995), it is recommended to take these factors into consideration rather than following the 'rule of thumb' (Venkatachalam, 2006); there have been some CV studies in Vietnam (Phuong and Gopalakrishnan, 2003; Pham and Tran, 2004). This promising method, however, has not been applied in Vietnam for designing water supply projects in practice. It is even doubtful that the CV studies can successfully be implemented in rural areas of a low-income transitional country like Vietnam, because CVM is based on hypothetical scenarios.

This case study applies the double-bounded dichotomous choice CVM to value piped rural water supply (RWS) services in the Mekong River Delta of Vietnam (VMRD) in an effort to answer the following questions: (1) Whether the CVM can be used for designing appropriate RWS projects in a low-income transitional country like Vietnam? (2) How much rural people are WTP for the piped RWS services? (3) What factors affect households' WTP for the piped RWS? (4) How can the results of the CV studies be used for cost-benefit analysis of RWS projects?

Water related problems and the need for innovation at the research site are described in Section 2; the methods for data collecting and analysing are presented in Section 3; the study's results are shown in Section 4 and discussion is provided in next part; and the final section being dedicated to concluding remarks.

STUDY AREA

The Mekong River Delta of Vietnam (VMRD) covers an area of 40,519 km^2 with a population in the year 2009 of 17,213,400 persons (GSO, 2010). The region is considered the nation's "rice bowl" because it annually contributes over 90% of the country's total rice exports and supplies 60% of the aquatic products for the whole country (MARD, 2010). It is characterized by low-lying topography bordered by the Gulf of Thailand, the East China Sea and downstream of the international Mekong River. Its climate is tropical monsoon with two seasons: the rainy season from May to November and the dry season from December to April.

The VMRD has been severely affected by the salinity intrusion during the dry season; and the affected land is approximately 2.1 million hectares (Le et al., 2007). Salinity intrusion has gradually increased due to the exploitation of underground water without proper management, global warming, and the development of dams within the VMRD and on the upstream Mekong River. The VMRD is also easily affected by floods during the rainy season; flooding in the VMRD cannot be directly mitigated and impacts a large area every year. According to Le et al. (2007), floods often take place over an area of 1.2 to 1.9 million ha, and they cause loss of life and substantial damage to crops and infrastructure. The sanitation in the delta is very poor; most people do not have any type of toilet or own only a fishpond toilet, and rural inhabitants have neither waste collection services nor sewage systems. Therefore, unwanted materials are directly discharged to surrounding areas, causing serious pollution to the environment and water quality. In addition, pesticides used in agriculture also significantly contribute to rural water pollution (Phuong and Gopalakrishnan, 2003). As a result, the VMRD is considered the region where people are most seriously affected by water-related diseases.

Given the limited budget and resources that can be used to providing water supply services, we focussed on the places where safe water has been urgently needed. Thus clustered and stratified methods were applied to select Phuoc Vinh Dong commune of the Long An province in the VMRD for this case study. This commune has three villages, 1622 households and 7776 persons. It has one secondary school and five primary schools, and one public infirmary. Electricity has been provided to almost every household. However, its sanitation system is as poor as other parts of the VMRD, and the water supply issue is even worse. Although, the commune has four drilled wells that can supply water directly to roughly 15% of its population through a piped system, the water from these wells cannot be used for drinking or cooking because of high salinity and contamination. It is used for cleaning, washing or having baths only; but the price for a cubic metre of the wells' water is 6000 Dong (VND). This is 2 or 3 times higher than the price for a cubic metre of drinking water in surrounding areas. The commune has only two drinking water sources: rainwater and water purchased from vendors (boats, tanks, and bikes). Water from vendors is sold to them at very high price, between 50,000 and 100,000 VND/m^3 (US$3.11-US$6.23/m^3), 20 to 50 times higher than the surrounding areas, because of high transportation costs.

METHODOLOGY

Survey Design

The survey questionnaire was designed based on questionnaires of 16 CV studies on water supply in developing countries, the Vietnam Household Living Standard Survey 2004, and background information of the study area. A pilot survey was done to investigate how the water supply problems could be solved, what type of water supply scheme was the most appropriate, and what kind of payment vehicle, management and provision the local people preferred, etc. Subsequent to the pretest, the survey data was analyzed to choose the optimal bids (Hanemann and Kanninen, 1999); develop the final survey questionnaire, the guidelines for focus group discussion, and the in-depth interview schedule. The final survey questionnaire had four parts: the introduction, background information, valuation questions and socio-economic characteristics.

The valuation components of the CV studies involve describing three main features: (1) scenarios; (2) the payment vehicle, or means by which the respondent will pay; and (3) the elicitation procedure. Describing scenarios based on the results of pilot survey, and the water supply scheme in Can Gio of Ho Chi Minh City was considered to be the most appropriate for the study area. The payment vehicle adopted the means used by Whittington et al. (2002) and reflected the way the local people paid for their water use. The respondents were also reminded of the substitute goods available to them, the budget constraints and their free choices of participating or not participating in the project before asking for their WTP. The double-bounded dichotomous choice (2DC) has been used to elicit households' WTP since Hanemann et al. (1991) proved it was statistically more efficient than single-bounded elicitation. The three different amounts of monthly water bills were randomly assigned to sub-samples of respondents, and each initial bid was followed up by either a higher or lower bid depending on the respondent's answer to the initial bid. A follow-up question was used for respondents who answered "no" to all the offered bids, in order to understand why they would not participate in the hypothetical project.

Sampling and Survey Management

The main objective of sampling is to obtain both desirable accuracy and an acceptable confidence level at a reasonable cost. The sample was selected from an updated list of total households in the commune using two-stage stratified random samples (Choe et al., 1999). The information from the sample of 219 households was obtained using in-person interviews. Two households in the sample were later excluded from the analysis because they were occupied by only one person who was over 60 years old, which is very rare. Thus, a final sample of 217 observations was analyzed. Compared with the straightforward tables of sample sizes needed for CV studies provided by Mitchell and Carson (1989), the sample size is satisfactory and can be considered representative of the interested population.

The in-person interview, the most preferred method, was applied for this CV study. Before the pilot survey, a study team of nine people was organized. One was the survey manager (Bui Duc Kinh) and two were supervisors, all of whom have done research in the region for many years. These three members of the team supervised the six enumerators. Since enumerator bias can be a problem in the administrative method of in-person interviews (Whittington, 1998), we carefully trained and checked enumerators prior and during the survey to make sure that everyone would ask the questions in the same way. Enumerators were also requested to give their respondents a sample questionnaire to read during the interviewing process to avoid enumerator bias as recommended by Mitchell and Carson (1989). Guidance notes from Whittington (2002) on managing and training enumerators for CV surveys in developing countries were also used as a reference for training and managing enumerators. In addition, the "4-time checking" was employed. A failed questionnaire, one that was not approved by the supervisors or manager, was returned to the enumerator, who was asked to re-interview the respondent. However, the principle of voluntary participation of all respondents was strictly respected.

Giving time for the respondents to think about their answers would also contribute to the accuracy of data obtained (Whittington et al., 1992). So each enumerator was limited to do about six questionnaires per day, even though the interviewing took, on an average, only about 15 minutes to complete.

The Statistical Models

Statistical models should make sense from the viewpoint of economic theory. Hanemann and Kanninen (1999), after reviewing many models in the recent literature that violated some of the restrictions of economic theory, provided their statistical model for the 2DC format. The initial bid was denoted by B_i, the second higher bid was B_i^u ($B_i^u > B_i$) and the second lower bid was B_i^d ($B_i^d < B_i < B_i^u$). There are four possible outcomes to double-bounded model: "yes-yes", "yes-no", "no-yes" and "no-no". And the likelihood of these outcomes was denoted by p^{yy}, p^{yn}, p^{ny}, and p^{nn}, respectively. Based on the random utility maximization, these likelihoods were derived as follows (Hanemann et al., 1991):

$$\Pr(yes/yes) = p^{yy}(B_i^u, B_i) = \Pr\{B_i \leq WTP_j \text{ and } B_i^u \leq WTP_j\} = 1 - G(B_i^u;\theta) \quad (1)$$

$$\Pr(yes/no) = p^{yn}(B_i, B_i^u) = \Pr\{B_i \leq WTP_j \leq B_i^u\} = G(B_i^u;\theta) - G(B_i;\theta) \quad (2)$$

$$\Pr(no/yes) = p^{ny}(B_i, B_i^d) = \Pr\{B_i \geq WTP_j \geq B_i^d\} = G(B_i;\theta) - G(B_i^d;\theta) \quad (3)$$

$$\Pr(no/no) = p^{nn}(B_i, B_i^d) = \Pr\{B_i > WTP_j \text{ and } B_i^d > WTP_j\} = (B_i^d;\theta) \quad (4)$$

where WTP_j denoted for true WTP of respondent j, $G(.;\theta)$ was the cdf of the individual's true maximum WTP with the parameter vector θ. The WTP follows the log-normal distribution if the function $G(.;\theta)$ is assumed to be a normal distribution; and it follows the log-logistic distribution if $G(.;\theta)$ is assumed to be a logistic distribution. The log-likelihood function for the 2DC now takes the form:

$$\ln L(\theta) = \sum_{i=1}^{n}\Big\{ I^{yy}\ln P^{yy}(B_i^u;B_i) + I^{yn}\ln P^{yn}(B_i;B_i^u) + I^{ny}\ln P^{ny}(B_i;B_i^d) + I^{nn}\ln P^{nn}(B_i;B_i^d)\Big\} \quad (5)$$

where I^{xz} is an indicator function that takes the value of one if the two responses are xz (yes-yes, yes-no, no-yes, and no-no), and zero otherwise. The maximum likelihood method was used for estimation. The maximum likelihood estimator is estimated by solving the equation (6)

$$\partial \ln L(\theta)/\partial\theta = 0 \quad (6)$$

This estimator was shown to be consistent and asymptotically efficient (Amemiya, 1985).

RESULTS

Statistical Descriptions of Sample and Population

The sample (n = 217) is representative of 13% of the target population; the statistical description of the sample and population is shown in Table 1. The signs (+/-) included in Table 1 indicate our expectations of the relationship between the explanatory variables and the households' WTP. Results of Table 1 show that 60% of samples had to pay an average monthly water fee of about 50,000 VND (US$3.11) or more; 53% of respondents reported that the water they used was either polluted or salty. As a result, many of them had water related diseases: 56% of the samples reported their household as being affected by water-diseases, and on an average around 1.6 persons in each household had been affected by water-diseases in the year 2006 (Table 1).

Table 1: Statistical descriptions

Variable names	*Sign*	*Description (n =13%*N)*	*Sample Mean*	*S.D*
		Geographical characteristics and water use behaviours		
Village		Location of respondent	0.48	0.50
Vtt	+	Dummy var. (1=Thanh Trung, 0=otherwise)		
Vvt	-	Dummy var. (1=Vinh Thanh, 0=otherwise)	0.31	0.46
Wfee2	+	Monthly water fee (1=more than 50,000 VND, 0=otherwise)	0.60	0.49
Qual2	+	Water quality (1=Polluted/salinity, 0=acceptable)	0.53	0.50
		Health risk characteristics		
Risk	+	(1=at least 1 affected by water-diseases last year, 0=no)	0.56	0.50
Hrisk	+	Number of members affected by water-diseases	1.60	2.20
		Demographic and socio-economic characteristics		
Male	–	Dummy var. (1=male, 0=otherwise)	0.47	0.50
Age	+	Respondent's age (continuous)	42.43	12.62
Education		Education of respondent		
Educ1	–	(1=never attended school, 0=otherwise)	0.10	0.30
Educ	+	Years in school (continuous)	5.31	3.28
Hsize	+	Number of members in household (continuous)	4.53	4.53
Children	+	Number of child/ren in household (continuous)	1.24	0.97
Female	+	Number of female in household (continuous)	2.27	1.14
Elder	–	Number of elder persons in household	0.38	0.72
Income	+	Monthly income of respondent's household	2,258	2,225
Linc	+	Log_{exp} of income		
Lbd	–	Log_{exp} of bids		

Source: Sample data was calculated based on CV survey at study area.

While 54% of respondents are heads of households, the remaining 46% are their spouses. The samples have a mean age of 42.43 years and have had about five years in school. The respondent's household, on an average, has nearly five members. The mean monthly income of household samples was 2,258,000 VND (US$140.56); the median monthly income was 1,700,000 VND (US$105.83).

Table 2 presents the responses' outcomes to the 2DC model. Those respondents that had No-No responses were asked for the reason why they did not vote for the hypothetical project. There were seven respondents (4.2%) that had No-No responses. Three gave the reason that they were old and didn't have money to pay for it, two reported the offered bids was too expensive, one provided that they wanted and were willing to pay but could not afford the required bid, and the last one (a water supply provider) said, "it brings no benefit to me".

Table 2: Offered bids and their responses

Thresholds	*Obs*	*Bid responses*				*Response frequencies*			
T1(T2)	*217*	*YY*	*YN*	*NY*	*NN*	*YY*	*YN*	*NY*	*NN*
30 (50/15)	72	55	15	2	0	0.764	0.208	0.028	0.000
50 (80/30)	73	48	17	7	1	0.667	0.233	0.096	0.014
80 (120/50)	72	24	31	11	6	0.333	0.431	0.153	0.083

Results of Log-logistic and Log-normal Models

The data was analyzed using Stata SE 9.1 and NLogit 3.0 (Limdep). Both log-logistic and log-normal models were used to check for robustness of the models. The final models were identified after all possible models had been estimated. From the viewpoint of statistical analysis, the results estimated from the two models using the same set of variables should not be significantly different. Table 3 presents the results estimated from our log-logistic and log-normal models. For simplicity, the log-logistic model is used for our discussion.

Table 3: Statistical regression results

Variables'	*Log-logistic model*		*Log-normal model*	
names	*Coefficient*	*St. Error*	*Coefficient*	*St. Error*
Cons	3,23	(2,74)	1,85	(1,65)
Vvt	-1,24 ***	(0,40)	-0,75***	(0,23)
Male	0,60 *	(0,34)	0,35*	(0,20)
Wfee2	1,15 ***	(0,34)	0,65***	(0,20)
Qual2	0,62 *	(0,34)	0,35*	(0,20)
Elder	-0,53 **	(0,24)	-0,27*	(0,15)
Hsize	0,22 *	(0,12)	0,12*	(0,07)
Hrisk	0,32**	(1,40)	0,19**	(0,81)
Linc	2,03 ***	(0,39)	1,17***	(0,22)
Lbid	-4,50 ***	(0,50)	-2,58***	(0,25)
Mean WTP	99.596 VND		99.633 VND	
Median WTP	98.739 VND		98.476 VND	
Log-likelihood	-152,96		-151,70	
AIC	325,93		323,41	

Note: ***, ** and * indicate statistical significance at 1%, 5% and 10% levels respectively.

DISCUSSION

Factors Affecting Households' Demand for Piped Water Supply

This empirical study shows that there are three sets of factors determining households' WTP for piped water supply in rural area of the VMRD: (1)

Geographic characteristics and water use behaviours; (2) Health risk characteristics; and (3) Demographic and socio-economic characteristics (Table 1). After several trials, the combinations of nine independent variables included in Table 3 were shown to be the most determined factors on households' preferences.

As we expected, the variables such as the present monthly water fee (Wfee2), the perception of existing water quality (Qual2), the health risk problem (Hrisk), the size of household (Hsize), and the household's monthly income (Linc), all have positive relationships with the WTP and are statistically significant at the 1% or 5% or 10% level (Table 3). Meanwhile, other variables, including the offered bid (Lbd), the proportion of elderly persons in the household (Elder), and the location of respondent (Vvt), have negative relationships with the WTP and are statistically significant at either the 1% or 5% level (Table 3). The positive signs of the coefficients of the variables denote that if the variables increase, the households' WTP will increase and vice versa. The variables having negative relationships with the WTP meant that if these variables increase, the household's WTP would decrease and vice versa. These empirical results are consistent with economic theory and the facts of our study area. The focus-group discussion and in-depth interviews also support this finding.

GENDER

In contrast to our expectation, the male respondents demonstrated a higher WTP for piped water supply than female respondents. Previous findings on the effects of gender on households' WTP vary from place to place. While female respondents demonstrated a higher WTP for access to public piped water in Tanzania and Haiti; they did not demonstrate as much WTP in Nigeria and India (WB, 1993). Results of our focus-group discussions and in-depth interviews support the finding of WB (1993) that the influence of gender on households' WTP depended on the specific cultural background. Result from the focus group discussion of females is presented in Box 1.

Box 1: Gender and water supply

'Clean and safe water is very important for us. Recently many kinds of water-related diseases have been found in our villages, such as diarrhea, malaria, or female diseases. Children and females are easily affected. We hope to have clean water to our villages for many and many years. We would like to pay as much as we can. But most of the females do housework, and do not earn money. Therefore, the offered prices are reasonable, but we have to ask our husbands before accepting a higher price.'

Focus group discussion of females at Vinh Thanh village on Mar. 16, 2007

EDUCATION

It was expected that higher educated respondents would be more WTP for the proposed project since they would be more aware of health benefits of improved water supply (WB, 1993). Surprisingly, it was not the case in this study. The results indicate that the respondents' education is not a factor affecting their WTP. There are two reasons that might explain this result: first, people with higher education attainment are usually younger, so they do not have much money or real estate as the older people do. Second, the Programs on Information, Education and Communication (IEC) about clean water and sanitation have been well implemented in the research site and this helped all of the people with different levels of education to understand the importance of clean water. Results from the focus group discussions and in-depth interviews also show that the IEC makes education serve a less important role (Box 2).

Box 2: People's knowledge on water-borne/related diseases

'... Provincial and local authorities have often had campaigns to raise people's awareness and knowledge on clean water supply and sanitation. We also recommend people not to use water from the drilled well of the clinic (built by UNICEF, but the water from this well is not safe) for eating/drinking. In general, almost all residents know the importance of clean water for their health...'

In-depth interview with local clinic staff at Thanh Trung village on Mar. 18, 2007

OTHER FACTORS

The proportion of females and children in the respondents' households have a positive relationship with the WTP (Table 1) as was expected, but these relationships were found not to be statistically significant. They are correlated with the size of family (Hsize), so they are not included in the final model.

Validity of This CV Study

CV studies can suffer from three potential biases: hypothetical bias, compliant bias, and strategic bias (Briscoe et al., 1990). According to Griffin et al. (1995) since piped water supply is a familiar good to all people, the hypothetical bias would be relatively low. Study by Johnston (2006) shows no statistical evidence of hypothetical bias. In addition, our scenario was finalized based on the discussion with the local people, and the cheap talk design (Murphy et al. 2005) was used; so this bias was not a problem in this study. The other two biases might be serious for CV studies in a transitional developing country like Vietnam.

Thus, enumerators were selected, trained and checked carefully. The "4-time checking" and re-interview process were applied to avoid these biases.

Finally, the statistical model was used to check the compliance bias, and the results of this analysis show no effect of this bias. The strategic bias occurs as respondents try to influence the CV results by over-stating or under-stating their WTP with the hope that they can gain benefits from doing so. This bias was addressed by informing the respondents that although it was a hypothetical project their information would be used for policy considerations and only their true answers would bring most benefit to them. In addition, our survey supervisors and manager checked for this bias every day ("4-time checking"); and nine cases were found to understate their WTP. These cases, however, were solved by re-interviewing. The conclusion is that these potential biases can be avoided by designing and implementing surveys carefully.

Benefit-cost Analysis

Table 4: Households' income and welfare estimates

	Log-logistic model	*Confidence Interval (95%)*
Mean WTP	99,596 VND* (US$6.20)	
Median WTP	98,739 VND (US$6.15)	89,892-108,458 (US$ 5.6- 6.75)
Mean household's monthly income		2,258,000 VND (US$140.56)
Median household's monthly income		1,700,000 VND (US$105.83)

*US$1~ 16,064 VND (average exchange rate during the main survey)

Table 4 presents the mean and median of monthly income and WTP of samples. The respondents' average monthly income varies from 200,000 VND (US$12.45) to 20,000,000 VND (US$1245.02). Since the standard deviation of the mean income is high, the median income was chosen for our discussion. The median WTP is US$6.15, accounting for 5.8% of the median monthly income (US$105.83) of households. The average monthly water bills of the surrounding areas ranged from US$3.42 to US$5.29, so this estimated WTP result is reasonable. The WTP and income ratio is also between the range of the estimated WTP for water supply by CV studies in developing countries (Whittington and Swarna, 1994).

The benefit estimation is calculated based on people's WTP, the target population and the probability of a person saying "yes" to the project as in equation (7):

$$Ln\left[\frac{\Pr(yes)}{1-\Pr(yes)}\right] = 3.23 - 1.24Vvt + 0.60Male + 1.15Wfee2 + 0.62Qual2 - 0.53Elder + 0.22Hsize + 0.32Hrisk + 2.03Linc - 4.50Lbid \quad (7)$$

As our target population is well-defined, the WTP aggregation is straightforward: the estimated monthly benefit for our hypothetical scenario is about 128,163,222 VND (US$7,978.29). The cost for this project can be minimized because the local government can support land use without fees.

And based on the benefit estimation results from the CV study; policymakers, donors or private sector participants can estimate the costs and compare with our benefit estimation before making the final decision.

CONCLUSION

Although there is still debate on the use of the CVM, Carson et al. (2001) concluded in their profound CVM review that "many of the alleged problems with the CVM can be solved by careful study design and implementation. We further conclude that claims that empirical findings are theoretically inconsistent are not generally supported by the literature." Our CV study at Phuoc Vinh Dong site also supports the study by Carson et al. (2001). However, our experiences at Phuoc Vinh Dong indicate that qualitative methods (focus group discussion and in-depth interview) should be done in conjunction with quantitative methods (survey questionnaire) to improve the quality of CV studies in rural areas of VMRD.

This study shows a growing demand for piped RWS services in the VMRD. The people, who live in the villages affected by salinity intrusion such as Phuoc Vinh Dong, demonstrate WTP as much as 5.8% of their household monthly income.

The findings of this study suggest that when designing water supply projects in Vietnam, policymakers, donors, and private actors should pay attention to the factors that affect household's WTP. In addition, the 'global factors' such as income, offered bid, perceived water quality, and health risk that have an effect on level of WTP, this study found that 'local factors' such as location, gender, proportion of elderly persons, etc. also play an important role. A final policy implication is that policymakers, donors and private sector participants can compare the costs of water supply projects with the estimated WTP from CV studies to decide on the most suitable programme.

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14

Coastal Sand Dunes—Vegetation Structure, Diversity and Disturbance in Nallavadu Village, Puducherry, India

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Abstract: Tropical coastal sand dunes (CSD) are exposed to various disturbances. CSD vegetation in South East coast of India was sampled by belt transect and quadrate method at three gradients of disturbance—highly disturbed, moderately disturbed and slightly disturbed. Three clear zones could be identified—*Cyperus* sps. > *Ipomea pescapre* > *Spinifix litoreus* in the fore dune, *Ginisekia pharmacoeides* > *Glinus oppositifolius* along with few minor dune species in the mid zone, and *Bulbostylis barbata,* along with a few dune species in back dune. In moderately disturbed sites species diversity was higher, supporting intermediate disturbance hypothesis.

Key words: Coastal sand dunes, intermediate disturbance hypothesis, vegetation structure, diversity.

INTRODUCTION

Coastal sand dunes, once distributed throughout the world except in Antarctica, are under higher human impacts and heavily degraded (Kumar et al., 1993; Mahmoud et al., 2007; Nordstrom et al., 2000; Varsha et al., 2001; Vandee, 1993). Wide range of sandy beaches was associated with sand dunes, while the

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spatial and temporal variations in the input of sediments and wind regimes, shape these dunes (Kurtbo et al., 2007; Hesp, 2000; Nordstrom, 1990; Pye, 1993). While several studies are available on coastal sand dunes (CSD) vegetation, restoration and stabilization in temperate regions (Koske et al., 1997; Sylvia, 1989; Sylvia et al., 1988), the tropical coastal dunes in general and Indian coastal dunes in particular are poorly studied (Sridhar et al., 2007; Kulkarni et al., 1997; Mohankumar et al., 1988).

Coastal dune formation ultimately depends on size and prevailing wind energy (Hesp, 2000; Kumar et al., 1993). Their heights differ in response to adequate sand supply, climate and local topographic features (Barbour, 1985; Brid, 1972; Ranwell, 1972). CSD constitute a variety of habitats of vital ecological and economic importance (Sridhar et al., 2007; Varsha et al., 2001; Martinez et al., 1996). Soil is the ultimate reservoir of plant nutrients and their availability decide the diversity, distribution and abundance of the native vegetation (Kurtbo et al., 2007; Zuo et al., 2007; Wilson, 1989; Kline, 1969).

CSD protect inland from various natural calamities like hurricanes, storm, and sea level rise. It also filter the rain water and recharge ground water, aquatic habitats, traps wind blown sand and prevent sand moving blown further inland, and provides critical habitats for both flora and fauna. Critical fragile coastal sand dunes were destroyed by various human interferences and infrastructure development activities like road, home construction etc., thus leading to disruption in dune process particularly in sand nourishment and development of dune and pioneer dunes (Vincent et al., 2008; Curr et al., 2000; Williams et al., 1997).

Quantitative surveys on the CSD provide information on the natural native flora and faunal species and their diversity. The most effective and durable methods in stabilizing/managing the dune is through re-vegetation, because it is least expensive, more durable, aesthetically appealing, and self regenerating technique (Spence et al., 2007; Mahmoud et al., 2007; Varsha et al., 2001; Grootjans et al., 1997). Dune plants stop and hold wind-borne sand effectively thus ultimately leading to dune stabilization, establishment and development. The main objectives of this paper are:

- to estimate the distribution and abundance of native flora and
- to identify key threats/disturbance to sand dunes/flora.

MATERIALS AND METHOD

Study Sites

Puducherry is located on the Coramandal coast between 11° 52' 56" and 11° 59' 53" of North latitude and between 79° 45' 00" and 79° 52' 43" of East longitude. It is limited on the East by the Bay of Bengal and on the other three sides by the Cuddalore district of Tamil Nadu State. Nallavadu is a small coastal village present at a distance of about 14 kms towards South on the way to Cuddalore from Puducherry main town.

Climate

Climate data for Puducherry available for 27 years (1980-2007) reveal a annual temperature of 31.1°C and mean annual rainfall about 1172-1311 mm. The mean number of annual rainy days is 55. The mean monthly temperature range from 21.3°-31.7°C for the same period. The climate is tropical dissymmetric with the bulk of the rainfall during northeast monsoon October-December (Indian Meteorological Department, Chennai).

Method

Three sites namely TD - totally disturbed site (residential area), MD - moderately disturbed site (about 200 m from the settlement areas) and slightly disturbed site (about 300 m from the settlement areas) where human pressure can be in the form of cattle grazing and drying fishes were identified for the study.

Belt transect is the most common standard method, used for vegetation surveys on systems with less proportion of flora such as sand dunes and grasslands (Espejel, 1987). The plants along the belt transect and about 1 m on either sides of the line were surveyed. Belt transects were made on both horizontal and vertical directions (with reference to the shoreline) on coastal sand dunes. Each transect measured about 100 m (three sites). Each site covered

Table 1: Comparison of disturbance ranking in three study sites

Disturbance	*Site 1 (TD)*	*Site 2 (MD)*	*Site 3 (SD)*
1. Site Encroachment			
i. For construction of roads	3	1	0
ii. For constructing houses, tanks etc	3	0	0
iii. For constructing factories	3	1	0
2. Landing of boats by visitors	3	1	0
i. Vehicle parking	3	1	0
ii. Cooking	3	1	0
iii. Festival occasions	3	1	0
3. Degree of cattle and goat browsing	2	3	1
4. Drying of fishes and nets	3	2	1
5. Using for sanitation	3	2	1
6. Resource removal			
i. Firewood	2	3	1
ii. Fodder	2	3	1
iii. Soil	0	2	1
Total	33	24	6
Disturbance Index	1.307	0.923	0.461

by 2 × 100 m (horizontal and vertical). Vegetation was sub-sampled for abundance and density by square quadrates of about 1 m^2.

Human disturbance was estimated qualitatively and the sub-classes of disturbances were ranked into none (score 0), relatively low (1), medium (2), and high (3) (Veblen et al., 1992). The sum of all score for each site provides an overall ranking of anthropogenic disturbance in the sites. High rank denotes significantly higher level of anthropogenic disturbance and low ranks, lower levels of disturbance (Table 1).

DATA ANALYSIS

For species diversity and evenness, Shannon and Simpson indices were used (Vincent et al., 2007; Hiroaki Ikeda, 2003; Beena et al., 2000).

$$\text{Simpson's index: } D.' = 1/\Sigma(pi)^2$$
$$\text{Shannon index: } H. = -\Sigma\,(\text{Pi} \times \ln \text{Pi}),$$

where *pi* is the proportion of individuals that species *I* contributes to the total.

The evenness (Oosting, 1942) is expressed by:

$$J. = H/H'_{max}$$

H'_{max} is the maximum value of diversity for the number of species present. Differences in Shannon's species diversity were statistically tested using ANOVA and Hutcheson's *t*-test (Vincent et al., 2008; Hutcheson, 1970). For disturbances, a synthetic disturbance index (DI) was also computed as follows: the values of the four factors of the "disturbances" data set were reduced to the [0–1.5] interval using the Gover's method $[X' = (X - X_{min})/(X_{max} - X_{min})]$ (Vincent et al., 2008; Legendre et al., 1998). The disturbance index was simply the average of these reduced values for each site.

RESULTS

The site 1 (TD) i.e., residential areas were disturbed due to various human activities. This study confirms that the native dunes species were found to be more in site 2 (MD) where disturbance were slight and limited (cattle and browsing, drying of fishes nets, resource removal e.g., firewood, fodder and soil), followed by site 3 (LD). Horizontal line transects parallel to shore does not show much variation as they are predominantly colonized by *Cyperus arenarus, Spinifex litoreus* and *Ipomoea pes-capre.*

The following results were reported from the present study which pertains to vertical transects only.

Species Diversity

Diversity surveys on the three sites, along the coastal sand dunes for the present study, indicated a total of 36 species belonging to 35 genera and 25 families (Table 2). Only one species was found to be common in all three sites, whereas

Table 2: List of families and species

Family	*Genera*	*Species*
Cyperaceae	5	5
Euphorbiaceae	3	3
Arecaceae	2	2
Rubiaceae	2	3
Poaceae	2	2
Verbenaceae	2	2
Aizoaceae	1	1
Molluginaceae	1	1
Convolvulaceae	1	1
Annonaceae	1	1
Cucurbitaceae	1	1
Meliaceae	1	1
Nyctaginaceae	1	1
Carricaceae	1	1
Casuarinaceae	1	1
Scrophulariaceae	1	1
Anacardiaceae	1	1
Moringaceae	1	1
Pedaliaceae	1	1
Onagraceae	1	1
Mimosaceae	1	1
Myrtaceae	1	1
Malvaceae	1	1
Zygophyllaceae	1	1

five species occur both in sites TD and MD, nine species only in MD and SD. Twenty-five families were recorded in all three sites, among this 17 families in TD, 13 in MD, and eight in SD were found.

Floras are classified into TF i.e. total flora, NF - native flora, CF - cultivated flora, and IF - invaded flora and their corresponding Shannon and Simpson indices value, evenness, families, genera, species in three sites are shown in Table 3 and Fig. 1. Plants found in site 1 (TD) mostly comprise cultivated and invaded species. MD and SD sites consist of native dune plants mostly. The plants are listed in Table 4 with their respective sites. The overall species diversity values among the three sites were not significantly different ($P>0.5$) but when we compare them as native dune species ($P<0.5$), introduced/cultivated species ($P<0.5$), invasive species ($P<0.5$), a significant difference among them was noted. While only one native dune species was found in site 1 (remaining are cultivated), it was more in MD and SD sites. The site MD species are higher than the species in site 3, supporting the intermediate disturbance hypothesis.

Table 3: List of plants found along transects

Botanical Name	*Family Name*	*Site 1 - TD*	*Site 2 - MD*	*Site 3 – SD*
Cyperus arenarius Retz.	Cyperaceae	39	257	362
Gisekia pharnaceoides L.	Aizoaceae	0	81	97
Glinus oppositifolius (L.) A. DC.	Molluginaceae	0	49	70
Bulbostylis barbata (Rottb.) C.B. Clarke	Cyperaceae	0	43	58
Spinifex littoreus (Burm.f.) Merr.	Poaceae	0	20	25
Ipomoea pes-caprae L. R. Br.	Convolvulaceae	0	19	24
Acalypha indica L.	Euphorbiaceae	13	0	0
**Annona squamosa* L.	Annonaceae	1	0	0
Azadirachta indica Adr. Juss.	Meliaceae	2	3	0
Boerhaevia diffusa L.	Nyctaginaceae	8	8	0
**Carrica papaya* L.	Carricaceae	2	0	0
**Casuarina equisetifolia* Forster & Forster f.	Casuarinaceae	7	0	0
Citrullus colocynthes (L.) Schrader	Cucurbitaceae	0	5	2
**Cocos nucifera* L.	Arecaceae	132	0	0
Croton bonplandianus Baillon	Euphorbiaceae	6	0	0
Dactyloctenium aegyptium (L.) P. Beauv.	Poaceae	0	1	3
Euphorbia rosea Retz.	Euphorbiaceae	0	8	0
Fuirena ciliaris (L.) Roxb.	Cyperaceae	0	0	1
Kyllinga triceps Rottb.	Cyperaceae	0	1	0
***Lantana camara* L.	Verbenaceae	4	0	0
Lindernia oppositifolia (Retz.) Mukerjee	Scrophulariaceae	0	1	0
Ludwigia perennis L.	Onagraceae	0	1	0
**Mangifera indica* L.	Anacardiaceae	3	0	0
**Moringa oleifera* Lam.	Moringaceae	2	0	0
**Musa paradisiaca* L.	Musaceae	2	0	0

(Contd.)

Table 3: (*Contd.*)

Botanical Name	*Family Name*	*Site 1 - TD*	*Site 2 - MD*	*Site 3 – SD*
Oldenlandia stricta L.	Rubiaceae	0	3	3
Oldenlandia umbellata L.	Rubiaceae	0	16	0
Pedalium murex L.	Pedaliaceae	7	0	0
Phoenix sylvestris (L.) Roxb.	Arecaceae	0	0	1
***Prosopis juliflora* (Sw.) DC.	Mimosaceae	3	2	0
**Psidium guajava* L.	Myrtaceae	2	0	0
Pycreus pumilus (L.) Nees ex C.B. Clarke	Cyperaceae	0	0	1
Spermococe ocymoides Burm. f.	Rubiaceae	0	1	0
**Tectona grandis* L.f.	Verbenaceae	2	0	0
**Thespesia populnea* (L.) Sol. ex Corr. Serr.	Malvaceae	6	0	0
Tribulus terrestris L.	Zygophyllaceae	3	0	0

* cultivated; ** invasive

Table 4: Shannon index, Simpson index, evenness, number of families, genera and species in three study sites

	Site 1 - TD				*Site 2 - MD*				*Site 3 - SD*			
	TF	*NF*	*CF*	*IF*	*TF*	*NF*	*CF*	*IF*	*TF*	*NF*	*CF*	*IF*
Shannon index	1.8	1.51	1.92	0.68	1.73	1.71	0	0	1.41	1.41	0	0
Simpson index	0.3	0.3	0.46	0.42	0.28	0.29	0	0	0.35	0.35	0	0
Evenness	0.6	0.78	0.86	0.98	0.6	5.90	0	0	0.57	0.56	0	0
Number of families	17	6	8	2	13	12	0	1	8	8	0	0
Number of genera	19	7	8	2	17	16	0	1	12	12	0	0
Number of species	19	7	8	2	18	17	0	1	12	12	0	0

TF - Total flora, NF - Native flora, CF - cultivated flora, IF - Invaded flora.

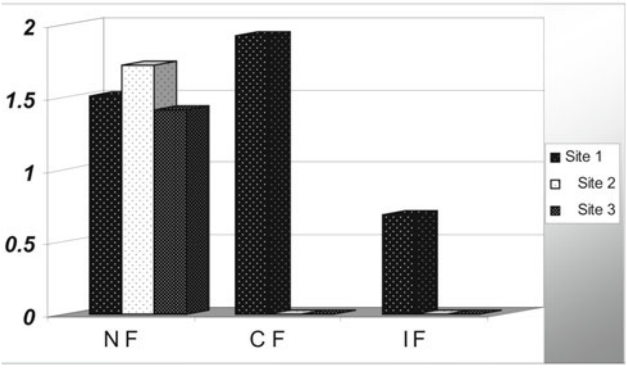

Fig. 1: Shannon indices in three study sites.
TF - Total flora, NF - Native flora, CF - cultivated flora, IF - Invaded flora.

Native Flora

The diversity and density ranking of native species are MD >SD>TD. When all the data for the three sites are pooled, the following results are obtained: H' = 1.716>1.511>1.411; D' = 0.3519>0.2906>0.2953; and J' = 0.7768>0.60597> 0.5681. ANOVA and t test (0.5 level of significance) confirming they are different significantly F = 3.129644; between df = 1; within df = 69; P = 0.286915). Three sites between themselves differed significantly, too; it is proved and confirmed by using ANOVA and t test (P<0.5). TD and MD F = 2.744078 < 4.084746; P = 0.10544. t_{stat} = –1.90566 P (0.0355 < 1.724 - one tail, 0.0711 < 2.0859 - two tails). MD and SD F = 0.082885 < 4.098172; P = 0.774989. t_{stat} = –1.17824 P (0.126625 < 1.729133 - one tail, 0.253249 < 2.093024 - two tails). TD and SD F = 2.385117 < 4.130018; P = 0.131754. t_{stat} = –1.70187 P (0.053498 < 1.739607 - one tail, 0.106995 < 2.109816 - two tails).

Cultivated Plants

The diversity and density ranking of cultivated species are TD>MD>SD. They are found in TD site only. ANOVA and t test (0.5 level of significance) confirms they are different significantly F = 3.554557; between df = 2; within df = 18; P = 0.289619. Three sites between themselves differed significantly; it is proved and confirmed by using ANOVA and t test (0.5 level of significance). TD and MD F = 1.328553 < 4.747225; P = 0.271507. t stat = 1.152629 P (0.146454 < 1.94318 - one tail, 0.292907 < 2.446912 - two tails) . TD and SD F = 1.328553 < 4.747225; P = 0.271507. t_{stat} = 1.152629 P (0.146454 < 1.94318 - one tail, 0.292907 < 2.446912 - two tails).

Invasive Species

The diversity and density ranking of invasive species are TD>MD>SD. They are found in TD and MD sites only. ANOVA and t test (0.5 level of significance) confirms they are different significantly. $F = 9.552094$; between $df = 2$; within $df = 3$; $P = 0.064776$. Three sites between themselves differed significantly; it is proved and confirmed by using ANOVA and t test (0.5 level of significance). TD and MD $F = 5 < 18.51282$; $P = 0.154846$. t stat = 1.666667 P (0.172021 < 6.313752 - one tail, 0.344042 < 12.7062 - two tails). MD and SD $F = 1 < 18.51282$; $P = 0.42265$]. $t_{stat} = 1P$ (0.25< 6.313752 - one tail, 0.5 < 12.7062 - two tails). TD and SD $F = 1 < 18.51282$; $P = 0.019804$]. $t_{stat} = 7$ P (0.045167 < 6.313752 - one tail, 0.090334 < 12.7062 - two tails).

DISCUSSION

Plant survey among the three sites shows significant variation in the composition of native dune species. Site 2 i.e. MD is more diverse than other two sites, supporting intermediate disturbance hypothesis (Bonte et al., 2003; Wood, 2001; Anthony, 2001; Beena et al., 2000; Gordon, 2000). The edaphic factors like salt spray and meteorological (water) features dictate distinct zoning in coastal vegetation (Stubbs, 2004; Ayyad, 1976; Oosting, 1942) that perhaps explain the distinct zonation of the species found in the study area. Most tropics and warm temperate shores consist of *Ipomoea pes-caprae* (John, 1970). It is a stoloniferous perennial, pioneer, mat-forming creeping strand species confined to the tropical beaches (Devall, 1992) established along with 73 typical beach plant species in the Gulf of Mexico and tolerates sand erosion, accretion and inundation (Devall, 1992; Britton, 1989). It is well adapted to coastal habitats with disturbance, especially burial, erosion and inundation (Corkidi et al., 1997; Martinez et al., 1996; Devall, 1992). The earlier report that *I. pes-caprae* also supports the coexistence of many other dune plants in moderately disturbed or stabilized dunes, the flora associated with *I. pes-caprae* include *Canavalia cathartica* Thouras, *Spinifix littoreus* L. and *Cyperus* sps (Rao et al., 1987) is confirmed in our study.

Low soil moisture in open dune (near high tide region) was found to be critical factor affecting diversity, distribution, survival and dominance of the flora found spatially and temporally (Ranwell, 1972; Williams et al., 1997). Further, they are also reported to be influenced by environmental factors such as temperature, desertification, sand erosion, sand accretion, salinity and salt spray (Woodhouse, 1978; Magurran, 1988).

Our findings on density and diversity of CSD vegetation agree with that of other earlier workers—increasing from shore towards land wards (Figs 2 and 3) (Xiaoan et al., 2008; Munoz-Reinoso, 2005; Bossuyt et al., 2004; Sykes et al., 1991). The effect of salt spray, wind exposure, sand accretion, evaporation, and heat stress decreases gradually inland facilitating the establishment of more flora from shore to inland, with enhanced diversity and richness (Castillo et al., 1991; Breed et al., 1979; Ranwell, 1972).

Out of the psammophytic strand vegetation reported from the CSDs of the Indian subcontinent (Sridhar et al., 2007; Rao, 1985) e.g. mat-forming creepers,

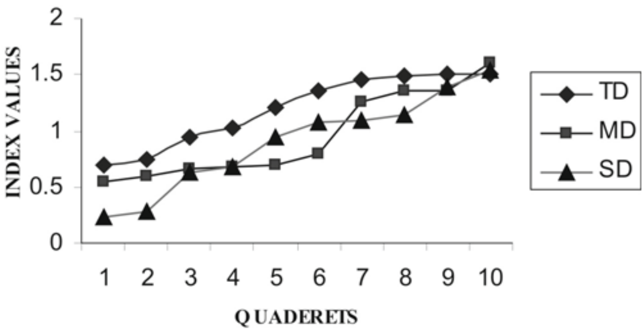

Fig. 2: Shannon wiener diversity index of the three study sites.
TD - Totally disturbed site; MD - Moderately disturbed site; SD - Slightly disturbed site.

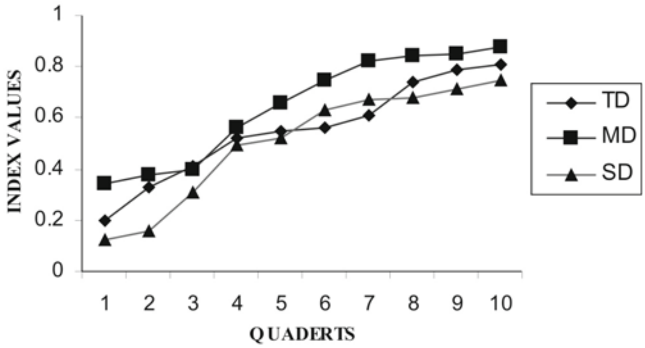

Fig. 3: Simpson dominance index of the three sites.
TD - Totally disturbed site; MD - Moderately disturbed site; SD - Slightly disturbed site.

prostrate/erect herbs and sedges, climbers, plants with penetrating organs, scrubs and trees, consisting of 154 species belonging to 108 genera and 41 families (Williams, 1997), our surveys indicated a total of 36 species belonging to 35 genera and 25 families in the study area.

Plant Families

Cyperaceae was found to be a common family to all three sites. Cyperaceae, Aizoaceae, Mollugniaceae, Poaceae, Convolvulaceae, Cucurbitaceae, and Rubiaceae were common families for sites MD and LD. The most species-rich family was Verbinaceae with two species in site 1-TD. Cyperaceae with five species in SD and TD. The percentage of families represented by single species was higher in SD (38%) and LD in TD (25%). It comprises all three sites. Cyperaceae was found to be the common family with five species followed by Euphorbiaceae (3), and Rubiaceae (3), Poaceae (2) and Arecaceae (2); nearly 18 families were represented only by single species. Temperate CSDs comprise mainly the members of Poaceae, while tropics with Asteraceae, Cyperaceae, Fabaceae and Poaceae (Sridhar et al., 2007; Moreno-cosasola, 1989; Rao, 1985).

Species Density, Dominance and Rarity

The density of species varied considerably between the sites. Site 2 i.e. MD comprises native dune floral species of 88% and 12% of invaded exotic species (weeds). Site 3 had 100% of native dune floral species. Site 1 i.e. TD was dominated by *Cocous nucifera* (54%), MD and SD by *Cyperus arenarius* for about 50% and 56%. *Cocous nucifera* and *Cyperus arenarius* formed nearly 70% of dune cover in site 1-LD; while *Cyperus arenarius, Gisekia pharmacoeides, Glinus oppositifolius, Bulbostylis barbata, Spinifix litoreus, Ipomea pescapre* and *Oldenlandia umbellata* together formed 93% of dune cover in site 2-MD, whereas in site 3-LD 98% covered by *Cyperus arenarius, Ginisekia pharmacoeides, Glinus oppositifolius, Bulbostylis barbata, spinifix litoreus,* and *Ipomea pescapre.* Measuring biodiversity helps to understand the ecology of the habitat and to develop the conservation strategies (Beena, 2007).

Based on species density, dunes species were classified into very rare (those represent by 1), rare (2-5), common (5-15), dominant (15-30) and predominant (>30). TD site totally comprises cultivated ones and so native dune species does not occur in this region. In site 2 i.e. MD 27% of very rare, 22% of rare and 16% of common species. SD site 3 comprised 50% of very rare and rare species.

FUTURE IMPLICATIONS

If coastal dunes and their vegetation are cleared it leads to serious problems like storm erosion and potential sea level rise, prevent sand blowing further inland where agriculture is carried out. CSD provides nesting places of the sea turtles; several dune specific floral and faunal species filter the rainwater and ground water etc. Such ecologically important and sensitive dune has to be restored and protected (Vincent Comor et al., 2008; Frihy et al., 2004; Nordstrom, 2000; El Raey et al., 1999; Henriques et al., 1998).

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15

Marine Drugs Development and Social Implication

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Abstract: Marine sources have attracted much attention as potential sources for natural products over recent years. The future of the biopharmaceutical holds great promise due to the many compounds that have and will be isolated from marine sources. Marine organisms have long been recognized as a source of novel metabolites with applications in human disease therapy. The marine environment is a rich source of both biological and chemical diversity, where it has been reported that oceans contain nearly 300,000 described species, representing only a small percentage of the total number of species that have to be discovered. The ocean represents a rich resource for ever more novel compounds with great potential as pharmaceutical, nutritional supplements, cosmetics, agrichemicals and enzymes, where each of these marine bioproducts has a strong potential market value. The reasons for the strong showing of drug discovery from natural products can be attributed to the diverse structures, intricate carbon skeletons, and the ease that human bodies will accept these molecules with minimal manipulation. With new pressures from the public and governments around the world to develop products to combat diseases and infections commonly encountered, new chemical entities need to be found and developed.

Today, the structures of around 1,40,000 secondary metabolites have been elucidated. But, owing to technical improvements in screening programmes, and separation and isolation techniques, the number of natural compounds discovered exceeds one million. This paper deals with the sources of drugs, discovery, isolation, identification, strain improvement, and its socio economic problems from marine sources. Detailed accounts are also given on novel marine metabolites, which were isolated from different (sponges, fishes, mollusks, cones, seaweeds and microorganisms) sources. Apart from that, we covered the role of natural products in disease treatment and commercial utilization of these compounds for possible drug improvement using advanced (metabolic engineering, post-genomics) approaches. The main challenge for future new drugs from the sea remains supply, but with production by fermentation and aquaculture two promising solutions are presented.

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INTRODUCTION

The marine environment is a rich source of both biological and chemical diversity, where it has been reported that oceans contain nearly 300,000 described species, representing only a small percentage of the total number of species that have to be discovered (Malakoff, 1997). The oceans comprise more than 70% of the Earth's surface, and each drop of water taken from the ocean will contain microbial species unknown to humans in a 9:1 ratio (Colwell, 2002). The ocean represents a rich resource for ever more novel compounds with great potential as pharmaceutical, nutritional supplements, cosmetics, agrichemicals and enzymes, where each of these marine bioproducts has a strong potential market value (Konig et al., 1994). Almost all forms of life in the marine environment e.g. algae, sponges, corals and ascidians, have been investigated for their natural products content (Faulkner, 2000). A lot of structurally and pharmacologically important substances have been isolated with novel antimicrobial, antitumor and anti-inflammatory properties (Rowley et al., 2002; Schwartsmann et al., 2004).

Natural products continue as a source for innovation in new drugs discovery by playing a significant role in this discovery and understanding of cellular pathways that are an essential component in the drug research process. In many cases, natural products provide compounds as clinical/marketed drugs, or as biochemical tools that demonstrate the role of specific pathways in disease and the potential of finding drugs. Numerous reviews have been written that describe the importance of compounds derived from microbes, plants and animal sources to treat human diseases (Butler, 2004; Newman et.al, 2003). In the areas of cancer and infectious disease, 60 and 75%, respectively, of new drugs originate from natural sources. Current strategies are employed to discover new natural products using recent advances in the understanding of genetic pathways for secondary metabolite production, under-explored sources of natural products and novel screening technologies. Examples of the essential role that natural product compounds play in the understanding of the basic science and development of novel therapeutics are described. The oceans cover over 70% of the Earth's surface and contain an extraordinary diversity of life. Our interest in understanding the function of marine ecosystems has been accelerated in recent years with growing recognition of their importance in human life. Marine microbes have defined the chemistry of the oceans and atmosphere over evolutionary time (Redfield, 1958). Thousands of different species of bacteria, fungi and viruses exist in marine ecosystems comprising complex microbial food webs. These microorganisms play highly diverse roles in terms of ecology and biochemistry, in the most different ecosystems.

Natural products with industrial/human applications can be produced from primary or secondary metabolism of living organisms such as microorganisms. Owing to technical improvements in screening programs, and separation and isolation techniques, the number of natural compounds discovered exceeds one million. Among them, 50–60% are produced by plants (alkaloids, flavonoids, terpenoids, steroids, carbohydrates, etc.) and 5% have a microbial origin. Of all the reported natural products, approximately 20–25% show biological activity, and of these approximately 10% have been obtained from microbes. Furthermore, from the 22,500 biologically active compounds that has been obtained so far from microbes, 45% are produced by actinomycetes, 38% by fungi and 17% by unicellular bacteria (Berdy, 2005). The increasing role of microorganisms in the production of antibiotics and other drugs for treatment of serious diseases has been dramatic. However, the development of resistance in microbes and tumor cells has become a major problem and requires much research effort to combat it. Evidence of the importance of natural products in the discovery of leads for the development of drugs for the treatment of human diseases is provided by the fact that close to half of the best selling pharmaceuticals in 1991 were either natural products or their derivatives (Cragg, 1997). In this regard, of the 25 top-selling drugs reported in 1997, 42% were natural products or their derivatives and of these, 67% were antibiotics. Today, the structures of around 1,40,000 secondary metabolites have been elucidated (Balaban and Dell'Acqua, 2005).

Several reviews explore the development of marine compounds as drugs (Wang et al., 2005). There have been reviews on aspects of the chemistry and bioactivity of compounds from microbes soft corals, cyanobacteria and microalgae, cyanobacteria and macroalgae, sponges (Sipkema et al., 2005), cnidaria, hoplonomertea, platyhelminthes, polychaetes, bryozoans and hemichordate, echinoderms, ascidians and fish, the gorgonian Pseudopterogorgia elisabethae, ascidians of the genus Aplidium (Zubia et al., 2005), the sponge genus Halichondria and terpenes from the soft coral genus Sinularia. Specific types of bioactivity associated with marine natural products have been reviewed in articles on anticancer drugs agents for treating tuberculosis, malaria, osteoporosis and Alzheimer's disease, antifoulants, treatments for neurological disorders, anti-inflammatory agents, anti-HIV compounds and topoisomerase inhibitors. Growing interest in marine microorganisms is reflected in several reviews (Zhang et al., 2005; Bull et al., 2005). Reviews on several aspects of the chemistry, toxicology, assay and risk factors of marine toxins have appeared. Particular classes of compounds from marine organisms continue to be well reviewed, with offerings on pyrroloiminoquinone alkaloids, polymethyleneamine alkaloids, fatty acids from lipids, indole alkaloids, guanidine derivatives, bromopyrrole alkaloids, phenylpyruvic acid oxime derivatives, triterpenoids, imidazole, oxazole and thiazole alkaloids, sponge alkaloids, iminium alkaloids, diterpene-containing adenine alkaloids, unusual sterols from sponges and briarane-related diterpenoids.

The future of the biopharmaceutical industry holds great promise due to the many compounds that have and will be isolated from marine sources. Marine organisms have long been recognized as a source of novel metabolites with applications in human disease therapy. Particular emphasis has been placed on the invertebrates such as sponges, mollusks, tunicates and bryozoans, but more recently advances in genetics and microbial culture have led to a growing interest in cyanobacteria and marine bacteria. Secondary metabolites, especially drugs, have exerted a major impact on the control of infectious diseases and other medical conditions, and the development of pharmaceutical industry. Their use has contributed to an increase in the average life expectancy in the USA, which increased from 47 years in 1900 to 74 years (in men) and 80 years (in women) in 2000 (Lederberg, 2000). Probably, the most important use of secondary metabolites has been as anti-infective drugs. In 2000, the market for such anti-infectives was US$55 billion and in 2007 it was US$66 billion. Among the anti-infective drugs, antivirals represent more than 20% of the market. Two antivirals that are chemically synthesized today were originally isolated from marine organisms. They are acyclovir (active against the herpes virus by inhibition and inactivation of DNA polymerase) and cytarabine (active against non-Hodgkin's lymphoma). Both compounds are nucleoside analog drugs, originally isolated from sponges (Rayl, 1999).

We consider the impact that natural products will have in the discovery of medicinal and biological agents in the next 50 or so years. Perhaps we can begin our path- way of gratefulness by acknowledging that natural products have provided, and continue to provide, essential materials for shelter, for furniture, for food, for clothing, for writing, for colouring materials, for weapons, for gifts, and for the treatment of numerous diseases (Balick and Cox, 1996). As a great promising source for new natural products which have not been observed from terrestrial microorganisms, marine bacteria are being developed for the discovery of bioactive substances with new types of structure, with growing intensive interest. The achievements have been well reviewed (Blunt et al., 2005), where many new antibiotics were obtained from microorganisms. With drug resistant strains of microbes appearing more frequently the biopharmaceutical industry has to move towards novel molecules in their development of new drugs. The oceans provide us with an opportunity to discover many new compounds, with over 13,000 molecules described already and 3000 of them having active properties. There are problems associated with the development of drugs from marine natural sources including economic, political and conservation issues.

SOCIO-ECONOMIC STATUS

A pharmaceutical company typically supports drug discovery in a number of therapeutic areas to which it is committed for product development. Consideration of the therapeutic target areas is made at the highest corporate levels, and typically involves market economists, clinicians, etc. Scientists experienced in the fundamental aspects of the discovery process are not usually involved. The diseases which are chosen for the development of new therapeutic agents are frequently those for which the company has biological, pharmaceutical and clinical expertise, and the market is already established or is projected to be very large (Kuhlmann, 1997). This is clearly, in part, due to the extraordinary costs ($500±600 million) of bringing a new drug to the market place and the consequent need to recover those costs within the lifetime of the patented material (Cragg, 1997). Thus, some of the diseases which are common therapeutic targets are cancer, heart disease, lung diseases, pain and inflammation, anti-infective agents, anti-HIV agents, diseases of aging and diabetes. While some of these diseases are also important globally, other diseases, including malaria, schistosomiasis, filariasis, diarrhea, hepatitis C and intestinal parasites, are responsible for substantially more deaths worldwide on an annual basis. Diarrhea is, for example, responsible for about five million deaths in infants (<4 years) annually. Regrettably, relatively little drug discovery in these areas is being conducted by the major pharmaceutical corporations at the present time, although a new WHO initiative for malaria may serve as a model for other global diseases. No area of drug discovery has changed more significantly in the past 10 years, as a result of biological and technological innovation, than the rate at which primary screening is being conducted (Demain and Sergio Sanchez, 2009).

Antibiotic Era

Back in 1928, Alexander Fleming began the microbial drug era, when he discovered in a Petri dish seeded with *Staphylococcus aureus* that a compound produced by a mold killed the bacteria. The mold, identified as *Penicillium notatum*, produced an active agent that was named penicillin. Later, penicillin was isolated as a yellow powder and used as a potent antibacterial compound during World War II. By using Fleming's method, other naturally occurring substances, such as chloramphenicol and streptomycin, were isolated. Naturally occurring antibiotics are produced by fermentation, an old technique that can be traced back almost 8000 years, initially for beverages and food production (Balaban and Dell'Acqua, 2005; Vignesh et al., 2011).

Why New Antibiotics be Developed from Marine Sources?

New antibiotics that are active against resistant bacteria are required. Bacteria have lived on the Earth for several billion years. During this time, they encountered in nature a wide range of naturally occurring antibiotics. To survive, bacteria developed antibiotic resistance mechanisms. Therefore, it is not surprising that they have become resistant to most of the natural antimicrobial agents that have been developed over the past 50 years (Katz et al., 2006). This resistance increasingly limits the effectiveness of current antimicrobial drugs.

The problem is not just antibiotic resistance but also multidrug resistance. In 2004, more than 70% of pathogenic bacteria were estimated to be resistant to at least one of the currently available antibiotics (Cragg, and Newman, 2001). The so-called 'superbugs' (organisms that are resistant to most of the clinically used antibiotics) are emerging at a rapid rate. The WHO has predicted that between 2000 and 2020, nearly one billion people will become infected with Mycobacterium tuberculosis (TB) and that this disease will cost the lives of 35 million people. Sexually transmitted diseases have also increased during these decades, especially in young people (aged 15–24 years). The Infectious Disease Society of America (IDSA) reported in 2004 that in US hospitals alone, around two million people acquire bacterial infections each year (http://www.idsociety.org/Content.aspx?id¼4682). *S. aureus* is responsible for half of the hospital-associated infections and takes the lives of approximately 100,000 patients each year in the USA alone (Hancock, 2007).

The human papilloma virus, chlamydia, genital herpes, gonorrhea and HIV/AIDS are examples. HIV/AIDS has infected more than 40 million people in the world. Together with other diseases such as tuberculosis and malaria, HIV/AIDS accounts for over 300 million illnesses and more than five million deaths each year. Additional evolving pathogens include the Ebola virus, which causes the viral hemorrhagic fever syndrome with a resultant mortality rate of 88%. It is estimated that this bacterium causes infection in more than 70,000 patients a year in the USA (Balaban and Dell'Acqua, 2005). In hospitals, there are also other examples of Gram-positive (*Enterococcus* and *Streptococcus*) and Gram-negative pathogens (*Klebsiella*, *Escherichia*, *Enterobacter*, *Serratia*, *Citrobacter*, *Salmonella* and *Pseudomonas*); these hospital-inhabiting microbes are 'nosocomial bacteria.' More than 60% of sepsis cases in hospitals are caused by Gram-n called negative bacteria. Among them, *Pseudomonas aeruginosa* accounts for almost 80% of these opportunistic infections. They represent a serious problem in patients hospitalized with cancer, cystic fibrosis and burns, causing death in 50% of cases. Other infections caused by Pseudomonas species include endocarditis, pneumonia and infections of the urinary tract, central nervous system, wounds, eyes, ears, skin and musculoskeletal system. This bacterium is another example of a natural multidrug-resistant microorganism.

In addition to the antibiotic-resistance problem, new families of anti-infective compounds are needed to enter the marketplace at regular intervals to tackle the new diseases caused by evolving pathogens. At least 30 new diseases emerged in the 1980s and 1990s and they are growing in incidence. Emerging infectious organisms often encounter hosts with no prior exposure to them and thus represent a novel challenge to the host's immune system. Several viruses responsible for human epidemics have made a transition from animal host to humans and are now transmitted from human to human. People with severely weakened immune systems are likely to have more severe and more persistent symptoms than healthy individuals. In the developing world, nearly 90% of the infectious disease deaths are caused by six diseases or disease processes: acute respiratory infections, diarrhea, tuberculosis, HIV, measles and malaria. In both the developing and developed nations, the leading cause of death by a wide margin is acute respiratory disease.

In the developing world, acute respiratory infections are attributed primarily to seven bacteria: *Bordetella pertussis*, *Streptococcus pneumoniae*, *Haemophilus influenzae*, *Staphylococcus aureus*, *Mycoplasma pneumoniae*, *Chlamydophila pneumoniae* and *Chlamydia trachomatis*. In addition, the major viral causes of respiratory infections include respiratory syncytial virus, human parainfluenza viruses 1 and 3, influenza viruses A and B, as well as some adenoviruses. These diseases are highly destructive in economic and social as well as in human terms and cause approximately 17 million deaths per year, and innumerable serious illnesses besides affecting the economic growth, development and prosperity of human societies. Morse (1997) identified six general factors in the emergence of infectious diseases: ecological changes, human demographics and behaviour, international travel, technology and industry, microbial adaptation and change, and breakdown in public health measures.

Marine Natural Products – Nester

The reasons for the strong showing of drug discovery from natural products can be attributed to the diverse structures, intricate carbon skeletons, and the ease that human bodies will accept these molecules with minimal manipulation. With new pressures from the public and governments around the world to develop products to combat diseases and infections commonly encountered, new chemical entities need to be found and developed. In the past, natural products have been a strong source for novel drug products, or have been a model for a drug that has made it to market. It is estimated that over 60% of new chemical entities can be attributed to natural sources either directly or indirectly (Constantino et al., 2004). The current trend within drug development is to find new precursor molecules from synthetic molecules as it is more cost-effective. This is because the techniques used with natural products include complex screening procedures that are time-inefficient and expensive. In addition, a biological response from the mixture containing the compound may not be attributed to the chemical entity in question, but by another substance within the extract interfering with the screening procedure (Kijjoa and Sawangwong, 2004).

The modern pharmaceutical shelves house a variety of compounds; however there are a limited number of products on store shelves that are derived from a marine source. Historically, the first two compounds to make it to market from a marine source are Ara-A (Vidarabine®, Vidarabin®, Thilo®) and Ara-C (Cytarabine, Alexan®, Udicil®) (Patrzykat and Douglas, 2003). These compounds were isolated by Bergmann et al., and are still prescribed today. Ara-A is an anti-viral compound isolated from a sponge; Ara-C is isolated from the same sponge (Cryptotethya crypta) and has anti-leukemic properties. Unfortunately since then marine natural products have not found their way to store shelves with much success. This is because compounds isolated from marine sources have failed to progress to the research stage in the past due to numerous reasons. Natural products are becoming more popular again as marine organisms, both multi- and single-cellular, are an excellent resource with which to find novel chemical entities. Further, many chemical compounds isolated from marine organisms have great potential as antimicrobials or cytotoxic compounds due to the reliance of marine organisms on antimicrobial compounds or cytotoxic molecules as their innate defense mechanisms. There are currently over 3000 new substances identified from marine organisms in the past three decades, giving researchers a large pool of novel molecules from which to find new compounds to develop (Table 1).

Table 1: Bioactive compounds from marine resources

Metabolites/ Compounds	*Sources*	*Application/ Activity*	*Reference*
Bryostatin 1	*Bugula nenitina*	Antibacterial	William Fenical (2006)
ACV 1	Conus victoriae	Antihelmintic	William Fenical (2006)
SS-228 Y	*Chainia* sp.	Antibacterial	Christie et al. (1997)
Keisslone	*Keissleriella* sp.	Antifungal	Isaka et al. (2002)
Artemisinic acid	*Saccharomyces cerevisiae* (Host cell – rDNA process)	Antiparasitic	Martin et al. (2003)
Hypothemycin	*Aigialus parvus*	Antiparasitic	Martin et al. (2003)
Halovirs A-E	*Scytidium* sp.	Antiviral	Feling et al. (2003)
Salinosporamide A	*Salinospora* sp.	Anticancer	Sudek (2007)
Apratoxin A	*Lyngbya majuscule*	Antitumor	Jung et al. (2006)
Tylactone	*Sterptomyces venezuelae*	Antibiotics	Narsinh et al. (2008)

Microbes and invertebrates generally lack an active means of defense, and thus have resulted in developing ‘chemical warfare’ to protect themselves from attack. In addition, many invertebrates (including sponges, tunicates, bivalves, etc.) are filter feeders, resulting in high concentrations of marine viruses and bacteria in their systems. For their survival, potent antiviral and antibacterials had to be developed to combat any opportunistic infectious organisms. It is hoped that many of these chemicals can be used as the basis for future generations of antimicrobials usable in humans.

METABOLITES FROM MARINE SOURCES

Marine organisms comprise approximately half of the total biodiversity on the earth and the marine ecosystem is the greatest source to discover useful therapeutics (Faulkner, 2006). Sessile marine invertebrates such as sponges, bryozoans and tunicates, mostly lacking morphological defense structures have developed the largest number of marine-derived secondary metabolites including some of the most interesting drug candidates (Haefner, 2003). In recent years, a significant number of novel metabolites with potent pharmacological properties have been discovered from the marine organisms. Although there are only few marine-derived products currently in the market, several marine natural products are now in the clinical pipeline, with more undergoing development (Kim et al., 2005). Similar work has been conducted targeting uncultivable microbes of marine sediments and sponges using metagenomic-based techniques to develop recombinant secondary metabolites (Kwon et al., 2006). Natural compounds extracted from marine organisms showed to be exceptionally promising for the treatment of cancer, inflammation and infectious diseases. Marine bacteria make up the largest potential single source of novelty in the world's oceans and of these the major components are the actinobacteria which include the actinomycetes. Actinomycetes are readily isolated from the marine environment and consequently are the best studied of the actinobacteria but the other more difficult to culture members are now being identified using advanced culturing and molecular techniques. Marine actinomycetes produce bioactive molecules and are used as antibiotics, antitumor compounds, immunosuppressants, and others. Consequently, the isolation of new organisms from the environment and their analysis for novel metabolites has been a cornerstone in drug discovery (Fig. 1). Marinomycin A is isolated from marine actinomycetes, which show significant antibacterial activity against methicillin-resistant Staphylococcus aureus and remarkable selectivity for melanoma cell lines in the NCI's 60-cell panel (Feling et al., 2003).

Marine bacteria are emerging as an exciting resource for the discovery of new classes of therapeutics. The promising anticancer clinical candidates salinosporamide A and bryostatin only hint at the incredible wealth of drugs hidden just beneath the ocean surface. Salinosporamide A, which is isolated from marine bacteria, is currently in several phase I clinical trials for the treatment of drug-resistant multiple myelomas and three other types of cancers. For example, if properly developed, marine bacteria could provide the drugs needed to sustain us for the next 100 years in our battle against drug-resistant infectious diseases. Over the past century, the therapeutic use of bacterial natural products such as actinomycin D, daunorubicin, mitomycin, tetracycline and vancomycin has had a profound impact on human health, saving millions of lives.

In the past years (1997–2008), 659 marine bacterial compounds have been described. Except for four compounds from sources with no taxonomic identification, all the compounds isolated between 1997 and 2008 originated from five bacterial phyla: Bacteroidetes (34 compounds), Firmicutes (35), Proteobacteria (78), Cyanobacteria (220) and Actinobacteria (256).

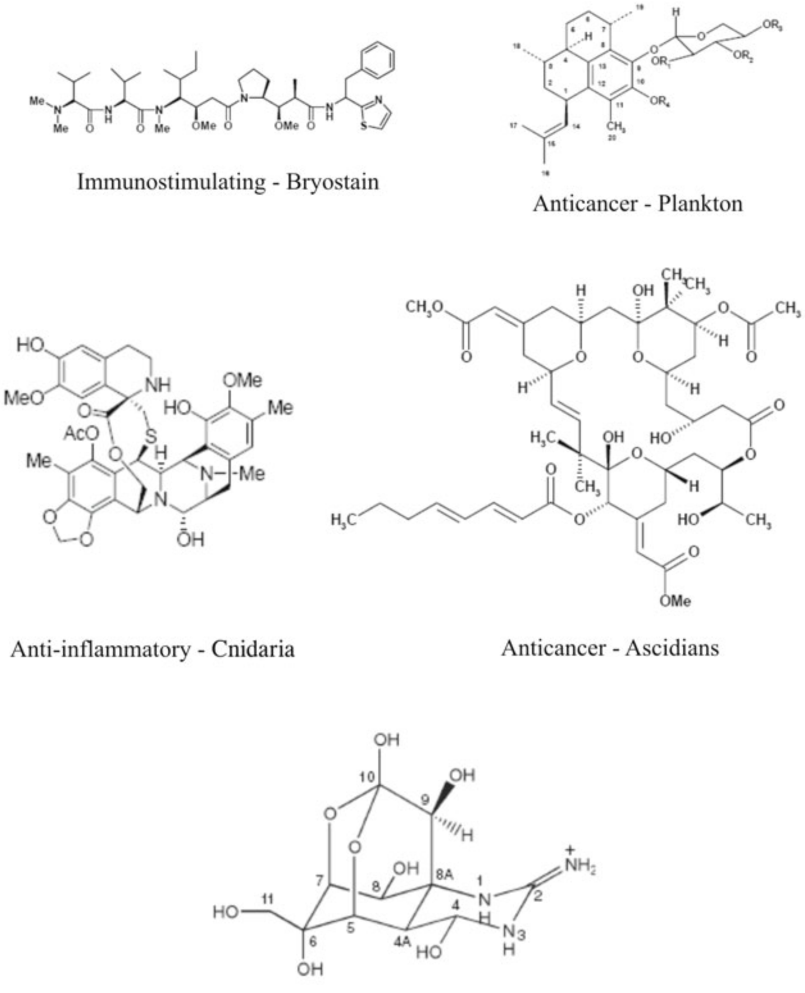

Fig. 1: Chemical structure of natural compounds from marine world.

Cyanobacterial compounds were primarily from the genera Lyngbya or Symploca and 85% of the metabolites from the phyla Actinobacteria were from the genera Streptomyces (57%) or Salinispora (28%). However, there are two differences: cyanobacteria from the marine environment have yielded a greater number of compounds than those from the terrestrial environment. For example, Spirulina is reported to have various beneficial effects including antiviral activity, immunomodulatory effects and a role in modulating metabolic function in humans which could be of value in managing diseases involving lipids and carbohydrates such as diabetes. Furthermore, studies indicate that pretreatment with Spirulina may reduce the toxic side effects observed with some drugs on mammalian organs such as the heart and kidneys (Thayer, 1998).

Marine fungi have proved to be a rich source of bioactive natural products. Most of these micro-organisms grow in a unique and extreme habitat and therefore they have the capability to produce unique and unusual secondary metabolites. To date, more than 272 new compounds have been isolated from the marine fungi and the number of compounds is on the increase (Tziveleka et al., 2003). Marine fungi have proven to be a rich and promising source of novel anticancer, antibacterial, antiplasmodial, anti-inflammatory and antiviral agents (Lam, 2006). Marine fungal-derived compounds such as sargassamide, halimide and avrainvillamide have shown selective inhibition of cancer cell lines, and shown in vivo activity in preclinical models (P-388 lymphocytic leukaemia). According to the World Health Organization (see http://www.who.int/infectious-diseasereport/pages/ch3text.html) 100 million of people in the developing countries are affected by infectious diseases (Sang Yup Lee, 2009).

NEW DRUGS FROM ENGINEERED MICROORGANISMS

Several successful examples of applying metabolic engineering for the development of microbial strains producing drugs and drug precursors have recently been reported. Many chemicals and biological molecules that have been used as drugs are found in microorganisms, plants and animals. As these drugs are synthesized in only minute amounts, it is difficult to obtain them in suitable amounts. This is where metabolic engineering comes into play. Recent advances in our understanding on the metabolic pathways for the synthesis of these drugs together with the development of various genetic and analytical tools have enabled more systematic and rigorous engineering of microorganisms for enhanced drug production (Figs 2 and 3). Drug production by metabolically engineered microorganisms has several advantages over total chemical synthesis or extraction from natural resources.

In Fig. 3, it explains the consideration of which drug is to be produced. Then, the suitable host strain is selected by considering various factors including metabolic characteristics and capabilities to produce the drug of interest, culturability of the host strain and availability of genetic engineering tools. Computational simulation and high-throughput omics analysis facilitate system-wide analysis of metabolic and cellular network, and prediction of the metabolic phenotype at the levels of transcript, protein, metabolite and flux under various conditions. On the basis of the information, actual engineering is performed. Metabolic pathway design and optimization are performed by establishing new pathways, optimizing the existing pathways, and regulatory circuit engineering. Using the developed strain, fermentation and downstream processing are performed to produce the drug. On the basis of the fermentation performance and observations from recovery and purification processes, further metabolic

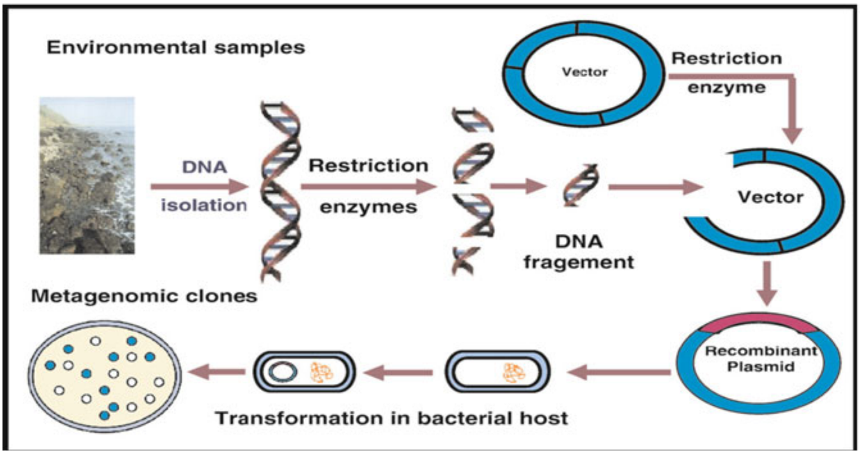

Fig. 2: Common schematic representation of rDNA (recombinant DNA) preparation from marine environmental (microorganisms) samples (Thakur, 2008).

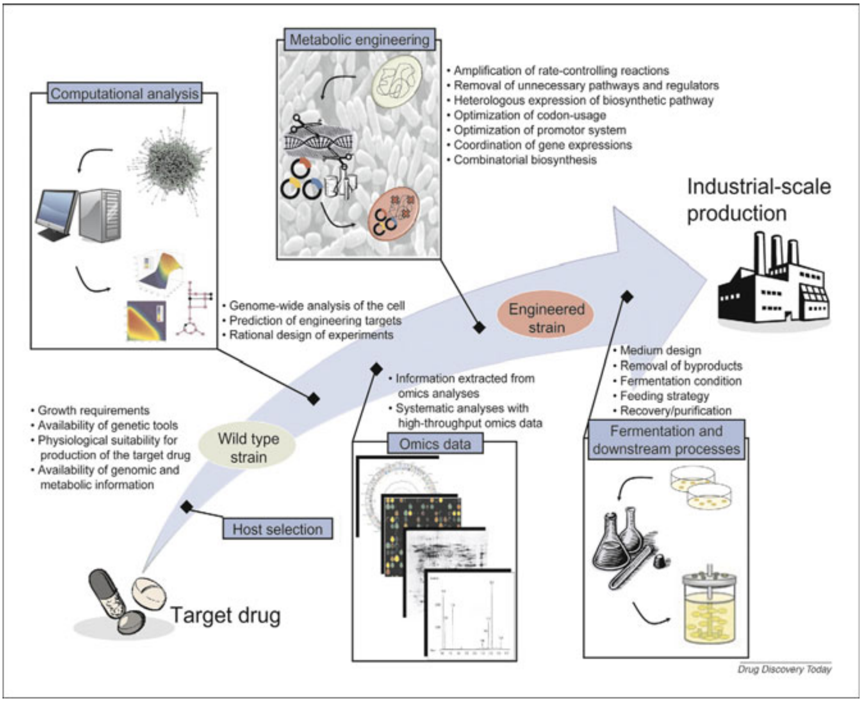

Fig. 3: General strategy for the metabolic engineering of microorganisms for drug production (Nguyen et al., 2006).

engineering can be performed. The final strain developed in this cyclic optimization is used for the industrial production of the drug (Nguyen et al., 2006). Much rapid growth of microbial cells compared with higher organisms is another obvious advantage. Furthermore, metabolic engineering of microorganisms can be performed more easily than mammalian and plant cells, which allows modification of metabolic pathways for the production of structurally more diverse analogs with potent biological activities, as in the cases of polyketides and non-ribosomal peptides (Minami, 2008). Although production of drugs at their final forms may be most desirable, biosynthesis of drug precursors is also favoured experimentally and economically in several cases. High impact of microbial metabolic engineering toward the biosynthesis of drug precursors is well illustrated by the recent development of microbial systems (Zhang, 2004). Various drug molecules can be produced by employing metabolically engineered *S. cerevisiae* with appropriate heterologous genes using the same precursor synthesized by engineered *E. coli.* This is a good example of what metabolic engineering can do for the design and production of drug precursors that are difficult to obtain otherwise. Bacteria are now able to perform glycosylation, an important post-translational modification to make protein drugs be functional, or even produce full-length antibodies (Mazor, 2007).

Metabolic engineering of microbes for the production of artemisinic acid is one of the best examples that show cases the impact of intensive engineering of metabolic pathways on efficient drug production (Martin et al., 2003). Since the advent of recombinant DNA technology, genetic engineering of cells, particularly microorganisms, has been successfully practiced for the development of strains capable of overproducing recombinant proteins and small molecule chemicals. Both findings regarding the biosynthetic capacity of marine Verrucosispora and Salinospora strains demonstrate that marine actinomycetes represent a new and potent source of bioactive secondary metabolites (De Vries and Beart, 1995). A possibility that will result from the determination of the origin of the compound, genetic engineering may be a possibility in the future. We may be able to incorporate the genes that produce the molecules scientists are interested in within plasmids of bacteria that we can easily grow. This would allow us to utilize techniques and facilities that are already proven and established, allowing the pharmaceutical industry access to a constant and predictable supply source.

PROMISING DRUGS ON THE HORIZON

Whilst much research is being carried out on a variety of compounds at this time, there are a few drugs that will be discussed in more detail. These are the drugs that hold the most promise for reaching store shelves as a marketable drug and include, but are not limited to, KRN7000, ET-743, Bryostatin-1 and Ziconotide. KRN7000 is a synthetic derivative of a compound isolated from an Okinawan sponge Agelas mauritianus. It has been observed to raise the level of IL-2, IL-4 and interferon-*g* in mouse models, and its mode of action is by activating the natural killer cells within the human body. ET-743 is one of the most heralded drug discoveries to occur recently, mainly due to its ability to combat cancerous growth from a variety of cell lines, including very high activity against advanced sarcomas that are resistant to most forms of conventional therapy. Ecteinascidin 743 was isolated from the marine tunicate Ecteinascidia turbinate. Bryostatin-1 is another anti-cancer compound and Phase II clinical trials for the treatment of melanoma, non-Hodgkin's lymphoma, renal cancer, and colorectal cancer (Website: http://www.science.fau.edu/drugs.htm).

Problems Facing from Marine Sources

With the potential of so many new compounds to combat bacteria, viruses and debilitating diseases such as alzheimers, osteoporosis and cancer why have marine sources not been thoroughly investigated before? One of the problems faced by the industry is the loss of value of compounds once they are discussed in literature. The disclosure of the compound, which organism it is isolated from, and its structure, devalues it due to pharmaceutical companies losing the advantage of working with it exclusively. Unfortunately, the pharmaceutical industry is very competitive and the economics of not only developing the compound, but the ability of said compound to recoup the investment must be considered. Developing a compound that is public knowledge is a significant risk for any pharmaceutical company. Another economic factor holding back the development of drugs from marine sources is that the majority of molecules are isolated in the laboratories of public institutions and patented. These molecules are again ill received by the pharmaceutical industry due to the poor defensibility of the pharmacological use of the compound. The accessibility of many organisms in their natural environment is also an issue. Many marine organisms are found in remote locations and can require large sums of money just to travel to and from these locations. Additional expenses including the specialized services of divers, submersibles, and the personnel able to carry out these procedures safely and quickly and costs can become quite steep. An example of the prohibitive costs associated with collection of marine organisms is that a ship and submersible costs $14,500 per day (Hale et al., 2002). Marine organisms also pose a problem in regard to culturing large batches; complex nutrient requirements and the lack of facilities large enough to encompass a large scale culture operation have held back the progression of this industry.

Disadvantages

One additional reason for developing new antibiotics is related to their own toxicity. As with other therapeutic agents, the use of antibiotics may also cause side effects in patients. These include mild reactions such as upset stomach, vomiting and diarrhea (cephalosporins, macrolides, penicillins and tetracyclines), rash and other mild and severe allergic reactions (cephalosporins and penicillins), sensitivity to sunlight (tetracyclines), nervousness, tremors and seizures (quinolones). Some side effects are more severe and, depending on the antibiotic, may disrupt the hearing function (aminoglycosides), kidneys (aminoglycosides and polypeptides) or liver (rifampin) (Balaban and Dell'Acqua, 2005).

Recent advances in the isolation and culture of marine bacteria using both flow cytometry and micro encapsulation-based methods have yielded a vast array of previously unknown bacteria. Increasingly, these bacteria are being tested for the presence of bioactive compounds with activities against a diverse range of human and infectious diseases including cancer, HIV, hepatitis C, malaria and those caused by the increasingly drug-resistant common bacterial pathogens (e.g., Staphylococcus aureus, Enterococcus faecalis, Mycobacterium tuberculosis). For example, the antibiotic abyssomicin C has been isolated from an actinomycete which was cultured from marine sediment collected in the Sea of Japan. Abyssomicin has been shown to interfere with the synthesis of the essential cofactor folic acid in bacteria and is active against the methicillin resistant Staphylococcus aureus (MRSA) pathogen. Thus, marine bacteria represent a vast untapped source for novel compounds with the potential for development as novel drugs.

Future Studies of Marine World

The future looks bright for the pharmaceutical industry to develop new drugs from chemical structures isolated from marine sources. As of 2001 over 13,000 compounds, with 3000 of those denoted as being 'active' compounds (those that have exhibited potential pharmaceutical effects), have had their chemical structures determined and documented (Website: http://www.science.fau.edu/drugs.htm). The vast majority of these compounds are being developed in the hopes of treating cancer, tumor growth and leukemia – over 67% of compounds isolated from marine origins have cytotoxic activity (Cragg et al., 2006). Fifty years ago the search for drugs from marine sources was in its infancy, and even though progress has been slow pharmaceutical companies are beginning to embrace the use of natural marine sources. Other industries will have to move forward along with the pharmaceutical companies for this to occur, as a steady supply of investigative material will have to be present. Some positive examples of this are from the bryozoan Bugula neritina as, when chemicals were first isolated from this organism, large quantities were needed and they were collected from the undersides of ships, docksides and any other substrate that it could grow on. Today it is produced commercially by aquaculture (Faulkner, 2002).

In the research being conducted today, we also see a future trend towards marine natural resources as the number of papers reporting total syntheses or synthetic analogues are quite extensive. Partial and formal syntheses of compounds with their origins from marine sources are not documented in review in comparison; thus there are many more lead compounds with their origins from marine natural sources than previously thought (Bourguet-Kondracki and Kornprobst, 2005). Investigators have a large amount of compounds to begin their investigations with, and will provide the basis for future generations of drug products. Anticancer drugs derived from marine sources have not yet been approved for market, yet a significant number are undergoing clinical trials and the future appears to hold a cancer treatment based on a marine natural source. Drugs we can expect to be discovered from marine sources will heavily favour drugs that treat cancer; this is due to the properties of the invertebrate species we isolate these compounds from. Many compounds are isolated from sessile invertebrate species such as sponges and tunicates that live their entire life on a coral reef. As they lack motility to avoid predation or any other negative pressure, they have developed over the millennia chemical defenses. These chemical defenses often produce some common effects: paralysis, cytotoxicity and antimicrobial properties. It is for this reason that the oceans hold the promise of future treatments for diseases and future drugs. Other drugs that have been derived from marine natural sources are antimicrobials, with cephalosporins leading the way. Giuseppe Brotzu, an Italian scientist, discovered cephalosporins in Italy in 1948. He noticed that they inhibited the growth of gram positive bacteria, and after further analysis it was deduced that this was because of its ability to arrest synthesis of the peptidoglycan layer. Its mode of action is similar to that of the penicillins; however it is stable in the presence of β-lactamase. Although it lacked a high activity with the product found naturally in the organism Cephalosporium acremonium, some of the synthetic analogues developed are now used to treat bacterial infections. From Table 1 we can see that products derived from marine sources are used to treat a diverse selection of diseases and maladies.

CONCLUSION

This paper describes marine microorganism role in drug production, recently enabling technologies and natural product compound discoveries in the therapeutic areas of cancer, antibacterials, antivirals, etc. In order for natural product drug discovery to continue to be successful, new and innovative approaches are required. This review illustrates numerous examples of recent discoveries that demonstrate the continuing innovation that can result from natural product drug discovery progress. The pharmaceutical industry has run out of lead compounds from their regular sources, namely terrestrial plants, molds and microbials that are active against current diseases and infections. By determining the structures of novel compounds that are not common to the disease agents encountered daily, hopefully we will develop drugs that do not lose their potency in the near future. Drugs developed from marine sources give us this hope, and also give us novel mechanisms to fight against diseases. This present review article will attempt to link these developments with some global issues, and begin to present a convergent vision of many disparate views of the development of medicinal and biological agents from natural sources.

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16

Phnom Penh Sewer Modelling and Contaminant Load Estimates

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Abstract: A version of the Stormwater Management Model (PCSWMM.NET) was applied to the sewer system of central and south Phnom Penh to model storm event flows. This section of the city is serviced by two main open sewer channels, Trabek and Meanchey, and the surface drainage area for these two channels was divided into 52 sewersheds for modelling purposes. A small (27 mm), medium (76.6 mm, the most representative storm) and large (392 mm, the worst case) storm event was modelled. Model calibration was done through observation of surface flooding locations and velocity measurements in the main sewer channels during the large storm. The model tended to under-predict mean velocity, but at a planning level seems to provide reasonable flow estimates. Storm event contaminant loadings were estimated for the large storm and Cu and Cr loadings were less than, but of the same magnitude, as an entire month of dry weather discharge. The model needs to be further refined by considering certain sewer flow diversions, pumping operations, and linking it to a wetlands model.

Key words: Stormwater management model, combined sewer system, surface flooding, metals loadings, Phnom Penh

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INTRODUCTION

Phnom Penh, the capital of Cambodia, is serviced by a combined sewer system that was constructed primarily during the golden age of King Sihanouk's rule in the 1960s. Years of neglect followed by limited maintenance budgets have resulted in a system with significant maintenance problems (Phyrun, 1996; JICA, 1999). JICA (1999) reported that many sewer lines were filled with sediment (mainly from unpaved streets) and solid waste (generated mainly by the neighbourhood inhabitants), such that flow capacity was reduced by between 50 and 90% of design. While the city has attempted to clear the pipes of the sediment and debris, progress has been slow due to budget constraints.

JICA (1999) noted that data showing the present sewer System's features, such as invert levels, longitudinal gradients, manhole locations, condition of the sewer, etc. were not well documented or registered. Furthermore, JICA (1999) took an understandably simple approach to developing runoff and inundation analyses whereby peak urban storm water flows were estimated using the Rational Method, while pipe diameters for new structures were designed using the Manning equation. JICA (1999) reported that between 1986 and 1998 the population of Phnom Penh grew from 581,000 to about 872,000 (the current population is 1.4 million). During this period the city developed with little planning or control, resulting in flooding problems, informal settlement along drainage ways, increased landfill, and poor urban infrastructure (Molyvann, 2003). Furthermore, it is anticipated that by 2020 the population of the city will be about two million and new construction in the city core and suburbs continues despite the global economic slowdown. It appears that there will be a restructuring of the dense residential areas in the city core, progressive increase in density of the existing suburbs, as well as an expansion of the suburbs and industry (Phnom Penh Municipality, 2005; Englund and Ryttar, 2008). Traditionally, wetlands adjacent to the city have been used as natural wastewater treatment systems for the city, but these wetlands also are under the development process. Development puts more pressure on the drainage and wastewater treatment systems, in particular, during the wet season.

In order to plan for effective urban development, including sustainable wastewater treatment, it is necessary to characterize sewer flow and contaminant loads. Therefore, the objectives of this research are to: (1) establish digital information layers in ArcGIS9.3 to characterize the sewer system of south central Phnom Penh as a prototype for the rest of the city and other urban areas in Cambodia; and (2) apply PCSWMM.NET to estimate the flow rates and contamination loading to the Boeng Cheung Ek treatment wetland from the sewers of south central Phnom Penh.

The intent of this study is to develop analytical tools that can assist or inform urban planners, engineers and water resource experts in making decisions regarding sustainable wastewater treatment and the impact of urban development on wastewater treatment in Phnom Penh. Application of dynamic, graphically-oriented models for sewer analysis and design are not as common in Southeast Asia as in the west (Chaosakul et al., 2009). The proposed modelling approaches for this study (in combination with GIS-based land use assessment) will provide the capability of evaluating different development scenarios and the impact on hydraulic capacity, flooding, contaminant loads, and risk of exposure to water-borne diseases. Furthermore, the Stormwater Management Model can be used to assist with the design work needed for system improvement.

RESEARCH METHODOLOGY

Data Collection

Primary data collection was done from July 2007 through December 2008. The primary objectives of these efforts were to verify the existing flow direction and diameter of sewers, to geocode the manholes and surface inlets using GPS, and to measure the surface and sewer pipe slope using standard surveying methods. Additionally, flow measurement during storm events was done for the sake of model calibration.

Tipping bucket rain gauges were installed at three locations (Royal University of Phnom Penh (RUPP), Mennonite Central Committee (MCC) office and east Phnom Penh (near the waterfront) to record all rainfall for the period from May to December 2008 (Fig. 1). The rainfall data were further analyzed to choose the most suitable events for input to PCSWMM.NET.

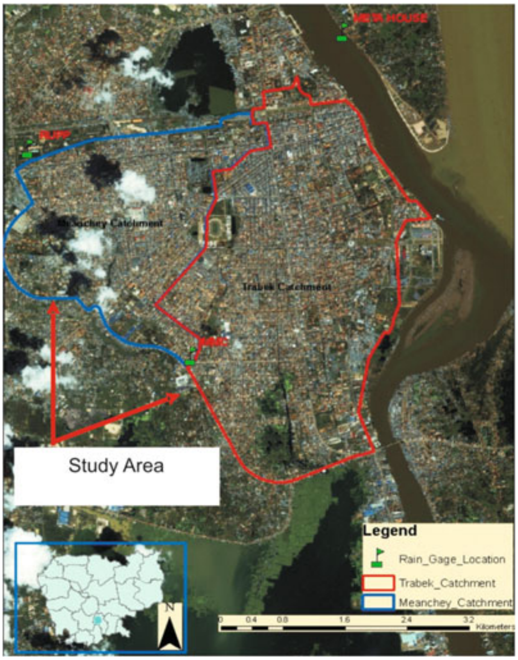

Fig. 1: Study area, including rain gauge locations.

Secondary data were obtained from various institutions, agencies, and ministries as well as the literature (e.g. James et al., 2005). The existing catchments and drainage network categorized by the Department of Public Work and Transport (2007), and the sewer modelling report from the Municipality of Phnom Penh (2004) were collected and used as the baseline information for data processing.

Data Processing

The surface runoff from each sewershed is routed to a single point within the sewershed. To estimate the surface flow rate, the existing catchments (Boeng Salang (Meanchey) and Trabek, Fig. 1) were further subdivided into smaller sub-catchments by directly digitizing boundaries on Ikonos satellite images (1 m resolution). Through the combination of the findings from the field work, the satellite imagery, and ArcGIS9.3, several parameters were quantified including subcatchment area, width, pervious and impervious area. Sewer lines for the model input were drawn based on the existing sewer network lines. Additionally, the rainfall data from MCC were adopted for the data input preparation for the model since this location seemed to provide the most reliable results.

Model Operation and Calibration

PCSWMM.NET was applied to predict the overall picture of flooding and flow rate for the selected catchments. The output from each sub-catchment (sewershed) became the input for the modelled sewer pipe or channel. In addition to this, three different storm events (small, medium and large) were selected and run with the model.

The flow velocities measured at various locations in the sewers were applied for model calibration to ensure that the model produced reliable outputs. Field observation (location of surface flooding) during heavy rain also was used an indicator for this purpose. This required the field teams to travel through the city by moto during rain events to record time and location of surface flooding.

Contaminant Loading Estimation

The mean concentrations of five parameters (Cu, Cr, nitrate, Zn and total phosphorus) reported by Yim et al. (2008) were selected for the estimation of contaminant load. The total flow volume (Q) was determined from the model's output itself. The calculation of contaminant loading at the end point of each channel was estimated using a simple volumetric approach which is frequently used in sewer studies (e.g. Marsalek and Ng, 1989; Marsalek, 1990; Irvine et al., 1993, 1998, 2005). The equation is given as $L = Q \times C$, where L is contaminant mass load (mg), Q is total flow volume for the period of concern (L) and C is contaminant concentration (mg/L).

RESULTS AND DISCUSSION

Sub-Catchment Identification

Sub-catchment identification was one of the most difficult tasks to complete and needed to be assessed carefully to optimize calibration effort and accuracy of model output. A total of 52 sub-catchments (sewersheds) were digitized for both Meanchey and Trabek catchments (Fig. 2). It was concluded that this number of sub-catchments provided enough detail to adequately characterize the variable surface types of the different neighbourhoods and not be too numerous to be onerous for calibration.

The two main sewer lines identified for modeling were the Meanchey and Trabek open sewer channels. Each modelled sewer line was combined by a series of connected pipes and nodes in the sub-catchments where nodes were identified depending upon the flow direction of water. The endpoints of the model were defined as C50 (Meanchey) and C56 (Trabek), both at locations near the pump stations. Pump station operation was not modelled in this study, but should be included in future work.

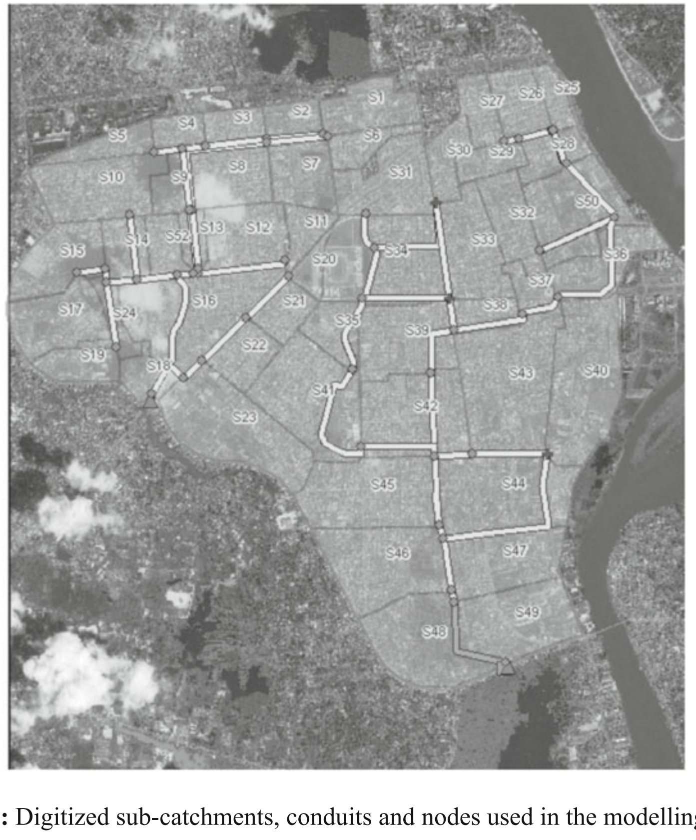

Fig. 2: Digitized sub-catchments, conduits and nodes used in the modelling effort.

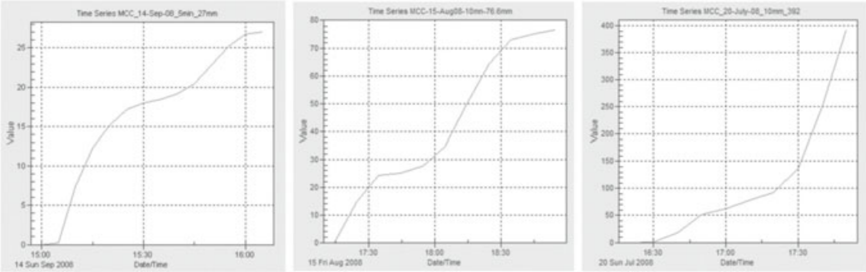

Fig. 3: Selected rainfall events (mm) used for model input with small storm (left), medium storm (middle) and large storm (right).

Storm Events

Three storm events, hereafter denoted as the small, medium and large storms, were processed for the model operation (Fig. 3). The selection of different levels of rainfall was done to predict and visualize the different level of flow rate and flooding associated with the given storm event. The largest rainfall on 20th July, 2008 reached 392 mm (it was a worst case for the city) over a period of one hour and half, whereas the medium rainfall was on 15th August, 2008 and had a depth of 76.6 mm over a three-hour precipitation time. The small event had a total rainfall depth of 27 mm over a period of one hour and occurred on 14th September 2008. A probability analysis of daily rainfall from the Phnom Penh International Airport (2001-2005) showed the data to be well represented by the Inverse Gaussian distribution and that the probabilities of exceedance for the small, medium, and large storms were 10%, 2.8% and 0.0002%, respectively.

MODEL RESULTS

Surface Run-off

The greatest peak run-off for all sub-catchments occurred at sub-catchment S43 reaching 183.3 m^3/s, 16.6 m^3/s, and 1.8 m^3/s for the simulation of the large, medium and small storm events, respectively. The lowest peak runoff for all sub-catchments was estimated for subcatchment S13 at values of 10.8 m^3/s, 1.10 m^3/s, and 0.21 m^3/s for the large, medium and small storm events, respectively. A complete result from the model simulation for peak run-off is illustrated in Fig. 4. The results from the model show that the sub-catchments (for instance, S39, S41, S43 and S44) having a larger area and greater width resulting in higher run-off rates.

Flooding Level and Duration

The maximum flooding overflows (surface flooding) for the sub-catchments are presented in Fig. 5. The level of flooding varied from one junction to another

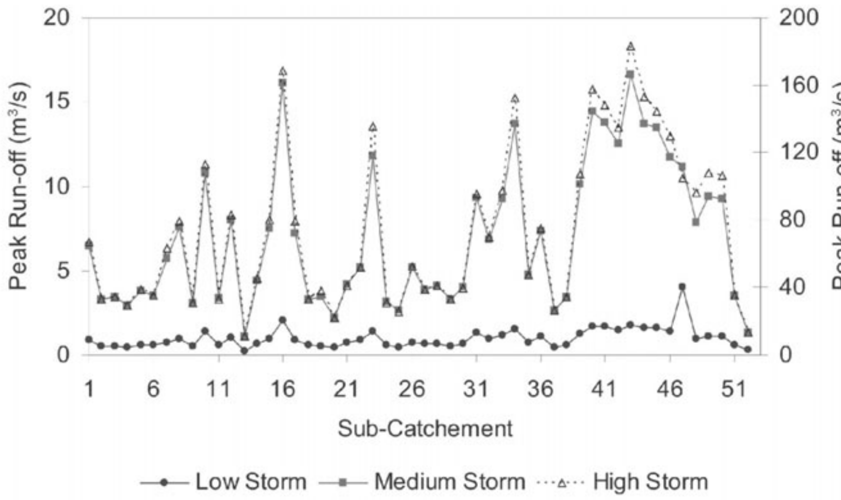

Fig. 4: Peak run-off from sub-catchments for the three different sized storm events. The low (small) and medium storm run-off rates correspond to the left y-axis and the high (large) storm run-off rates correspond to the right y-axis.

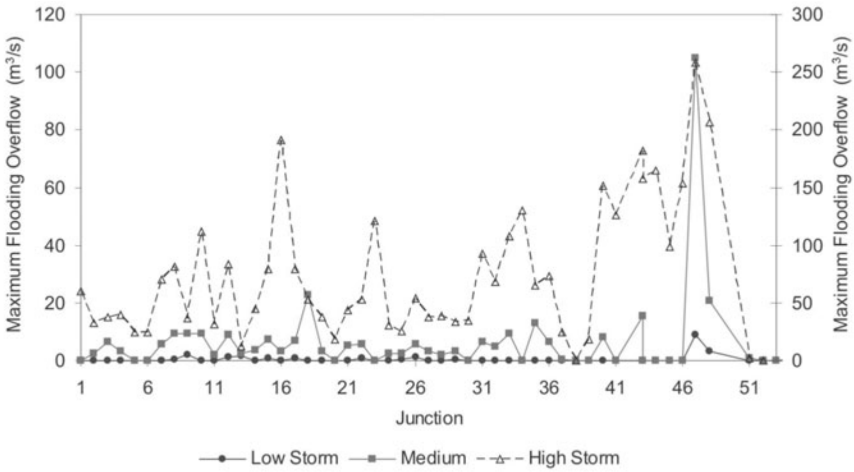

Fig. 5: Maximum flooding overflow (surface flooding) for the three different sized storm events.

due to the properties of the nodes and the maximum peak flooding overflow at J47 was estimated as 266.45 m^3/s, 104.94 m^3/s, and 9 m^3/s, resulting from the simulation of the large, medium and small storms, respectively.

The flooding duration for each junction also was computed by the model. The average flooding duration for the large, medium and small storms were 87, 46, and 9 minutes, respectively (Fig. 6). Examples of floods occurring during the large storm are illustrated in Fig. 7. There are several points to be discussed in this section since there were some junctions that the model

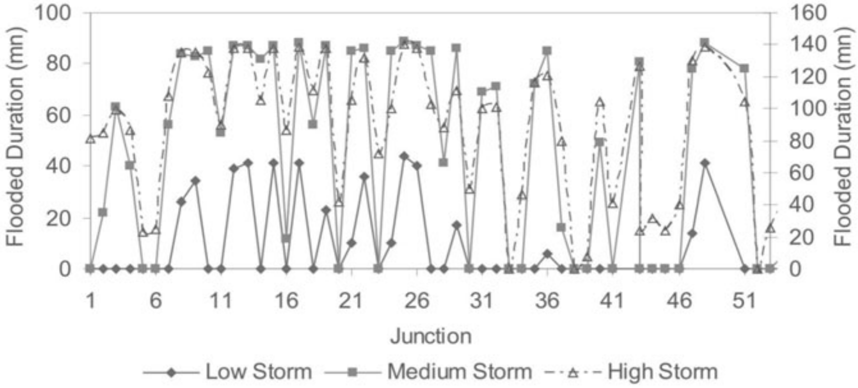

Fig. 6: Flooding duration for the three different sized storm events. The low (small) and medium storm flooding durations correspond to the left y-axis and the high (large) storm flooding durations correspond to the right y-axis.

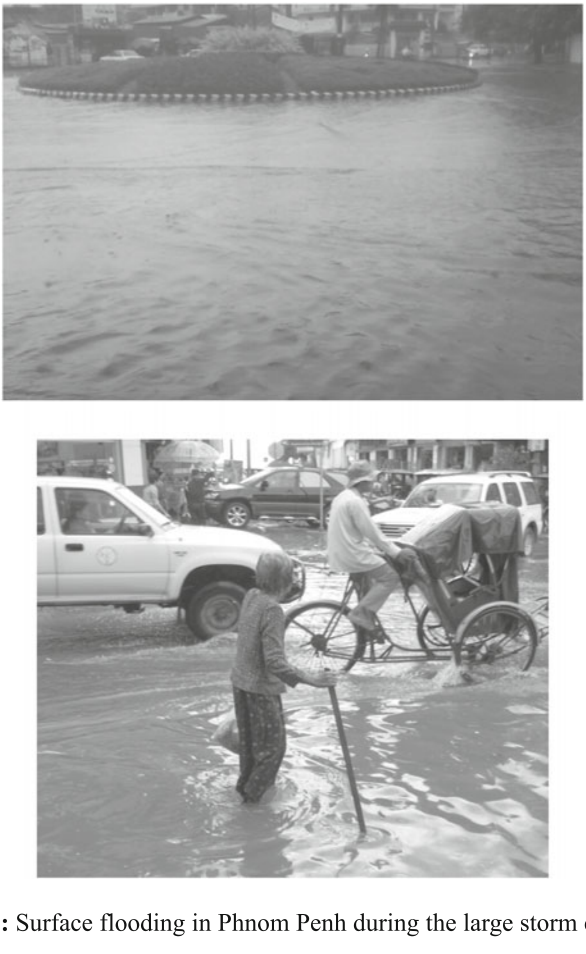

Fig. 7: Surface flooding in Phnom Penh during the large storm event.

suggested were experiencing flooding overflow even though in reality this did not happen, and other junctions for which flooding was predicted, but not at the magnitude observed. The possible factors contributing to model error are: (1) the diversion of flow along the modelled sewer lines was not considered at some locations, although it may occur; (2) the impact of sediment accumulation is unknown; (3) pumping activities at Trabek and Meanchey outlets were excluded; (4) the informal water releasing practices to the natural ponds and reservoirs nearby were not taken into account; and (5) possible inaccurate representation of diameter of sewer pipe.

MODEL EVALUATION

It is important to evaluate model output to ensure that the model is producing a logical, reliable and acceptable output. For this project, in addition to observed surface flooding patterns, it was possible to compare the measured flow velocity with the modelled velocity at a limited number of locations. The flow velocity measurements recorded at Trabek Up (C37) and Trabek Down (C56) during the storm event on 21st July, 2007 were selected for the calibration (Table 1). The comparison in Table 1 indicated that the velocity from the model is lower than the actual measurement. The discrepancy between measured and modelling results may be due, in particular, because the pump station operation was not modelled. Pump capacity for the Tumpun (Meanchey) pump station is 15 m^3/s and 8 m^3/s at the Trabek pump station.

Based on the comparisons between observed and modelled surface flooding patterns and measured and modelled flow velocity it can be concluded that the results from model simulation were acceptable andreasonable at a planning level. Therefore, the outputs fromthe model can be used as a tool or baseline for urbanplanners, decision-makers and other concerned agenciesin assessing future drainage and sewage treatmentoptions.

Table 1: Comparison between actual and modelled flow velocity

Conduit's Location	*Actual Flow Velocity (m/s)*	*Modelled Flow Velocity (m/s)*	*Differences (%)*
Trabek Up (C37)	5.9	4.6	22
Trabek Down (C56)	10.5	8.35	20.5

CONTAMINANT LOAD ESTIMATION

The contaminant load estimation at Trabek Down (C56) and Meanchey Up (C50) sites were computed based on the available concentration data obtained from Yim et al. (2008). The contaminant loading estimation is summarized in Table 2. The nutrient concentrations at the Meanchey Up (C50) site generally were higher than at the Trabek Down (C56) site during storm events, which resulted in higher loading rates (Table 2). It also is interesting to note that the Cr and Cu loadings at the Trabek Down site (Table 2) were less, but of a similar magnitude, as the dry weather flow loadings of an entire month reported by Visoth et al. (2010). The nitrate and total phosphorus loadings from the large event are much less than the monthly dry weather flow loadings reported by Visoth et al. (2010) (8-13% of the monthly loading), primarily because of concentration dilution for the storm (Yim et al., 2008).

Table 2: Contamination mass loading (kg)

	Mass Loading (kg)				
Location	*Cr*	*Cu*	*Zn*	*Nitrate*	*Total Phosphorous*
Meanchey Up	16.57	104.02	133.99	2,327.29	881.55
Trabek Down	16.44	115.67	3,572.10	1,190.70	623.70

CONCLUSIONS AND RECOMMENDATIONS

PCSWMM.NET was successfully applied to provide planning level estimates of urban runoff and combined sewer flows, together with contaminant loadings, for central and south Phnom Penh, Cambodia. The model has good potential for use as a decision-making tool in urban drainage design work, as well as to assess sustainable sanitation options to support future development of the city. Rivard et al. (2006) note that stormwater management in tropical countries poses some specific challenges not encountered in temperate climates, particularly in relation to rainfall data, surface flooding, debris and sediment, and design criteria. They caution that urban stormwater control measures for tropical countries must consider region-specific issues that prevent the direct use of approaches routinely used in temperate climates. This issue can be seen particularly with respect to surface flooding in Phnom Penh. As such, it will be important to refine the PCSWMM.NET model in the future, through collection of additional rainfall, runoff, and pollutant data. The operation of the major pump stations also needs to be included in the future. Nonetheless, this was a good first step in establishing urban stormwater modelling principles in Cambodia. Future modelling efforts also must extend to include technical training workshops for government line agencies and dissemination of results to the public.

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Index

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