Building with Nature

EcoShape

Background risk of water quality (nutrients and contaminants) for local ecosystems of Singapore

Environmental risk assessment in case Singapore

EcoShape – Building with Nature

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Summary

The marine ecosystems of Singapore are challenged by pressures resulting from a large number of human activities such as land reclamation works and related dredging. Around Singapore, marine ecosystems as seagrass meadows, coral reefs and mangroves are in decline which could be the result of altered sedimentation and turbidity within the coastal waters.

Ecodynamic building measures taken in Singapore are aimed to improve the status of ecosystem elements by contributing to the maximisation of the local potential of ecosystems. Furthermore, water quality of the marine waters around Singapore is the key factor to the health of the ecosystem elements. However, poor water quality might restrict the recovery or potential of these ecosystem elements, and hamper the effectiveness of ecodynamic building measures. The role of the actual water quality of Singapore in ecosystem performance is thus important to be discussed in order to place measures as "Building with Nature" in context. Water quality factors considered in this report are contamination and nutrient status.

The DPSIR methodology was used to designate the most relevant linkages between activities and impact on the ecosystem through water quality aspects. The DPSIR framework is a more extensive methodology by assuming a chain of causal links between Driving forces and the resulting environmental Pressures, on the State of the environment, the Impacts from changes in environmental quality and the societal Responses to these changes. DSPIR is commonly used by the European Environment Agency in the execution of integrated environmental risk assessment studies. The framework helps to design an environmental assessment and to identify indicators, and to communicate results. We used the DPSIR framework to structure information on water quality for each aspect of the framework by structuring the information via DPSI elements in corresponding chapters.

Drivers in Singapore affecting water quality can be both shore and offshore based. Land based activities responsible for nutrient emissions are e.g. sewage treatment plants, but indirect emissions from agriculture activities via the run off of rivers of both Singapore and Malaysia are important to consider. Aquaculture and shipping are the main activities for nutrient emissions offshore. The input of contaminants to the environment relates to many activities, and depending on the compound specific activities can be addressed. An overview is provided in chapter 2.

Information on pressures, thus the actual emissions to the environment per activity, was limited and a comprehensive overview could not be provided.
State information, considering the actual concentrations of nutrients and contaminants, is limited to studies describing data collected 8-10 years ago. Studies on contamination are relatively young and stand alone, and consequently no historical trends could be deduced. Concentrations of nutrients and various contaminants as heavy metals, alkylphenols, PAHs, PCBs and some pesticides are reported. Most reported studies were performed in 2000-2006 and therefor it should be noted that actual water quality can be different from reported water quality.

Actual and local impact information was limited. Nutrient influxes may stimulate primary production that in turn may lead to an increase in phytoplankton biomass and sustain elevated levels of phytoplankton standing crop. Further nutrient increase can lead to the formation of Harmful Algal Blooms (HABs) and oxygen depletion. These observations are however mainly restricted to coastal waters of Singapore. There is a strong variation in effect of nutrient enrichment on coral reefs. A wide range of nutrient impacts has been reported in literature, from little or no impacts to major changes in coral reef community structure. Complex local factors often determine the magnitude and extent of the impacts of

nutrient enrichment. Local information on the impact of nutrient enrichment on seagrasses and mangroves in Singapore were not found in literature.

Toxicity effects have been observed in the marine environment of Singapore which could be attributed to different contaminants, such as heavy metals, petroleum compounds and organotin compounds. Phytoplankton was inhibited by the background concentrations of heavy metals that were biologically available from the sediments resuspended by dredging. Total petroleum hydrocarbons were significantly negatively correlated with species number, abundance and diversity, suggesting harmful effects from petroleum hydrocarbons on macrobenthic communities in Singaporean waters. Inhibition of phytoplankton was reported as well. Imposex in snail species (the masculinization of females of certain marine snails in response of the exposure to TBT) has been observed as a localized effect from the presence of organotins at Johor Straits. An overview of general impact indicators is provided in this report.

Due to the limited local available information on the impacts of water quality aspects, additional evaluations were performed. Interviews with local experts were held, and an environmental risk assessment for both nutrient state and contaminant state was carried out.

The overall consensus among the interviewed experts was that in general turbidity and sedimentation are the most important factors influencing coral reefs and sea grass meadows viability. Mangrove forests decline as a result from a unbalance of fine sediments; input is lower than outflow. Water quality issues (nutrients, heavy metals and other toxic compounds) are considered less important but it was emphasized that an overview of concentrations of pollutants and their effects is lacking and conclusions cannot easily be made. Water quality is monitored in Singapore by agencies (e.g. National Environmental Agency) and institutes (e.g. TMSI has been monitoring over a long time span) but given confidentiality these data are not publically available. This corresponds with our experience in gathering data.

The evaluation of the risk caused by nutrients enrichment in Singapore marine environments was performed using two approaches- ASSETS and OSPAR. Both assessments were strongly hampered due to limited data availability.
It was concluded that for the entire Johor Strait the susceptibility for eutrophication remains high. Even with projected changes in agricultural and population pressures and improved sewage treatment the overall eutrophication status is expected to only slowly improve. In contrast the Singapore Strait is likely to worsen according to the analyses. Although susceptibility is much lower for this region (due to size and stronger currents that will strongly dilute inflow of nutrients), a relative increase in nutrients originating from a much larger region and numerous river systems is to be expected. This may increase the impact of eutrophication. Only when the pressures (over a much wider area than the Singapore region alone) are reduced and natural biological communities recover the situation may improve.

The evaluation of the impact of contaminants is performed using the PEC/PNEC approach. This methodology is commonly used as a first tier in ecotoxicological studies. Based on this first tier environmental risk assessment it is concluded that the marine environment of Singapore faces a high risk to be affected by water quality as reported in various scientific references. Especially the alkylphenol concentrations are of serious concern as calculated risk factors are extremely high. No risk of heavy metals is to be expected, and PAHs are of minor concern. TBT risk factors are high, but due to the ban on TBT containing paints, this risk will phase out with time.

Most data used in the evaluation are based on short term monitoring periods. These studies are usually stand alone and do not relate to incentives for long term monitoring. Furthermore, most studies are performed within the last decade. This indicates that trend analysis on the presence of contaminants and nutrients in the coastal surroundings of Singapore cannot be performed. Therefore no indication on future concentrations or translocations across compartments can be given based on chemical history. In the absence of specific preventative measures, an increase in intensity of human activities in and around Singapore may result in an increased influx of chemicals. As a result of this increased influx persistent compounds may accumulate to higher levels in ecosystem components.

The risk of misinterpretation of the causes of direct and indirect effects is substantially reduced when all categories (emissions of contaminants, nutrient enrichment, concentrations in the environment, direct effects, and indirect effects) as well as supporting environmental information are monitored and assessed together.
The availability of studies reporting both pressure and impact is very limited for the Singapore marine environment. Based on the results from this report it seems highly recommendable to invest in such environmental research. Monitoring of both contaminants and nutrients related issues should be performed in a coherent way, to reflect the cause/effect relationships.

Concerning the DPSIR framework, we have not addressed the Response element in this report. The Response element deals with questions such as "What are we doing about it, or what can be done about it?" and reflects the societal and political response to the previous element in the framework. In our opinion the DPSIR framework is only a useful instrument if all aspects of the framework can be analysed and discussed implying data is available. The limited availability of data on pressures and impacts does not give an overview of all relevant pressures, states and impacts of water quality aspects in Singapore. The societal response to the issue of water quality aspects towards better regulation is herewith hampered.

In the scope of Building with Nature programs, the lack of data on water quality issues is a concern as well. Measures taken in the scope of Building with Nature aiming at positive effects on the environment may be hampered by low water quality such that the desired effect of the measures taken is not reached. In order to fully exploit the potential of "Building with Nature" measures it can be beneficial to consult governmental departments and other economic sectors involved in water quality issues, to raise awareness and to combine efforts aiming at investigating and improving water quality and thus better ecosystem performance.

Contents

1 Introduction

1.1 General introduction

The marine ecosystems of Singapore are challenged by pressures resulting from a large number and high intensity of human activities. Around Singapore, marine ecosystems as seagrass meadows, coral reefs and mangroves are in decline (Chou, 2006; Hamid et al. 2009; Chou and Tun, 2007; Ng & Sivasothi 1999). In general this decline is considered in the context of land reclamation works and related activities such as dredging, which alter sedimentation and turbidity within the coastal waters of Singapore and strongly impact the above mentioned ecosystems.

Ecodynamic building is currently a topic of large research programmes, such as Building with Nature (see Box 1). These programmes aim to minimise negative effects of construction and maintenance works at sea, and to move forward to design approaches and designs that target the maximisation of system potential.

Box 1 Building with Nature programme

Building with Nature is geared towards the next step in hydraulic engineering: moving away from defensive design approaches with the aim of minimising negative effects and moving forward to design approaches and designs that target the maximisation of system potential.
As we learn to understand the dynamics of nature better, we can expand potential for integrating nature in the development and design process. With new insights and knowledge, nature itself becomes the driving force behind the sustainable development of hydraulic engineering infrastructure.

The Building with Nature programme started in 2008 with activities that were essential to launch the various programme components. Different case studies were selected of which the "Singapore case" is one. Within the Singapore case various studies are performed. This report describes the findings of Singapore project *1.3 Environmental risk assessment in case Singapore- Background risk of water quality and other human activities*

More information about the programme can be found at www.ecoshape.nl

Ecodynamic building measures improve the status the ecosystem elements and this contributes to the maximisation of the local potential of the ecosystem. However, other limiting factors might still restrict the recovery or potential of these ecosystems. Other limiting factors to consider are e.g. water quality aspects such as contamination and nutrient status.

Marine water quality of Singapore is a key factor to the health of the ecosystem elements. Activities affecting water quality, might potentially impact marine ecosystems, and are therefore important to identify. The role of the actual marine water quality of Singapore in ecosystem performance is thus important to be discussed in order to place measures as "Building with Nature" in context.

1.2 Scope and objective

The aim of this study was to assess the present impact of water quality as a consequence of human activities on local coastal ecosystems in order to assess its relevance in relation to marine infrastructure developments as reclamation and associated dredging.

Within the Building with Nature programme – Singapore case- other projects focus on the relevance of reclamation works and sedimentation, and thus specific impacts of sedimentation and related aspects will therefore not be evaluated in this report.

Water quality aspects in this report are delimited to chemical water quality as human induced contamination and nutrients. Sources of contamination and nutrients from neighbouring countries are outside the scope of this study, i.e. only activities and related pressures from Singapore are included. The impact is delimited to Singapore's ecosystems: coral reefs, seagrasses, and mangroves.

1.3 Methodology

The relevance of water quality aspects towards the health of marine ecosystems in Singapore is discussed using different approaches.

1.3.1 DPSIR

We use the DPSIR methodology to designate the most relevant linkages between activities and impact on the ecosystem.

The DPSIR (Driving Forces-Pressures-State-Impacts-Responses) framework is derived from the pressure-state-response framework as developed by The organisation for Economic Cooperation and Development (OECD), offering a structuring methodology for the analysis of biodiversity loss. The DPSIR framework is a more extensive methodology by assuming a chain of causal links between Driving forces and the resulting environmental Pressures, on the State of the environment, the Impacts and on the societal Responses resulting from these changes in the environment. DSPIR is commonly used by the European Environment Agency in the execution of integrated environmental risk assessment studies.

The DPSIR framework can be used to structure the linkages between environment and socio economic activities. The framework helps to design an environmental assessment and to identify indicators, and to communicate results. This framework has been widely adopted by e.g. the European Environment Agency to integrate socio economic and ecological processes to understand the forces that drive patterns of ecosystem changes. In Figure 1 the framework is visualized. In Table 1 the definitions of DPSIR are explained. This approach has proven to provide an excellent basis for identifying the main activities (drivers), pressures, state descriptors and impacts and visualizing causal chains. It provides a conceptual model that helps to gain an overview of the problem.

In this report the DPSIR is used to structure information on water quality for each aspect of the framework by structuring the information via DPSI elements in corresponding chapters.

A literature review of relevant papers found in scientific databases was performed to retrieve information on all aspects. A general internet search was performed on Singapore websites from e.g. ministries, companies, country profiles. Besides the descriptions on DPSI elements in corresponding chapters, an overview of references is provided in ANNEX 1. In this table, Drivers, Pressures, States and/or Impacts are identified in literature related to Singapore. In the Annex, a distinction is made between assumed relations between the elements and studied relations between the elements. It is clear from this overview that hardly any research is reported on causal relationships between DPSI elements.

Table 1 Definition of DPSIR elements

D=	*Driving forces*: the socio-economic and socio-cultural forces driving human activities, which increase or mitigate pressures on the environment. In this report human activities are taken into account as Drivers.
P=	*Pressures*, the stresses that human activities place on the environment, such as pollutant emissions.
S=	*State*, or state of the environment, the condition of the environment.
I=	*Impacts*, the effects of environmental degradation, e.g. biodiversity loss (relative to a previous State).
R=	*Responses*, refers to the responses by society to the environmental situation, e.g cleaner production

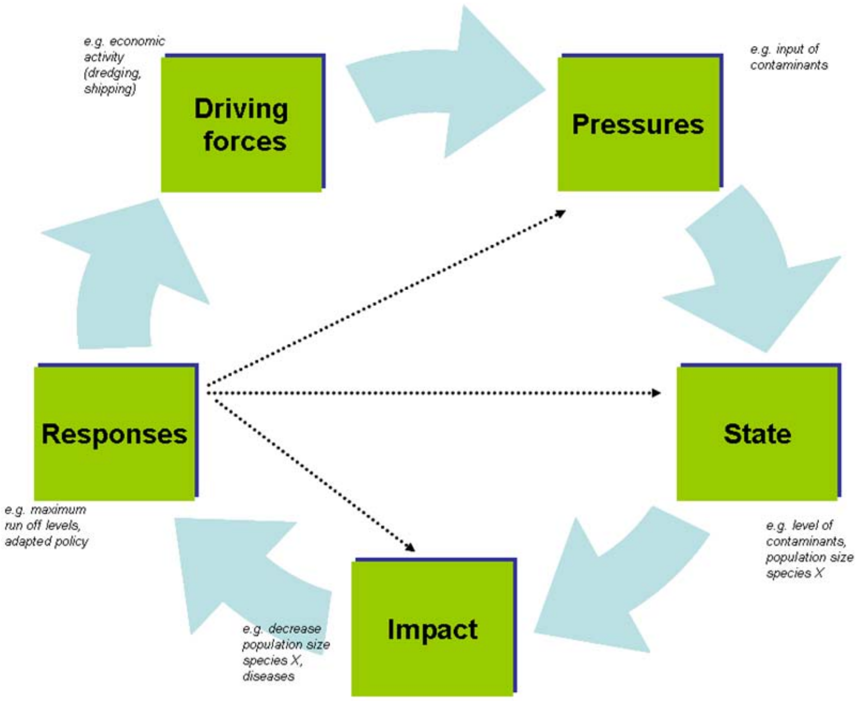


Figure 1 DPSIR framework

The response (R) part of the DPSIR approach has not be taken into account in this report. The focus is on the linkages between activities and ecology, not on the response from society or policy. In this report DPSIR is used a tool to organize the various aspects around water quality.

1.3.2 Nutrients

To assess the impact of nutrients in the marine environment of Singapore, we described and applied both the integrated methodologies for the Assessment of Estuarine Trophic Status (ASSETS) of the United States National Estuarine Eutrophication Assessment (NEEA), (see Bricker et al., 1999) and the OSPAR Comprehensive procedure (OSPAR, 2001 and 2003).

These methodologies can be applied comparatively to rank the eutrophication status of several Singaporean estuaries and coastal areas based on available information, and to address management options. Both the approaches may include quantitative and semi-quantitative components, and use field data, models and expert knowledge on the Pressure-State-Response (PSR) indicators.

1.3.3 PEC/PNEC

The evaluation of impact of contaminants is performed using the PEC/PNEC approach. This methodology is commonly used as a first tier in ecotoxicological studies.
PEC/PNEC represents a ratio between the Predicted No Effect Concentration (PNEC) that is, the concentration that causes no adverse effect to the Environment, and the Predicted Environmental Concentration (PEC)--which is the concentration one expects to find in the environment.
If the ratio is larger than 1, a risk to the environment cannot be excluded.

This approach is used to evaluate the risk of impacts caused by different types of contaminants (Heavy metals, PCBs, PAHs, Alkylphenols) on the ecosystems in Singapore waters.

1.3.4 Interviews

In February 2010 interviews were held with researchers of the National University of Singapore (Prof. Chou Loke Ming, Dr Peter Todd, Dr James Guests, Dr Tedd Web, Dr Dan Friess, Jani Tanzil, Siti Maryam) and TMSI (Dr Sin Tsai Min, Dr Pavel Tkalich). The interviewed researchers are active in the field of water quality or coral reef-, mangrove- and sea grass ecology.
The aim of the interviews was to gain insight in whether water quality (e.g. nutrients, heavy metals and other toxic compounds) is seen as an important factor influencing the three marine ecosystems coral reefs, sea grass beds and mangroves. Furthermore we were interested to gain insight in the causes of decline in these ecosystems, and their protection in Singapore.

Interview summaries were written down and reviewed by the corresponding experts. Feedback to the summaries were incorporated in the summaries as provided in this report.

1.4 Reading guide

In this report the DPSIR framework is used to structure information on water quality for each aspect of the framework by structuring the information via DPSI elements in corresponding chapters. In Chapter 2 an overview of relevant drivers (activities) influencing water quality in Singapore is given. Note that only activities in Singapore are included. Chapter 3 provides an overview of pressures in Singapore, chapter 4 an overview of states. Chapter 5 provides an overview of environmental impact in Singapore.

Furthermore, a summary on the interviews is provided in chapter 6. Risk evaluations of nutrient and contaminant levels are described in chapter 7 and 8.

Discussion and conclusions of this study, including recommendations, are described in chapter 9

2 Drivers in Singapore

2.1 Introduction

Singapore has a highly developed and successful free-market economy. The economy depends heavily on exports, particularly in consumer electronics, information technology products, pharmaceuticals, and on a growing service sector (CIA 2009). The Port of Singapore, one of the world's busiest in terms of shipping tonnage, is also a key component of Singapore's prosperity and economic health (EIA 2007). All these activities cause potential pressures on the environment.

In this section the main human activities affecting water quality in Singapore are identified (Table 2). The overview is limited to those activities currently present in Singapore. Past activities and activities taking place in neighbouring countries are not included. Their spatial and temporal aspects and if possible their intensity is described. Questions attributed are:

- Which activities are present in Singapore that determine overall water quality?
- Which temporal and spatial scales are significant for these activities?
- What is the intensity of the activities?
- What are the related pressures?

In ANNEX 2, a broader overview is provided of activities and related pressures, not limited to water quality aspects.

Table 2 Overview of activities in Singapore and (potential) related pressures on water quality

	Pressures	
Drivers	Input of contaminants	Nutrient enrichment
Agriculture	X	X
Aquaculture	X	X
Oil refineries and petrochemical industry	X	
Desalinitation facilities	X	
Docking	X	
Port activity	X	
Shipping	X	X
Wastewater treatment plants	X	X
Dredging	X	
Coastal reconstruction & Land reclamation, including land fills	X	
Construction of dams (and causeways)	X	
Land based activity (includes various activities that contribute via run off and atmospheric deposition)	X	X

2.2 Agriculture

Description
Agriculture is the production of food and goods through farming and forestry. Fish production is addressed separately in the paragraph 2.3 'aquaculture'. Agriculture encompasses a wide variety of activities, including ways to cultivate the land, by digging water-channels and other forms of irrigation.

Chemicals are used within this sector, such as pesticides and fertilizers, but also antibiotics and hormones that stimulate growth of foodspecies.

There are six agrotechnology parks in Singapore, which are modern agriculture estates developed with the necessary infrastructure for farming. These include livestock and its products, e.g. eggs, milk, meat; fish as food source and for ornamental use (aquarium fish) (see paragraph 2.3), vegetables, fruits, ornamental (e.g. orchids), and aquatic plants, as well as food for the breeding of birds and dogs. Agriculture is associated with the introduction of pollutants (i.e. pesticides (Wurl & Obbard 2005a&b) and nutrient enrichment (fertilizers).

Spatial and temporal scales
Agriculture in Singapore is very small. Only 1.5% of the country's area (appr. 1000 ha) is arable land of which 1.5% is planted with permanent crops. Singapore cultivates orchids for domestic and export markets. There has been some interest in the greenhouse production of certain fruits and vegetables for domestic consumption, but this sector is not strongly developed (remains small). The agrotechnology parks are located at Lim Chu Kang, Murai, Sungei Tengah, Nee Soon, Mandai and Loyang. The agrotechnology parks use a land area of 506 ha (fish farms are excluded in this figure).

Agriculture in the neighbouring country Malaysia is of a much larger scale. Rubber, palm oil and cocoa are the three main crops, but fruits and vegetables are also produced. Furthermore, logging is an important activity.

Intensity
In short, only small scale agriculture exists in Singapore. The large agricultural industry of Malaysia might probably be a more significant factor influencing the water quality in Singapore.

The use of land for the various types of farming activities in the agrotechnology parks is given in Table 3.

Table 3 Farming activities in Agrotechnology Park October 2009 (AVA 2009a)

Activities	**No of Farms**	**Total Area (ha)**
Livestock		
Poultry	5	72
Others	21	44
Horticulture		
Vegetable	53	107
Orchid / Ornamentals, etc	69	283

2.3 Aquaculture

Description
Aquaculture is the farming of freshwater and saltwater organisms such as finfish, molluscs, crustaceans and aquatic plants. The development and expansion of large-scale hatchery and fish farming production in Singapore and the region is facilitated by the Marine Aquaculture Centre (MAC) of the Agri-Food and Veterinary Authority of Singapore (AVA), located on St John's Island in the open southern waters of Singapore.

Aquaculture in Singapore can be divided into food fish farms and ornamental fish farms. Food fish aquaculture is mainly from coastal fish farms (AVA 2009b). They produce marine fish species like groupers, seabass, snappers and milkfish as well as green mussels and crustacean (shrimp/mangrove crabs). There are also freshwater food fish farms producing snakeheads, tilapia, catfishes and carps and other cyprinids.

Aquaculture is associated with changes in pH; changes in salinity; conversion/destruction; erosion; introduction of microbial pathogens; introduction of non-native species and translocations; non- selective extraction of species (bycatch); introduction of pollutants; change in sedimentation, nutrient enrichment and water/tidal flow changes.

Spatial and temporal scales
Even with limited available sea space, Singapore has a small but thriving and increasingly important food fish industry (AVA 2009b). The area used for the agrotechnology parks producing aquarium fish is 174 ha and for food fish and shrimps 28 ha (AVA 2009a). The food fish farming is mainly from coastal fish farms.

Intensity
Singapore's consumption of fish is estimated to be 100,000 tonnes per year of which about 5% is accounted for by local aquaculture production. Figure 2 shows the aquaculture production over the years. Production has recently strongly increased (*Figure 2*).

Singapore is the top exporter of ornamental fish in the world. Exporters deal with 500 species of ornamental fish, buying from the local farms, which accounts for about 40% of the sales, as well as from farms in the region and elsewhere for re-exporting (AVA 2009b). The area used for the two types of fish farming activities in the agrotechnology parks is given in *Table 4*.

Table 4 Fish farming activities in Agrotechnology Park October 2009 (AVA 2009a)

Aquaculture	**No of Farms**	**Total Area (ha)**
Aquarium Fish	75	174
Foodfish & Shrimps	5	28

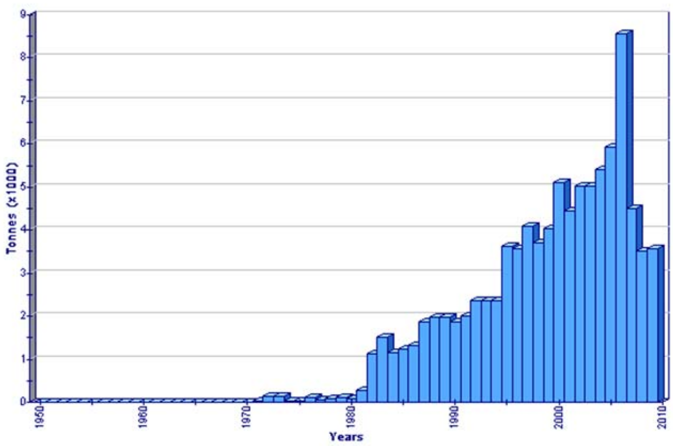


Figure 2 Aquaculture production

2.4 Oil refineries and petrochemical industry

Description
Although Singapore does not produce any oil, it is one of the top bunkering (ship refuelling) ports in the world.

An oil refinery is an industrial process plant where crude oil is processed and refined into more useful petroleum products, such as gasoline and diesel fuel. The two main classes of petrochemical (chemicals derived from petroleum or natural gas) raw materials are olefins (including ethylene and propylene) and aromatics (including benzene and xylene isomers). At oil refineries, olefins are produced mainly from hydrocarbons by processes such as fluid catalytic cracking and steam cracking. This industry is associated with the introduction of pollutants, specifically the introduction of petroleum/oil and heavy metals.

Spatial and temporal scales
Singapore has no national oil or gas reserves thus there are no offshore oil and gas activities in the territorial waters of Singapore. However. oil consumption in Singapore has increased 15 percent since 2000 (EIA 2007) and despite its lack of domestic oil resources, Singapore is a major oil refining and trading hub.

The petroleum industry is mainly concentrated on Jurong Island and secondly, Bukom Island (Pulau Bukom), see Table 5. Jurong Island is a man-made island located to the southwest of the main island of Singapore, off Jurong Industrial Estate. It is linked to the main island by a 2.3 km causeway. It was formed from the amalgamation of several offshore islands, through land reclamation. When completed, Jurong Island will form a land area of about 32 km^2 from an initial area of less than 10 km^2(http://en.wikipedia.org/wiki/Jurong_Island). Pulau Bukom, also known as Pulau Bukum, is a small island located about five kilometres to the south of the main island of Singapore, off the Straits of Singapore. The size of Pulau Bukom is about 1.45 km^2.

Crude oil, condensates, naphtha and gas-oil is planned to be stored in underground rock caverns. Work on the caverns is expected to be completed by 2009. Total underground storage capacity could reach up to 3.2 million cubic metres (http://en.wikipedia.org/wiki/Jurong_Island).

Table 5 Overview of petrochemical industries located in Singapore, based on EIA (2007)

Location	Plant type	Operator	Capacity
Jurong Island	Ethylene cracker[1]	ExxonMobil	25,400 bbl/d (800,000 metric tons/year)
	Two ethylene crackers	Petrochemical Corporation of Singapore (PCS)	total capacity of 44,500 bbl/d (1.4 million metric tons/year)
	Propylene cracker	Petrochemical Corporation of Singapore (PCS)	6,400 bbl/d (200,000 metric tons/year)
	Naphtha cracker (produce of ethylene)	Shell	28,600 bbl/d (900,000 metric tons/year)
	Mono-Ethylene Glycol (MEG) plant	Shell	Unknown
	Synthetic gas plant	Messer Group of Germany and Texaco of the US.	Unknown
	Naptha cracking plant	Petrochemical Corporation of Singapore (PCS) and partners	Unknown
Bukom Island (Pulau Bukom)	Crude distillation	Shell	500,000 barrels-per-day
	Two polyols plants	Shell	Unknown
	Styrene monomer and propylene oxide plant	Shell joint venture	Unknown
	Steam cracker (produce of ethylene)	Shell	28,600 bbl/d (900,000 metric tons/year)

Shell's investments in the Singapore petrochemicals industry include two polyols plants, a joint-venture styrene monomer and propylene oxide plant and other joint ventures. In addition, the Shell Eastern Petrochemicals Complex (SEPC) is an integrated refinery and petrochemical project comprising modifications to Bukom, a world-scale ethylene cracker and a world-class mono-ethylene glycol plant.

A synthetic gas plant has recently been built on Jurong Island by the Messer Group of Germany and Texaco of the US. Also, Singapore's second naphtha cracking plant was launched in 2002 on Jurong Island by the Petrochemical Corporation of Singapore and its partners (Anonymous 2009).

In 1999 a Bisphenol-A plant with a 70,000 tpa capacity started production in Singapore (Economics Department Monetary Authority of Singapore 1999).

Intensity

Because of Singapore's strategic location at the crossroads of the Indian and Pacific Oceans, its deep-water berths, and well-established infrastructure including oil refineries and storage terminals, the country has become an important oil trading and refining hub. Petroleum refining is a well-established industry in Singapore. After Rotterdam and Houston, Singapore is the world's third largest refining

[1] Cracking is a petroleum refining process in which heavy-molecular weight hydrocarbons are broken up into light hydrocarbon molecules by the application of heat and pressure, with or without the use of catalysts, to derive a variety of fuel products. Cracking is one of the principal ways in which crude oil is converted into useful fuels such as motor gasoline, jet fuel, and home heating oil.

center. The petrochemical industry has grown rapidly as a direct result of Singapore's refinery capacity. Nevertheless, regional rivals increasingly challenge Singapore's leading position in the Asian market.

Table 5 shows the capacity of the known petrochemical industries in Singapore. Many oil refineries produce ethylene, which is used as a raw material for the petrochemical industry.

Production capacity from five refineries (capable of processing 40 different types of crude oil) in 2006 was 1.3 million barrels per day (EIA 2007). According to Oil and Gas Journal (OGJ) the country’s three refineries are ExxonMobil's Jurong/Pulau Ayer Chawan 605,000-bbl/d facility; Royal Dutch Shell's Pulau Bukom 458,000-bbl/d complex; and the Singapore Petroleum Company’s Pulau Merlimau 273,600-bbl/d refinery.

Shell's 500,000 barrels-per-day Bukom refinery is today the largest Shell refinery in the world in terms of crude distillation capacity. The planned steam crackerof Shell at Palau Bukom would reportedly produce 28,600 bbl/d (900,000 metric tons/year) of ethylene when it becomes operational in 2009 (EIA 2007).

2.5 Desalinitation facilities

Description
The Tuas seawater reverse osmosis (SWRO) plant provides fresh water for domestic use. Desalination is associated with changes in water quality parameters and the introduction of pollutants. In addition to high salt levels, brine from seawater desalination facilities can contain concentrations of constituents typically found in seawater, such as manganese, lead, and iodine, as well as chemicals introduced via urban and agricultural runoff. Chemicals used throughout the desalination process may also be discharged with the brine. The majority of these chemicals are applied during pretreatment to prevent membrane fouling. Some known chemicals used and discharged by desalinitation plants are ((Cooley et al. 2006)): chlorine and other biocides; sodium bisulfite; anti-scalants (such as polyacrylic or sulfuric acid); coagulants (such as ferric chloride and polymers); industrial soaps; dilute alkaline; and acid aqueous solutions. Furthermore, corrosion of the desalination equipment leaches a number of heavy metals, including copper, lead, and iron, into the waste stream. Chemicals known to be used at the Tuas desalination plant are at least growth inhibitors, pH correctors and polymer coagulants (Water-technology.net 2010).

Spatial and temporal scales
The desalinitation plant is located at Tuas, in the Southwest of Singapore (see Figure 3). The brine is discharged in the Singapore Strait. In 2005 the plant went into operation (Water-technology.net 2010). It is assumed that the discharge is a continuous process.

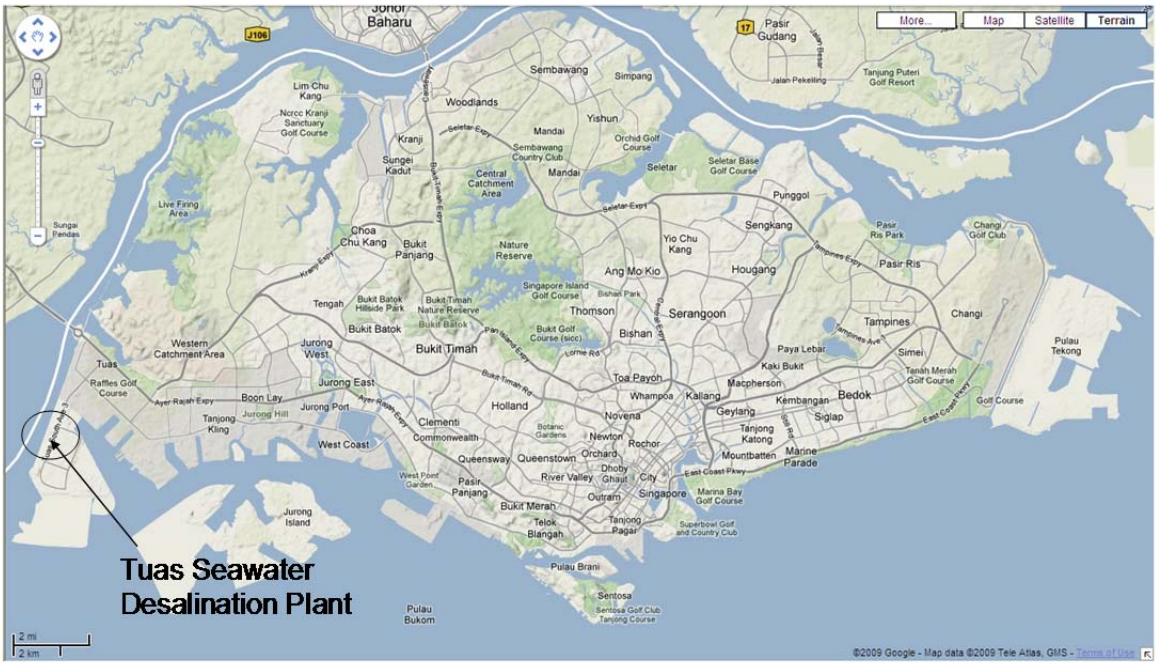


Figure 3 Map of Singapore, showing the location of the Tuas seawater desalination plant

Intensity
The plant produces 110,000 m^3 water per day, which is around 10% of the national demand (Water-technology.net 2010). The volume of discharged brine is unknown.

Ocean discharge is the most common and least expensive disposal method for coastal desalination plants (Cooley et al., 2006). Brine discharged into the ocean can be pure, mixed with wastewater effluent, or combined with cooling water from a co-located power plant. The plant at Tuas, Singapore, discharges a brine stream into the sea through a submerged outfall (Water-technology.net 2010).

2.6 Docking

Description
Docking in this report refers to the construction, maintenance, and repair of ships, boats, and other watercraft. These activities are associated with the introduction of pollutants (e.g. antifouling; heavy metals; petroleum/oil).

Spatial and temporal scales
Shipyards are concentrated along the West Coast of Singapore.

Intensity
Singapore has of total of 29 docks, of which 15 are graving docks and 14 floating docks, see Table 6 and Table 7.

Table 6 Capacity of graving docks, as at February 2009 (ASMI 2009)

Capacity	No. of docks	Total deadweight tonnes
5,000	1	5,000
7,500	1	7,500
10,000	1	10,000
100,000	2	200,000
150,000	1	150,000
170,000	1	170,000
200,000	1	200,000
300,000	2	600,000
330,000	1	330,000
360,000	1	360,000
400,000	2	800,000
500,000	1	500,000
Total	**15**	**3,332,500**

Table 7 Capacity of floating docks/ shiplifts, as at February 2009 (ASMI 2009)

Capacity	No. of docks/ shiplifts	Lifting capacity (tonnes)
5,000 & below	4	16,400
5,001 – 10,000	2	13,500
10,001 – 15,000	1	14,000
15,001 – 20,000	3	49,000
20,001 – 25,000	2	43,000
25,001 – 30,000	1	28,000
30,001 – 35,000	0	-
35,001 – 40,000	1	40,000
Total	**14**	**203,900**

2.7 Port activities

Description

A port is a facility for receiving ships and/or transferring cargo. Although it is related to the driver 'shipping', which is described in paragraph 2.8, it is regarded as a separate driver because of the difference in pressures and spatial scales. Ports are associated with the introduction of pollutants, specifically the introduction of petroleum/oil.

Spatial and temporal scales

The Port of Singapore is the biggest port of Singapore and lies in the south west of Singapore. Jurong Port is the second port operator in Singapore (Figure 4).

The Port of Singapore includes terminals located at Tanjong Pagar, Keppel, Brani, Pasir Panjang, Sembawang and Jurong. They can accommodate all types of vessels, including container ships, bulk carries, ro-ro ships, cargo freighters, coasters and lighters. Jurong Port can also handle all kinds of vessels.

Figure 4 Location of the port of Singapore and Jurong port.

Intensity
The terminals are managed by two commercial port operators – PSA Singapore, which manages the major share of container handling in Singapore and Jurong Port, which is Singapore's main bulk and conventional cargo terminal operator, it also has facilities to handle containers.

The Port of Singapore is one of the top bunkering (ship refuelling) ports in the world and the world's largest container transhipment hub. It handles about one-fifth of the world's total container transhipment throughput.

Jurong Port is the main bulk and conventional cargo gateway for Singapore and the region. The port handles steel products, cement, project cargo and copper slag, among others. It is also a designated hub for the storage and transhipment of metals.

2.8 Shipping

Description
This activity comprises the maritime transportation of goods (cargo) or people. Shipping consists of the following types of vessels: container, freighters, coasters, bulk carriers, tankers, passenger ships, regional ferries, barges, tugs and other. Shipping is associated with the introduction of pollutants (antifouling compounds, heavy metals, PAHs and petroleum/oil); introduction of litter; introduction of microbial pathogens; introduction of noise; introduction of non-native species and translocations; nutrient enrichment and resuspension from sediment.

Spatial and temporal scales
Singapore is situated at the crossroads of the main shipping routes, and therefore serves as a major shipping hub in Asia. As mentioned before, Singapore has two main ports, and is well-connected to more than 600 ports in over 120 countries.

The main shipping lane is the Strait of Singapore (Figure 5). The Singapore Strait is a 105-kilometer long, 16-kilometer wide strait between the Strait of Malacca in the west and the South China Sea in the east. Singapore is on the north of the channel and the Riau Islands are on the south. The Indonesia-Singapore border lies along the length of the straits. It includes Keppel Harbour and many small islands. The strait provides the deepwater passage to the Port of Singapore, which makes it very busy. Phillip channel deep water channel near Singapore Strait. The Straits of Johor in the north (between Singapore and Malaysia) is currently impassable by all ships as the Johor-Singapore Causeway links Singapore to Malaysia.

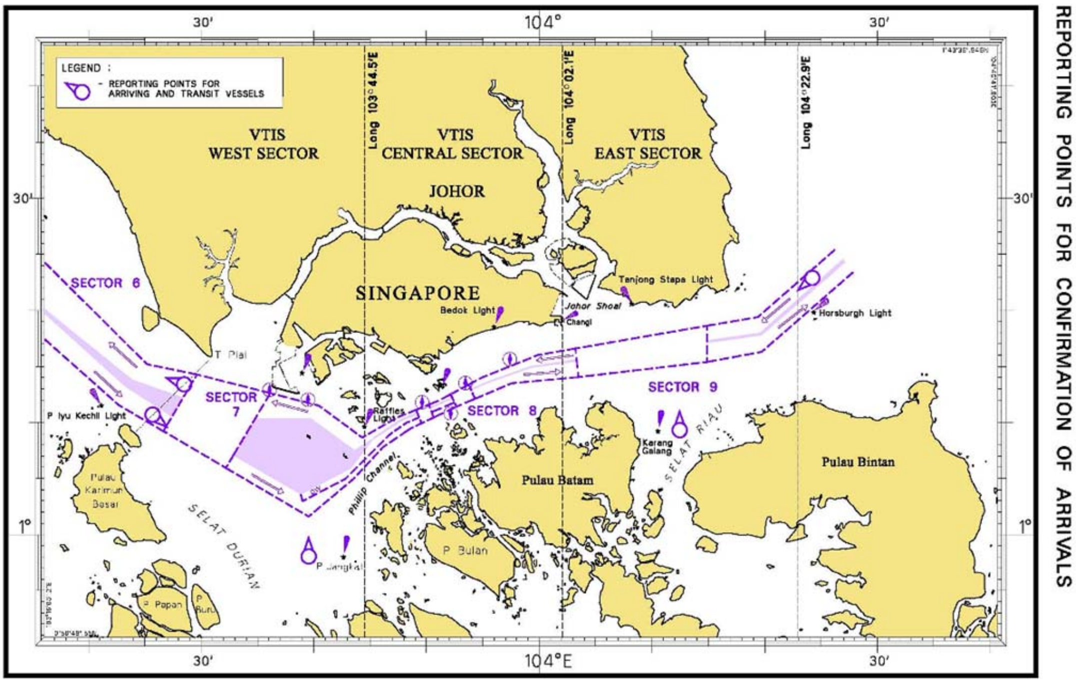


Figure 5 *Main shipping lane of Singapore (source: http://www.mpa.gov.sg/sites/pdf/Confirmation-of-arrival.jpg).*

In Figure 6 an overview is given of vessel positions in the coastal water of Singapore. These overviews highlight the vessel concentrations.

Figure 6 *More detailed overview of vessel positions in Singapore coastal waters. Data from www.vesseltracker.com*

Besides maritime shipping lanes regional ferry lines are important and busy navigational routes. Ferry lanes exist between Singaporean islands, and between Singapore and neighbouring countries. In Figure 7 the mayor routes are presented. Four ferry ports are connected to multiple lanes.

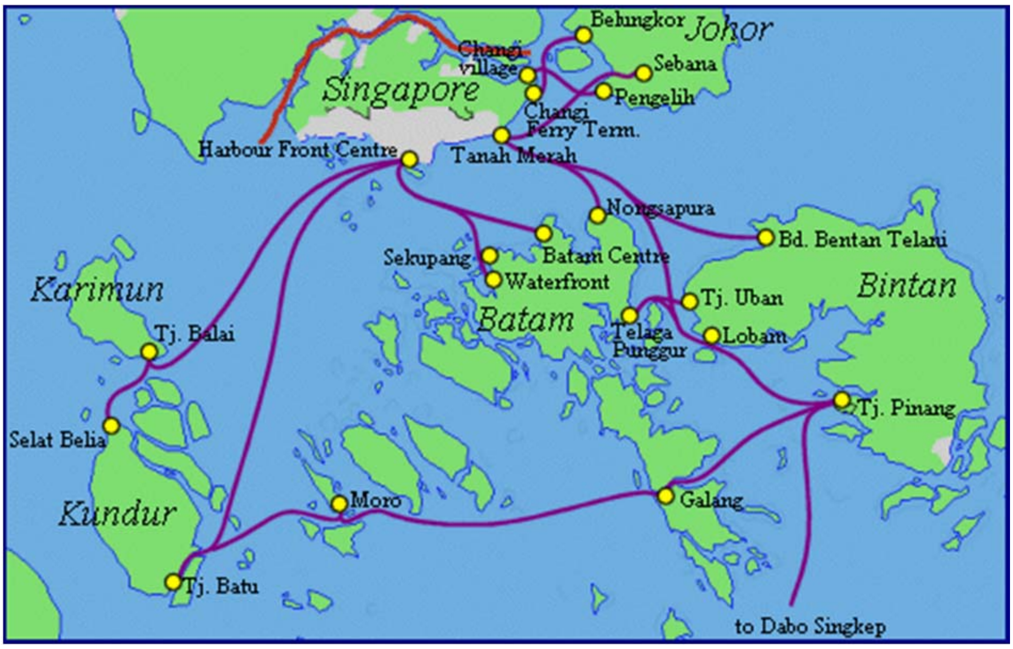


Figure 7 Ferry lanes between Singapore and neighbouring countries. Figure obtained from: http://user.chollian.net/~hwayon/sing/ferries.gif

Regional ferry routes lay between Singapore and surrounding islands. Main routes to southern islands are presented in Figure 8.

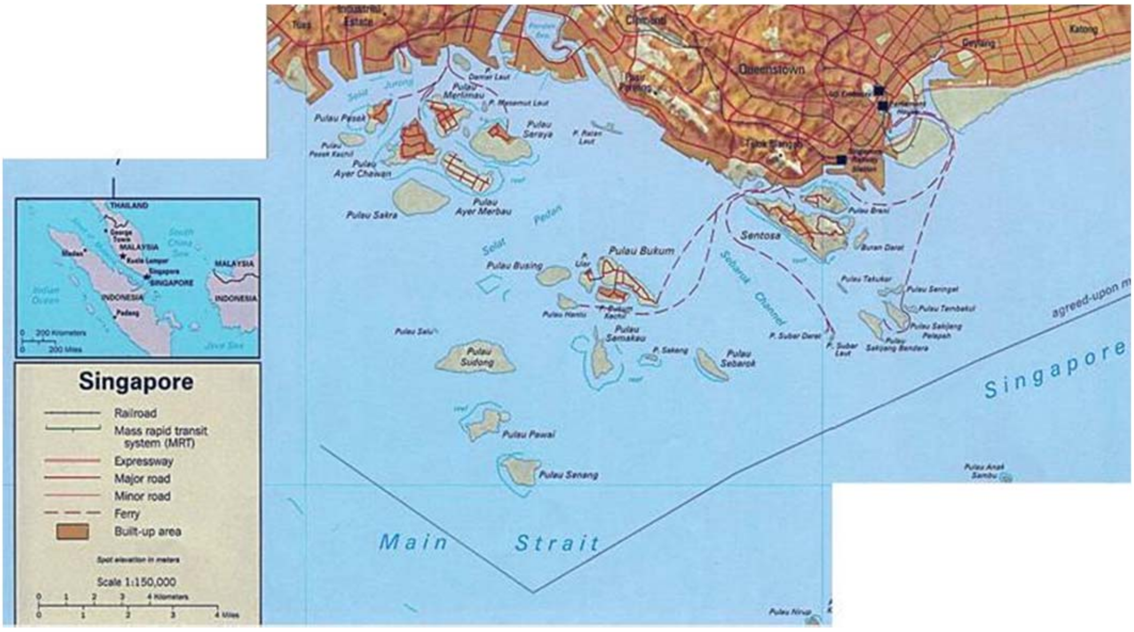
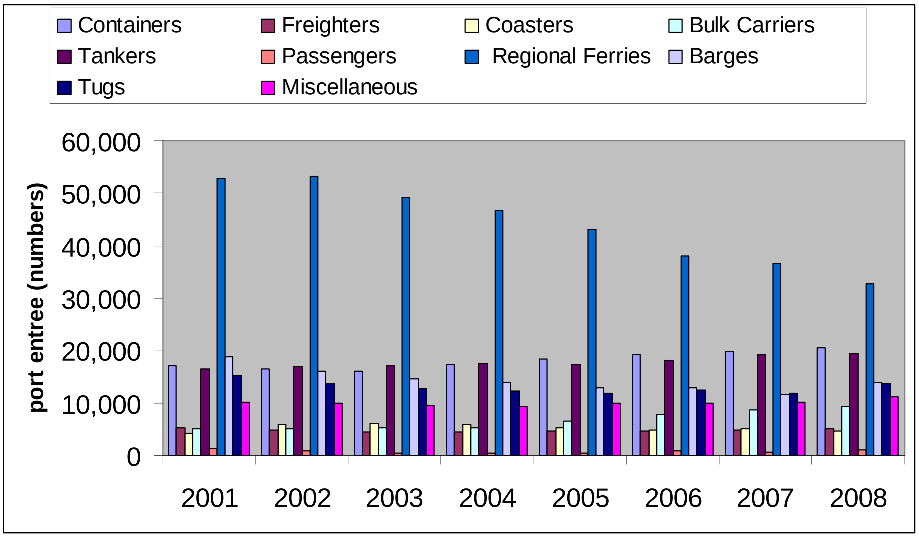


Figure 8 Regional ferry routes. Data merged from [*http://www.nationsonline.org/oneworld/map/singapore_map.htm*](http://www.nationsonline.org/oneworld/map/singapore_map.htm)

Intensity
In general Singapore maritime transport sector has a high intensity.
Based on data provided by the Maritime and Port Authority of Singapore (MPA) the intensity can be described in term of number of arriving vessels and port entrees. Every minute, about 2 to 3 ships arrive or leave Singapore, and annually more than 120,000 ships call at Singapore. About a million visitors cruise into Singapore annually in a continuous cycle (MPA 2009). In Figure 9 the total number of port entrees per year is given per type of vessel. These data show that in the last 8 years the number of regional ferries make the highest number of port entrees, but are decreasing in numbers. Other vessel types seem more constant over time in numbers. However, in tonnage (measure for ship size) is it obvious from Figure 9 that especially number of large containerships, bulk carriers and freighter ships the number of port entrees is increasing.

In 2007 a total of 128,568 vessels and 19,312 tankers arrived at Singapore port with a total load of 1,459,221 thousand GT and 445,448 thousand GT, respectively (source: ASMI at http://www.asmi.com/index.cfm?GPID=192.)



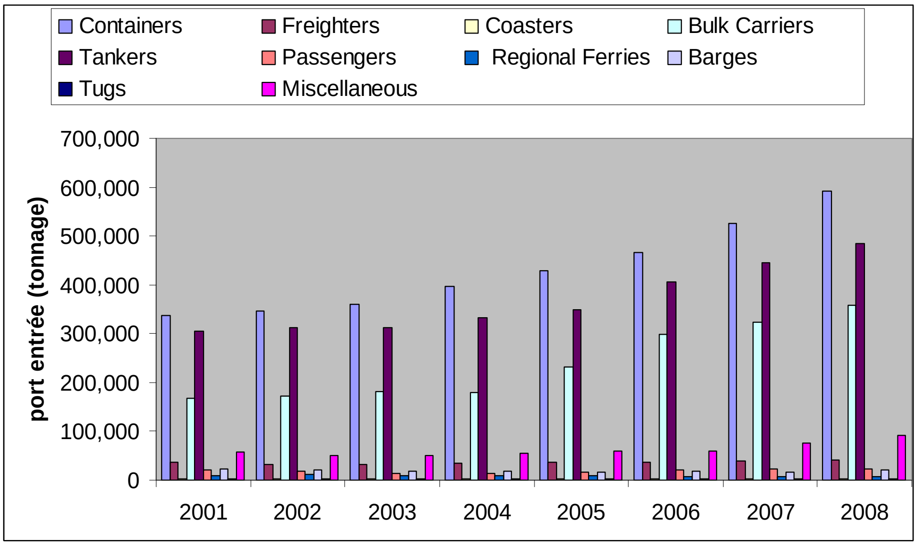


Figure 9 Vessel arrivals at port of Singapore. Top figure vessel arrivals in numbers, bottom figure arrivals in tonnage. Data obtained from MPA http://www.mpa.gov.sg/sites/pdf/vessel-arrivals.pdf

2.9 Wastewater treatment plants

Description
Wastewater in Singapore is treated at Water Reclamation Plants before discharged into water courses. The Singapore Effluent Discharge Standards is not really so high but the enforcement is good (http://www.watertreatment.com.cn/plants/list/Singapore.htm).

Sewers also play an important role in the proper conveyance of used water island-wide to the water reclamation plants for treatment before further treatment at NEWater[2] plants or for discharge to the sea, see Figure 10.
The effluent of treatment plants is associated with increase of organic loads, change in oxygen and the introduction of pollutants.

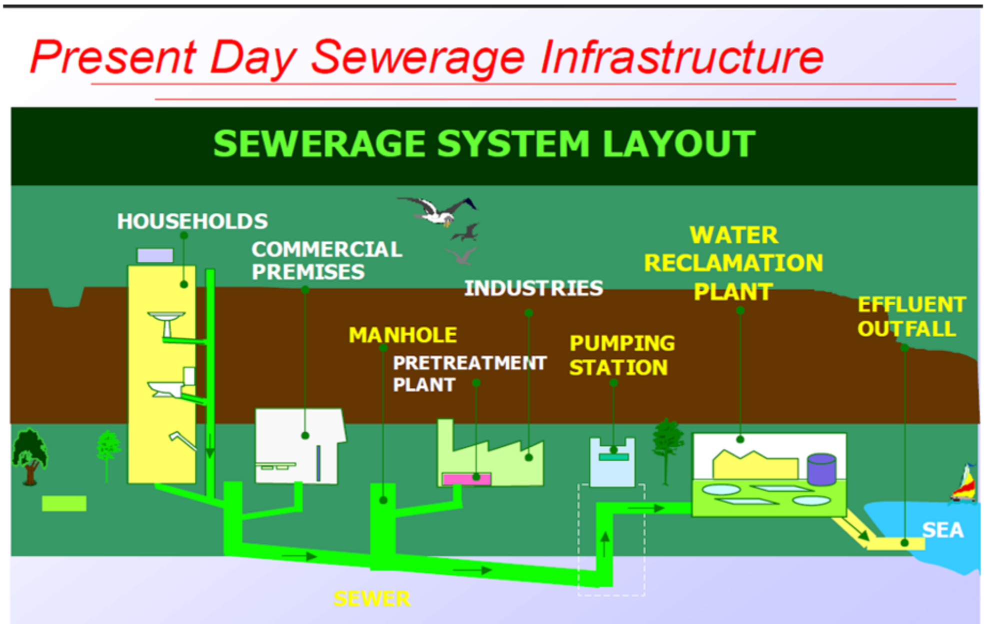


Figure 10 Present day sewage treatment system in Singapore (Meiyappan 2004).

Spatial and temporal scales
Singapore has over 3,400 km of public sewers. The major wastewater /sewage treatment plants are:

- Changi Water Reclamation Plant (officially opened in 2009)
- Bedok Water Reclamation Plant (shut down in 2009)
- Jurong Water Reclamation Plant
- Kim Chuan Water Reclamation Plant (shut down in 2008)
- Kranji Water Reclamation Plant
- Seletar Water Reclamation Plant (to be shut down in 2011)
- Serangoon Sludge Treatment Works
- Tuas Water Reclamation Plant
- Ulu Panda Water Reclamation Plant

Figure 11 shows the sewage catchment of Singapore.

[2] NEWater is treated used water that has undergone stringent purification and treatment process using advanced dual-membrane (microfiltration and reverse osmosis) and ultraviolet technologies. NEWater could be mixed and blended with reservoir water and then undergo conventional water treatment to produce drinking water (a procedure known as Planned Indirect Potable Use or Planned IPU).

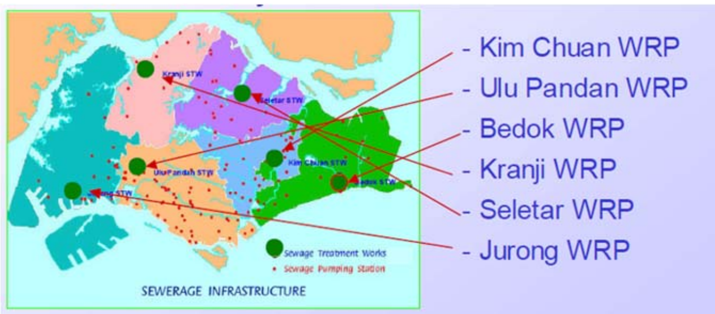


Figure 11 Sewage catchments of Singapore (Meiyappan 2004)

With the Deep Tunnel Sewerage System in place, used water treatment is centralised at the Changi Water Reclamation Plant (PUB 2009). As such, the conventional water reclamation plants has been progressively phasing out. In 2008, the Kim Chuan Water Reclamation Plant was shut down. In April 2009, the Bedok plant closed. It is planned to be replaced by a third water reclamation plant at Seletar in 2011.

Besides the sewage treatment plants, there are also industrial waste water treatment plants. The industrial water treatment and discharge is schematically presented in Figure 12.

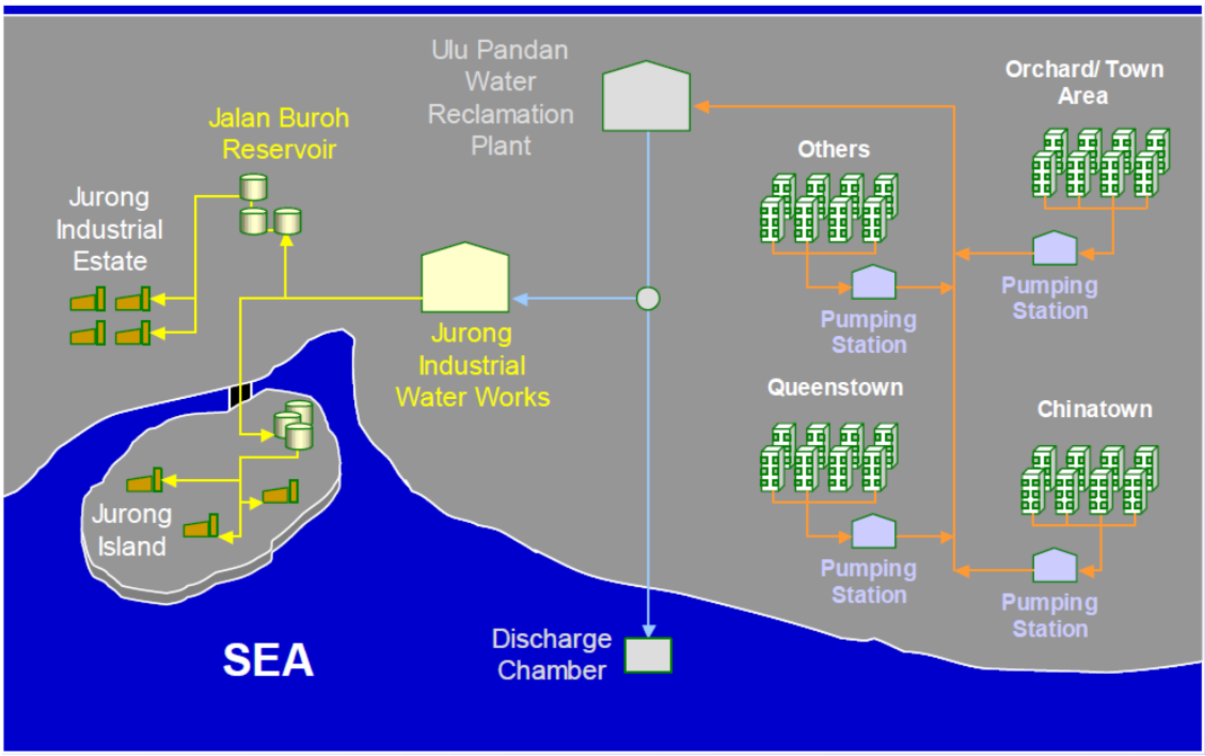


Figure 12 Industrial water discharge in Singapore (Meiyappan 2004)

Intensity

Total volume of used water treated in year 2006 = 511 million cubic metres. Total volume of used water treated in year 2008 = 516 million cubic metres (http://www.pub.gov.sg/mpublications/FactsandFigures/Pages/WaterReclamation.aspx#usedwaterbreakdown)

Breakdown on volume of used water treated by various WRPs in year 2008 is schematically presented in Figure 13.

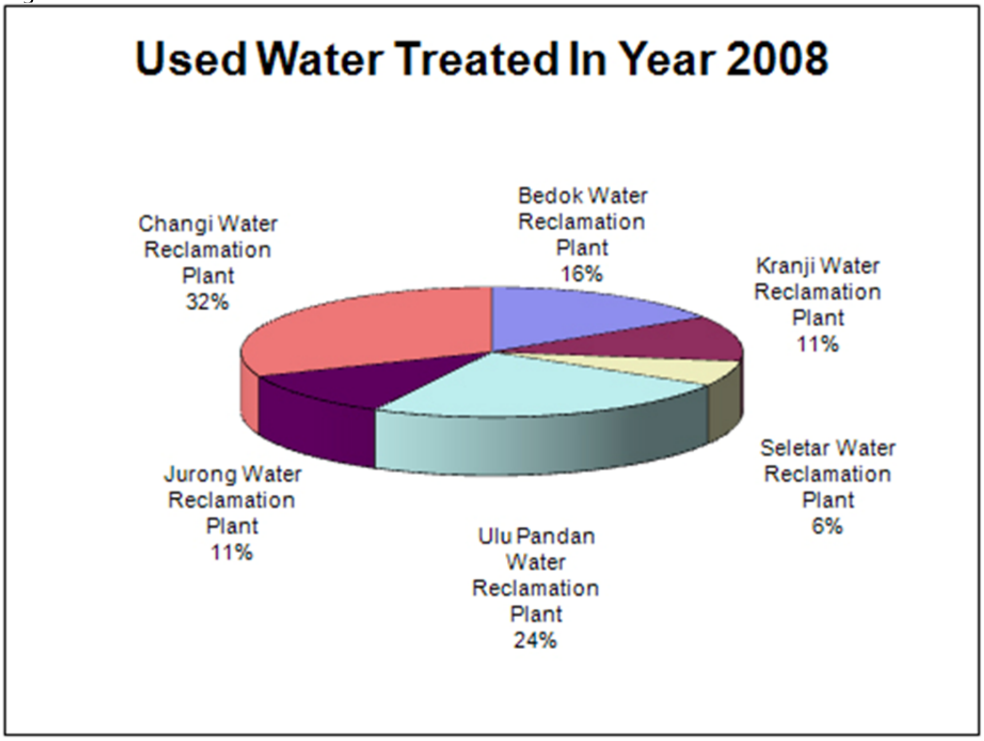


Figure 13 Used water treated in year 2008 (http://www.pub.gov.sg/mpublications/FactsandFigures/Pages/WaterReclamation.aspx#usedwaterbreakdown)

2.10 Land based activities

2.10.1 Atmospheric deposition

Description

This driver comprises the nonpoint source of atmospheric deposition. Introduction of pollutants through atmospheric deposition can have its origin from different sources, i.e. emissions to air. These are for example, combustion processes from industries and transport and the use of chemicals in agriculture where volatile pesticides can be emitted into the air. These sources can also originate from other countries. Introduction of pollutants, such as the introduction of heavy metals; introduction of PAHs; introduction of PCB's; and the introduction of petroleum. For example, emissions to air from the petrochemical industry could include: alkenes (such as propylenes and ethylene), benzene, butadiene, 1,2-dichloroethane, and vinyl chloride, and nutrient precipitation of both P and N are associated with atmosphweric deposition.

Spatial and temporal scales

Atmospheric deposition varies spatially and temporally with weather conditions (such as precipitation), long and short distance transports of constituents and other events (fires, incidental releases, etc).

Intensity

The importance of atmospheric deposition is considerable. For example, a recent study confirmed that wet deposition is a major pathway for the transfer of PAHs from the atmosphere to the sea-surface microlayer (SML) (Lim et al. 2007).

2.10.2 Land based run off

Description
The category 'land-based input' comprises all emissions from activities on land that end up in the marine environment through runoff (rainfall washing to coastal waters) and rivers. Land-based sources from Malaysia (e.g., palm and oil industries and pig farms) may represent significant sources to Johor strait (Choo et al., 1994). However, nearby riverine input, urban runoff, domestic and industrial sewage represent the main sources of organics and nutrients to the coastal waters of Singapore. Densely populated Singapore has sewerage system with major effluents situated at Seletar, Punggol and Serangoon areas ((Cheong et al. 2001)). Land based input is associated with the introduction of pollutants (in specific introduction of heavy metals and PAHs); introduction of litter; and nutrient enrichment of due to e.g. "managed greenspace" as (golf courses, recreative areas and parcs)

Spatial and temporal scales
Land-based input trough runoff is very diffuse as rainfall can wash into the sea along the coastline of Singapore. The spatial scale of riverine input can be based on river flows. There are about 90 rivers in Singapore and its islands. The mouths of the rivers are scattered along the coastline of Singapore, with two large estuaries in the north and the Singapore River ending in the south. The Singapore River is the most famous river in Singapore. After damming this river has now become part of the Marina Reservoir.

Intensity
Land-based input is regarded as a significant source of pollution (Bayen et al. 2003, Cuong et al. 2005, Wurl & Obbard 2005b, 2006, Lim et al. 2007), litter (Ocean Conservancy 2009) and nutrient enrichment (Yew-Hoong Gin et al. 2002) in Singapore's marine environment.

2.11 Coastal reconstruction & land reclamation (including dredging and land fills)

Description
The shorelines of Singapore have been extensively modified by coastal engineering (Chou 2006). Coastal reconstruction comprises sea walls, coastal structures, artificial beaches, swimming lagoons and reefs. Coastal reconstruction often goes together with dredging and land reclamation. Land reclamation refers to the creation of new land where there was once water. Coastal reconstruction is associated with changes in turbidity; conversion/destruction of natural habitat; introduction of heavy metals; and water/tidal flow changes. Land reclamation can be associated with introduction of noise; introduction of pollutants; reduction in sedimentation; resuspension from sediment; and increased sedimentation.

With the reconstruction of coastline new habitats are created, some of which support biodiversity enhancement. In all cases, species associated with the original habitats are invariably affected, resulting in distribution pattern changes (Chou 2006).

A landfill is a site for the disposal of waste materials. In the scope of this report we consider only the landfills at sea. Landfills are associated with changes in turbidity and increased sedimentation.

Spatial and temporal scales
Nearly all of Singapore's coastline is reconstructed. Very few natural beaches remain and they are located mostly along the northwestern sector of the main island and some of the offshore islands (Chou 2006). A rich intertidal flat that represents what most intertidal flats were like in the past is Chek Jawa, located at the eastern tip of Pulau Ubin in the Johore Straits. In spite of coastal reclamation adjacent to it, sediment carried down the Johor River, and the wash from passing vessels, the flat supports seagrass,

corals and a rich diversity of marine life. About the only original beach along the southern coastline is a short stretch of rocky shore at Labrador with seagrass patches and a reef community. Its existence remains threatened by future extension of the container port to its west.

The development of sea walls to contain reclaimed land and provide berthing for vessels eliminated the original shore profile extensively along the southwestern coastline and many of the offshore islands (Chou 2006).
Concrete jetty piles were constructed at the southern islands. At Raffles Marina on the northwest coast a variety of structures was used in the reconstruction works, including floating pontoons, sea walls and pilings.

Figure 14 shows a map of Singapore indicating the locations of land reclamation.

Figure 14 Land reclamation in Singapore (http://www.southchinasea.org/miranda/singapore.gif).

Most of the recreational beaches on the main island are created from coastal reclamation. They have a steeper profile than the original beaches buried by the reclamation. The extent of intertidal flats is also reduced. Protected swimming lagoons were constructed at a number of the southern islands, replacing existing reef flats.

Artificial reefs were constructed between 1989 and 1996. These structures were deployed on the seabed at a 12 m depth close to a reef system in the southern islands, facing a shipping lane (Chou 2006).

Part of Singapore's sea to the east of the island of Pulau Semakau was assigned for landfill use after sites on the main island ceased to be available (Chou & Tun 2007). The Semakau Landfill (Figure 15), commissioned in 1999, covers a sea area of 350 ha. A 7 km rock bund encloses the landfill.

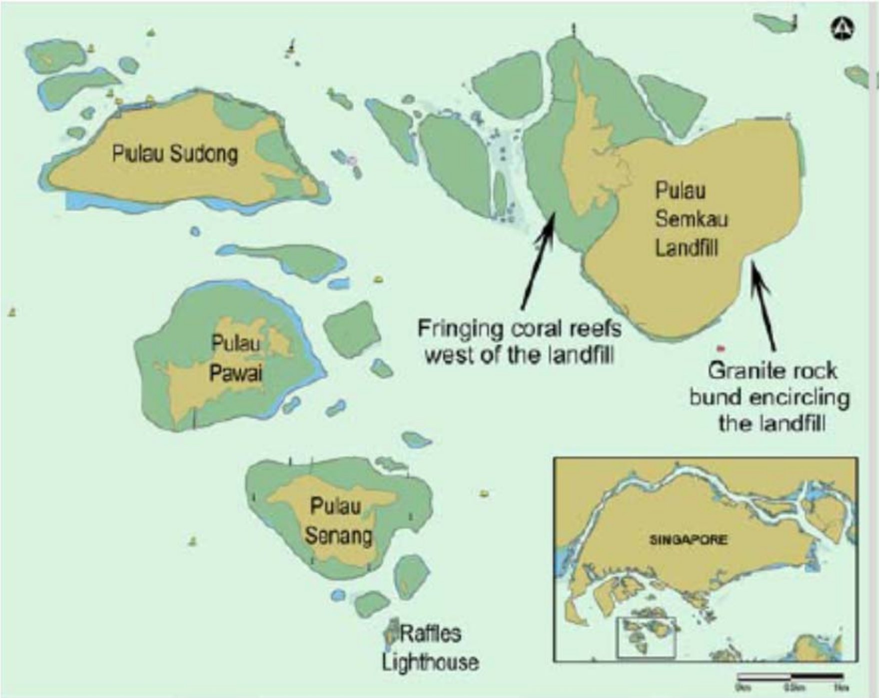


Figure 15 Pulau Semakau Landfill and adjacent islands (Chou & Tun 2007).

Intensity
Coastal reconstruction is a highly intense activity in Singapore. Although already many transformations have occurred, the land is still under development.

Singapore's land area grew from 581.5 km2 (224.5 sq mi) in the 1960s to 704 km2 (271.8 sq mi) in 2005, and may grow by another 100 km² (38.6 sq mi) by 2030 (Ministry for the environment and water resources 2005). The projects sometimes involve some of the smaller islands being merged together through land reclamation in order to form larger, more functional islands, such as in the case of Jurong Island.

The Semakau Landfill provides a capacity of 63 million m3, forecast to meet the country’s waste disposal needs beyond 2030 (Chou & Tun 2007). The rock bund encircling the landfill is lined with an impermeable membrane and marine clay to prevent refuse leachate from contaminating the surrounding waters. It is operated as a sanitary landfill, to receive only incinerated ash and construction and renovation debris (Chou & Tun 2007).

2.12 Construction of dams (and causeways)

Description
Dams are constructed to impound water and can be build for various purposes such as power generation, water supply, stabilize water flow / irrigation, flood prevention, land reclamation, water diversion, recreation and aquatic beauty. Causeways are build to connect two areas separated by (sea)water. These constructions are associated with the introduction of pollutants; reduction in sedimentation; erosion and water/tidal flow changes.

Spatial and temporal scales

There are 15 reservoirs in Singapore: Bedok Reservoir; Jurong Lake; Kranji Reservoir; Lower Peirce Reservoir (former Peirce Reservoir); Lower Seletar Reservoir; MacRitchie Reservoir (former Thomson Road Reservoir); Marina Reservoir; Murai Reservoir; Pandan Reservoir; Poyan Reservoir; Pulau Tekong Reservoir; Sarimbun Reservoir; Tengeh Reservoir; Upper Peirce Reservoir; and Upper Seletar Reservoir (former Seletar Reservoir).

Bedok Reservoir was constructed under the Sungei Seletar/Bedok Water Scheme, completed in 1986. The scheme involved the damming of Sungei Seletar to form a reservoir (Lower Seletar Reservoir). Jurong Lake is a freshwater lake and reservoir located in the western region of Singapore formed with the damming of Sungei Jurong further downstream. Kranji Reservoir is a reservoir in the northern part of Singapore, near the Straits of Johor was a former freshwater river that flowed out into the sea that dammed at its mouth to form a freshwater reservoir. Built across the mouth of the Marina Channel, the Marina Barrage created Singapore's 15th reservoir, and the first in the heart of the city. With a catchment area of 10,000 hectares, or one-sixth the size of Singapore, the Marina catchment is the island's largest and most urbanised catchment.

There are two man-made connections to Johor, Malaysia — Johor-Singapore Causeway in the north, and Tuas Second Link in the west.

Intensity

As shows from the large number of reservoirs in Singapore, the construction of dams has been a major activity. In addition to the 15 reservoirs as listed above, there are two reservoirs planned: Punggol Reservoir (planned for Sungei Punggol); and Serangoon Reservoir (planned for Sungei Serangoon).

3 Pressures

3.1 Introduction

Pressures are here defined as the stresses that human activities place on the environment. Pressures reflect many stresses, and could be described in terms of habitat damage or loss, due to e.g. smothering, underwater noise, marine litter, contamination or nutrient enrichment. The pressures related to the activities as described in previous chapter are obviously many.
In this report only pressures related to chemical water quality are addressed, as the aim of this study is to assess the present impact of water quality as a consequence of human activities on local coastal ecosystems.

The main pressures known to determine the quality of the marine environment of Singapore are listed in Table 8 and described in the following paragraphs. The related state descriptors are described in the next chapter (Chapter 4).

Table 8 Overview of pressures in Singapore and (potential) related state descriptors of the marine environment

	State							
		Contaminant concentrations in water and sediment						
Pressures	Level of nutrients	Heavy metals	Phenols	POPs	PAHs	Antifouling compounds	Ecosystems	Contaminant concentration in biota
Nutrient enrichment	X						X	
Input of antifouling compounds						X	X	X
Input of heavy metals		X					X	X
Input of PAHs					X		X	X
Input of POPs (PCBs, pesticides)				X			X	X
Input of petrochemicals/oil			X		X		X	X

POPs (Persistent Organic Pollutants); PAHs (Polycyclic Aromatic Hydrocarbons); PCBs (PolyChlorinated Biphenyls)

3.2 Nutrient enrichment

Nutrient enrichtment comprises the enhanced (anthropogenic) input of N and P. This could lead to changes in primary production, biological structure and turnover and resulting in a higher trophic state (eutrophication).

Overview of the main loads into Singapore coastal waters is given in Table 9.

Table 9 Land-based contributions fo BOD (Biological Oxygen Demand), Total Nitrogen (total-N) and Total Phosphorus (Total-P) as percentage of total emitted from adjacent area compartments into the Johor estuarine system. Indicated at bottom Table are Total loads and Demand in tons per year.

Area compartiment	BOD	Total-N	Total-P
W.East Johor Straits	35	18	36
M.East Johor straits	17	8	9
East Johor straits	35	13	10
Kuala Johor	1	1	2
Sungei Johor	11	51	40
Calder Harbour	1	10	3
Total Load/demand	5289	2758	296

Nutrients concentrations in the coastal water around Singapore have been subject of a number of studies (see Table 9) among which one of the most comprehensive is the work from Wolanski (2006).

Land-based input (rivers, runoff) and shipping and atmospheric deposition are sources of nutrient enrichment to the marine environment of Singapore. Singapore and Malaysia sewage effluents, runoff and rivers contribute the most to the load of nutrients to Johor Strait (Wolanski, 2006).

Pressure indicators are e.g the actual discharge of nutrients.

3.3 Input of contaminants

In general, marine pollution in Singapore has been attributed to exhaust emissions from boats, increased shipping activities, release of antifouling paints from boats, industrial sources, and dredging (Nayar et al. 2004b). Other identified sources of pollution in tropical marine environments are terrestrial runoff from rivers and streams, urban areas (sewage outfalls, tourism, recreation), agricultural areas, desalination plants, leaching landfills, fishing, waste disposal, mining and smelting, oil and gas activities and petroleum refineries (Peters et al. 1997). The input of contaminants can be divided into different types: anti-fouling; heavy metals; PAHs; PCB's; pesticides and; petroleum/oil. These are described in the following sub-paragraphs.

Pressure indicators could be the presence of sources of pollution, as listed above. If available, the emissions should be used as pressure indicators: the substances released, including their quantities, would provide a better indication of the pressure by chemical stressors compared to only source identification. However, emission data on contaminants are hardly available for Singapore.

3.3.1 Introduction of antifouling compounds

To reduce fouling of the hull during the operations of a ship, a special antifouling coating is applied to the ship's hull. These coatings inhibit the growth of organisms through the controlled release of biocides. Paints are formulated with toxic copper, organotin compounds or other special chemistry. The most common and effective chemical used to date in antifouling paints has been tributyltin (TBT).
However, TBT causes many environmental problems. In 2001, IMO adopted a new International Convention on the Control of Harmful Antifouling Systems on Ships, which will prohibit the use of harmful organotins in antifouling paints used on ships and will establish a mechanism to prevent the

potential future use of other harmful substances in antifouling systems. This Convention entered into force on September 15, 2008.
DNV (Det Norske Veritas) calculated the global TBT emission from ships to be (DNV, 1999): Tankers 252.8 ton/yr, bulk carriers 220.5 ton/yr, general cargo 150.2 ton/yr, containers 57.1 ton/yr and other ships 119.1 ton/yr. These calculations are based on a leaching rate of 2 mg TBT per cm^2 painted surface per day. The TBT emission by worldwide shipping (above 100 GRT, which were 43325 vessels in 1996) is estimated between 750 and 1500 ton per year (DNV 1999). The average yearly emission per vessel is thus between 17 and 35 kg. Assuming an average number of vessels present in the marine waters in Singapore to be 320 (based on data from www.vesseltracker.com, accessed on November 25, 2009), the yearly TBT emission is between 6 and 11 ton. The TBT emission is expected to decrease through the implementation of the IMO convention.

Due to its persistence TBT can still be found in the environment (see state chapter). Other compounds which are used in anti fouling paints are e.gg Irgarol, and copper.

3.3.2 Introduction of heavy metals

Heavy metals naturaly occur in the environment and some are essential to life but can become toxic through accumulation in organisms. Arsenic, cadmium, chromium, copper, nickel, lead and mercury are the most common heavy metals which can pollute the environment.

The introduction of heavy metals in the marine environment of Singapore could be caused by: coastal reconstruction; docking; dredging; land reclamation; land-based input (rivers, runoff); petrochemical industry; shipping and atmospheric deposition. No data for heavy metal emissions were found.

3.3.3 Introduction of PAHs

Polycyclic aromatic hydrocarbons (PAHs) are a class of persistent organic compounds, or perstistent organic pollutants (POPs). PAHs occur in oil, coal, and tar deposits, and are produced as byproducts of fuel burning (whether fossil fuel or biomass). The U.S. EPA has designated 16 PAH compounds as priority pollutants. They are naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, dibenz[a,h]anthracene, benzo[g,h,i]perylene, and indeno[1,2,3-cd]pyrene.

PAHs can be introduced into the marine environment of Singapore by land-based input (rivers, runoff), shipping and atmospheric deposition. No emission data on PAH were found.

3.3.4 Introduction of PCB's

Another class of POPs are polychlorinated biphenyls (PCBs). PCBS were widely used but are now restricted because of their persistence and toxicity. The atmosphere is regarded as the major pathway for the global distribution of organochlorine compounds (OCs), including PCBs (Wurl & Obbard 2005a). A main source of PCBs in the marine environment of Singapore is therefore atmospheric deposition.

3.3.5 Introduction of pesticides

Pesticide have been found in the marine environment of Singapore. For example, it has been found that DDT residues in Singapore’s coastal sediments may act as a local source of DDT to the marine waters. The major pesticides detected included DDTs, HCHs, Chlordane, Heptachlor, Heptachlor epoxide and Dieldrin (Wurl & Obbard 2005b).

Pesticides can be introduced into the marine environment of Singapore through the use of these products in agriculture and aquaculture. No data on emissions of pesticides were found.

3.3.6 Introduction of petrochemicals/oil

Petrochemicals comprise a large range of chemicals derived from petroleum or natural gas, such as ethylene, propylene and aromatics. Petroleum, or crude oil, is a mixture of mainly hydrocarbons and some other organic compounds. It is refined and separated into a large number of products, e.g. fuel, asphalt and chemical reagents used to make plastics and pharmaceuticals (petrochemicals). When oil enters the environment due to an oil spill at sea, a floating oil layer will form on the water surface. Effects of a floating oil layer are physical (e.g. smothering of birds and sea mammals) as well as toxicological. Some compounds are persistent and can stay in the environment for a prolonged period of time.

Because of the oil industry (e.g. trading and refining) in Singapore the (potential) introduction of petrochemicals/oil into the marine environment of Singapore is highly relevant. Other sources of petrochemicals/oil into the marine environment of Singapore are docking, (petro)chemical industry, port activities, shipping and atmospheric deposition. Nayer et al. (2005) traced the sources of petroleum hydrocarbons in Ponggol Estuary to accidental spillages of diesel fuel from storage tanks on dredgers operating in the estuary, fuel and engine oil leaks from recreational boats in the marina, oil tanker traffic and shipping operations in the adjacent Johor Strait, and land runoff from the numerous monsoon drains which empty into the river.

Emission of oil can either occur through accidental spills or operational discharges and emissions. Under MARPOL 73/78, Annex I, discharges of oil are strictly regulated.

The petrochemical industry is also a major driver of the introduction of petroleum compounds (e.g. dethylene and propylene, benzene, butadiene, 1,2-dichloroethane, and vinyl chloride) in the marine environment of Singapore through short distance atmospheric deposition following emission to air.

Oil spills in Singapore
Oil is not only introduced to the environemt by the refinery industry. Oil spills occur due to e.g. collisions resulting in a release of oil or related products to the environment. In Singapore several oils spills have occurs in history. An overview is given in *Table 10*

Table 10 Overview of oil spills in the marine environment of Singapore.

When	Where	Volume	Type of oil	Cause
25 May 2010	East coast	2500 tonnes	Crude oil	collision
12 June 2003	Horsburgh Lighthouse, in the eastern approaches of the Singapore Straits	150 tonnes	Fuel oil	
12 June 2002	South eastern singapore	450 tonnes	Fuel oil	Collision
5 December 2002	Middle Singapore straits	350 tonnes	Crude oil	collision
13 June 2001	Johor		Phenol, diesel	Capsizing

When	Where	Volume	Type of oil	Cause
4 October 2000	Indonesia Batu berhanti, reaching Sentosa Island	7000 tonnes	x	grounding
15 October 1997	Singapore strait, but spreading over more than 3000km2 including shoreline	> 25000 tonnes	Heavy fuel oil	Collision of tanker Evoikos
5 June 1995	East coast	100 tonnes	Fuel oil	Collision with bunker fuel barge
1977, 1976	Raffles lighthouse	> 2300 tonnes	Crude oil	Collision and grounding

4 State

4.1 Introduction

The environmental state of Singapore's marine environment can be described by several state descriptors. These state descriptors, including the related impact, are presented in Table 11. Related pressures are presented in Table 8 (see Chapter 3). This chapter describes the state of the marine environment of Singapore regarding nutrient levels, contaminant concentrations (in water, sediment and biota) and ecosystems. The impacts of an affected state are described in the next chapter (Chapter 5).

Table 11 State descriptors for Singapore, including the related impact

	Impact		
State	Eutrophication	Contamination effects*	Contaminants in biota*
Nutrients	X		
Heavy metals		X	X
Phenols		X	X
POPs		X	X
PAHs		X	X
Antifouling compounds		X	X
Ecosystems		X	
Contaminants in biota**		X	

* Contamination of water and sediment (i.e. state descriptor) could lead to contamination effects and/or contaminants in biota (i.e. impact).
** Contaminants in biota (i.e. state descriptor) could also be regarded as impact descriptor.

As state indicators, contaminants could be measured in water, sediment and/or biota. Annex 3 provides an overview of condition indicators under different environmental conditions.

4.2 Nutrients

Nutrient concentrations in the coastal water around Singapore have been subject of a number of studies (see Table 12) among which one of the most comprehensive is the work from Wolanski (2006). The study examined both Singapore and Johor Straits. In general, lower nutrients concentrations were found in Singapore Strait, with a total N concentration varying from 200 to 1100 µg l^{-1} against the 1300 to 2300 µg l^{-1} of Johor Strait, with no obvious temporal trend.
Wolanski (2006) found DIN/DIP ratios varying from 6 to 8 (average of 11) in Singapore Strait, implying possible nitrogen limitation. In Johor Strait, due to the higher and more variable nitrogen load from Singapore and Malaysia sewage effluents, runoff and rivers, DIN/DIP ratios were in a range from 16 to 32.

Comparable differences in N and P levels between Singapore and Johor strait have been found by Yew-Hoong Gin et al. (2002); similar total N and P concentrations for East Johor Strait and Singapore were found during more recent sampling campaigns (e.g., Delft Hydraulics, 2007; Palani et al., 2008). Also, relatively high nutrient concentrations were found in Pongol estuary (Nayar et al., 2005).

According to (Cheong et al. 2001), in Johor Strait and in particular the Seletar and Serangoon areas there is an increased risk of eutrophication in the areas around sewage outfall. In the vicinity of these outfalls, the eutrophication effects of elevated concentration of phosphorus stimulation sustaining increased algal growth are likely to be intensified when nearby waters would be enriched further by nitrogen compounds.

As stated earlier, the available data show that the level of nutrients in the marine environment of Singapore is highly variable, mainly depending on local sources of nutrients (i.e. pressures).

Table 12 Summary of water quality parameters around Singapore in the different literature studies examined (EJS =East Johor Strait; PS = Paulau Semakau; SS = Singapore Strait; WJS = West Johor Strait; PE = Ponggol Estuary; EJ = East Johor)

Reference	**Location**	**Concentration (µg/l)**							
		NO3 + NO2_N	NO3_N	NO2_N	NH4_N	NH3_N	PO4_P	Tot N	Tot P
Cheong et al., 2001	EJS	-	10-40	-	40-1490	-	38-110	-	-
Chou et al., 2004	PS	-	-	-	5-141	-	-	-	-
Gin et al., 2002	SS; EJS; WJS	-	-	-	-	-	-	210-1100; 1900-7300; -	5-31; 20-280; 26-167
Nayar et al., 2005	PE Surface 1 m 2 m 3 m	-	16-107 16-117 26-92 24-79	7-15 7-15 8-16 8-19	-	14-225 22-153 57-132 35-252	21-60 30-66 36-87 42-108	-	-
Palani et al., 2008	EJS	60-200	-	-	340-730	-	10-80	1970-5700	20-120
Wolanski, 2006	SS; EJ	1-20; <1	-	-	-	n.d.-17; n.d.-57	n.d.-8; 2	200-1100; 1300-2100	5-31; 20-167
Tkalich et al., 2003	Baseline model	-	20	-	-	-	3	-	-
Delft Hydraulics, 2007	SS	-	-	-	3-28	-	3-24	6-220	10-60

The level of nutrients can be considered as a state indicator. An elevated level of nutrients may lead to increased phytoplankton biomass and eutrophication (see impact Chapter 5.2) and the abundance of bio-eroders.

4.3 Contamination

4.3.1 Heavy metals

Concentrations of As, Cd, Cr, Cu, Ni, Pb and Zn in the subsurface water samples, sea surface microlayer (SML) and in sediments collected from two mangrove sites (Sungei Buloh and Sungei Khatib Bongsu) and two coastal sites are presented in Table 13, Table 14 and Table 15, respectively. Heavy metal levels in the SML for both mangrove sites were more contaminated than coastal SML samples. No substantial enrichment of metals is evident in the coastal SML compared to subsurface water. In contrast, enrichment factors (EFs) for all metals in S. Khatib Bongsu mangrove were between 1.18 and 1.93 times higher than in subsurface water, reflecting an enrichment of heavy metals in the SML within mangrove habitats (Cuong et al. 2005).

Table 13 Concentrations of heavy metals (µg/l) in mangrove and coastal subsurface waters of Singapore (Cuong et al. 2005)

	As	Cd	Cr	Cu	Ni	Pb	Zn
Singapore's mangrove water							
S. Buloh	0.470 ± 0.017	0.159 ± 0.097	0.094 ± 0.004	0.284 ± 0.017	0.272 ± 0.022	0.193 ± 0.106	1.577 ± 0.095
S. Khatib Bongsu	1.083 ± 0.237	0.051 ± 0.010	0.208 ± 0.035	0.656 ± 0.141	0.447 ± 0.083	0.104 ± 0.091	1.378 ± 0.406
Singapore's coastal water							
Seletar	1.080 ± 0.046	0.254 ± 0.024	0.213 ± 0.012	0.640 ± 0.022	0.508 ± 0.015	0.980 ± 0.017	3.731 ± 0.162
Kranji	0.312 ± 0.009	0.015 ± 0.005	0.067 ± 0.003	0.170 ± 0.006	0.234 ± 0.014	0.006 ± 0.008	2.366 ± 0.168

Table 14 Concentrations of heavy metals (µg/l) in the SML of Singapore (Cuong et al. 2005)

	As	Cd	Cr	Cu	Ni	Pb	Zn
Singapore's mangrove water							
S. Buloh							
Concentration	0.580 ± 0.024	0.027 ± 0.007	0.119 ± 0.006	0.338 ± 0.017	0.290 ± 0.014	0.054 ± 0.016	1.381 ± 0.203
Enrichment factor	1.23	0.17	1.26	1.19	1.07	0.28	0.88
S. Khatib Bongsu							
Concentration	1.455 ± 0.191	0.076 ± 0.022	0.272 ± 0.031	1.108 ± 0.328	0.595 ± 0.076	0.201 ± 0.018	1.626 ± 0.316
Enrichment factor	1.34	1.50	1.31	1.69	1.33	1.93	1.18
Singapore's coastal water							
Seletar							
Concentration	1.068 ± 0.028	0.299 ± 0.011	0.215 ± 0.006	0.654 ± 0.012	0.526 ± 0.006	1.070 ± 0.032	4.461 ± 0.069
Enrichment factor	0.99	1.18	1.01	1.02	1.04	1.09	1.20
Kranji							
Concentration	0.350 ± 0.033	0.018 ± 0.001	0.075 ± 0.006	0.292 ± 0.014	0.246 ± 0.018	0.027 ± 0.007	2.469 ± 0.188
Enrichment factor	1.12	1.20	1.12	1.72	1.05	4.50	1.04

Table 15 Concentrations of heavy metals (µg/g dry weight) in mangrove and coastal sediments of Singapore relative to other countries (Cuong et al. 2005)

	Cd	Cr	Cu	Ni	Pb	Zn
Singapore's mangrove sediment						
S. Buloh	0.181 ± 0.349	16.61 ± 7.23	7.06 ± 6.03	7.44 ± 3.46	12.28 ± 5.18	51.24 ± 39.97
S. Khatib Bongsu	0.266 ± 0.171	32.07 ± 7.67	32.00 ± 14.32	11.65 ± 4.49	30.98 ± 6.16	120.23 ± 13.90
Singapore's coastal sediment						
Ponggol estuary	0.24		34.65	6.07	17.30	
Straits of Johore	0.18 ± 0.06	45.2 ± 11.2	30.7 ± 22.5	30.2 ± 6.6	42.3 ± 11	132.5 ± 52.6
Twenty coastal locations around Singapore	Nd[a]–1.4		2–204		2–60	5–280
Mangrove sediment elsewhere						
Guanabara bay, Brazil		37.4–43.4	79.6–91.7		165.5–169.5	447.5–505.1
Mai Po, Hong Kong	0.5–0.6	7.8–17.4	41.9–49.8	65.3–66.0	161.6–219.8	277.2–321.2
Deep Bay, Hong Kong	3	40	80	30	80	240
Mazatlan harbor, Mexico	< 2	7.6–42.5	7.7–90.9	6.1–30.3	<150	46.4–347.8
Brisbane river, Australia	<0.1–1.9	13.3–54.3	3.1–30.2		20.1– 81.9	40.8–144.0

[a] Nd: Not detected.

Metal concentrations were monitored at Ponggol Estuary, located on the northeastern coast of Singapore (Nayar et al. 2004a). The 1-year sampling from July 1999 to June 2000 spanned a period during which the estuary was affected by reclamation, dredging, construction, and shipping. Results showed elevated levels of five heavy metals, viz., tin, lead, nickel, cadmium, and copper, in Ponggol Estuary. Tin, lead, nickel, cadmium, and copper in particulate and dissolved fractions and sediments ranged from ND (undetectable)[3]–92 ppm, ND–303.2 ppm, ND–2818.4 ppm, ND–74.4 ppm and ND–1117.7 ppm, respectively. Similarly high concentrations of heavy metals in the coastal and estuarine waters of Singapore have been reported (Nayar et al., 2004a). These maximum concentrations of lead, nickel, cadmium and copper in Ponggol Estuary, as reported by Nayar et al. (2004a), are higher than those reported by Cuong et al. (2005), (18 to 464 times higher see Table 15). Intensive dredging activity during the monitoring period may have led to increased resuspension and bioavailability of particulate metals (Nayar et al. 2004a). For all metals greater concentrations were observed in the suspended particulates and then in the sediments.

Metals dissolved in water were always low and in certain instances below the detection limits of the instrument. Heavy metals are known to accumulate in mangroves (Cuong et al. 2005).Several factors collectively explain the higher concentrations of heavy metals in the particulates and sediments of the Ponggol estuary (Nayar et al. 2004a): the Ponggol estuary is a mangrove ecosystem, mangrove mud binds metals; fine sediments have a larger surface area, which allows heavy metals and other contaminants to be adsorbed easily; and organic matter, which is abundant in a mangrove-fringed estuarine ecosystem like the Ponggol Estuary, tends to preferentially associate with the finer sediments, and this leads naturally to their complexing with metals. Accumulation of heavy metals has also been observed in several seagrass species, for example the accumulation of zinc in *Halodule ovalis* (Peters et al., 1997).

Levels of contaminants in water, sediment and biota could be used as state indicators of pollution. Contaminants, such as heavy metals, could be measured in water, sediment and/or biota. Such concentrations of chemicals should be related to the valued characteristics selected as the assessment

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[3] The detection limits were 0.1, 0.01, 0.01, 0.002, and 0.01 ppb for tin, lead, nickel, cadmium, and copper, respectively.

endpoint, for example, fish population size and condition, areal coverage of mangroves or seagrasses, or coral reef community composition (Peters et al., 1997).

4.3.2 Phenols

Octylphenols, nonylphenols and pentachlorophenols are some of the more commonly encountered groups of surfactants collectively known as alkylphenol ethoxylates (Basheer et al. 2004). Table 16 and Figure 16 show the mean alkylphenol and bisphenol-A concentrations in Singapore coastal waters. The data show a high variability within the geographical sectors. The lowest levels are found offshore.

Table 16 Mean alkylphenol and bisphenol-A concentrations in Singapore coastal waters (Basheer et al. 2004)

Location no.	Sampling locations	Mean concentration in μg l⁻¹ ($n = 6$) (nd = <0.002 μg l⁻¹)										
		4-*n*-butyl-phenol	4-*t*-butyl-phenol	4-*n*-pentyl-phenol	4-*n*-pentyl-phenol	4-*n*-octyl-phenol	4-*t*-octyl-phenol	4-*n*-heptyl-phenol	4-nonyl-phenol	2,4-dichloro-phenol	Pentachloro-phenol	Bisphenol-A
Eastern Straits of Johor and Singapore												
1	Sembawang Park	1.57	2.30	0.05	0.10	0.36	0.14	2.14	1.08	1.44	0.40	1.70
2	Punggol	0.06	0.01	0.02	0.13	0.06	0.04	0.28	0.64	0.03	0.10	2.47
3	Pasir Ris	0.01	0.06	nd	0.05	0.01	0.02	0.02	0.34	1.97	0.01	0.03
4	Changi	0.89	0.27	0.32	0.19	0.53	0.46	2.92	2.08	0.59	0.53	0.75
5	Off-Pulau Tekong (off shore)	nd	0.01	0.01	nd	0.07	0.02	0.02	1.00	nd	0.03	1.02
6	Bedok Jetty	0.01	0.01	nd	0.03	0.02	0.01	0.01	1.26	0.87	nd	0.01
7	East Coast Park	0.00	0.07	nd	0.01	nd	0.01	nd	0.43	0.02	nd	0.02
Eastern and Central Singapore Straits												
8	Off-East Coast Park (off shore)	0.01	0.01	nd	nd	0.05	0.03	0.05	1.00	nd	0.33	0.02
9	Marina East	nd	0.07	nd	0.02	nd	0.01	0.01	0.93	0.01	0.00	0.03
10	Off-Marina (off shore)	nd	0.10	0.00	nd	0.11	0.15	0.09	0.33	nd	0.36	0.33
11	Clifford Pier	nd	0.12	nd	0.02	0.01	0.02	nd	0.67	0.02	0.01	0.04
12	Sentosa	0.59	0.95	0.06	1.86	0.13	0.32	0.07	2.76	1.55	0.09	0.04
13	Harbourfront	0.44	1.06	0.20	0.55	0.19	0.54	1.59	2.40	0.53	1.65	0.17
14	Labrador Park	0.01	0.01	nd	0.03	nd	nd	0.89	0.02	0.17	nd	nd
Southern Islands												
15	Sisters Island (off shore)	0.01	0.03	nd	0.01	0.05	0.04	0.03	1.03	0.05	0.03	0.04
16	St. John Island (off shore)	0.02	0.03	Nd	nd	0.10	0.01	0.01	0.32	nd	0.01	0.05
17	Pulau Hantu (off shore)	0.11	0.01	0.01	0.03	0.02	0.04	0.01	1.63	0.24	0.14	0.19
18	Pulau Satumu (off shore)	nd	0.31	nd	0.03	nd	0.01	nd	0.61	nd	0.05	nd
19	Cyrene Reef (off shore)	nd	0.01	0.01	0.01	0.03	0.02	0.03	0.44	nd	0.10	1.71
Western Singapore Straits												
20	West Coast Park	nd	0.11	nd	0.01	0.01	0.01	0.01	0.77	0.01	0.00	0.03
21	Jurong Island (off shore)	0.02	0.40	0.03	0.18	0.14	0.13	0.06	1.36	3.33	0.13	0.02
22	Jurong Pier	nd	0.01	0.04	0.00	0.11	0.06	0.02	0.28	0.08	1.06	0.97
23	Sultan Shoal (off shore)	0.05	0.03	nd	0.04	0.02	0.02	0.01	0.37	0.08	0.10	0.04
NW Johor, W Singapore Straits												
24	Tuas Jetty	0.68	2.25	0.07	1.03	0.65	0.80	0.07	1.26	1.67	2.15	0.22
25	Raffles Marina	0.01	0.01	nd	0.03	0.01	0.01	nd	0.20	0.06	nd	nd
26	Sarimbun (off shore)	nd	0.05	nd	0.01	nd	0.01	0.01	0.93	0.01	nd	0.01
27	Off Lim Chu Kang (off shore)	0.02	0.05	nd	0.02	0.02	0.02	0.01	1.51	2.93	0.09	0.03
28	Off Kranji (off shore)	0.02	0.05	0.01	0.01	0.01	0.04	0.01	1.01	2.84	0.05	0.04

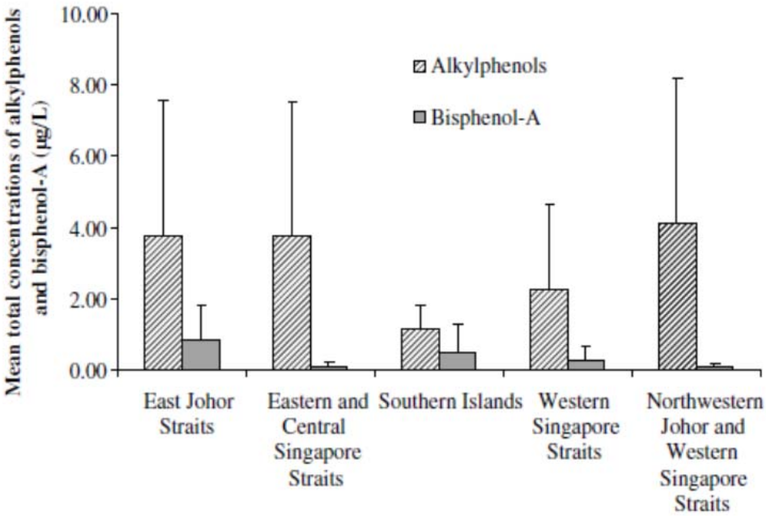

Figure 16 Mean concentration±standard error of total alkylphenols and bisphenol-A in seawater from Singapore waters. A total of 28 sampling locations were grouped into five geographical sectors (Basheer et al 2004) (for details refer to Table 16).

4.3.3 POPs

POPs are present in all compartments of Singapore's marine environment, including marine sediments, seawater and biota (Bayen et al. 2005). POPs of concern include 'conventional' POPs, such as polycyclic armotic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs), but also the polybrominated diphenyl ethers (PBDEs), which have emerged in the last decade as potential 'new' POPs of concern. PAHs are described separately in paragraph 4.3.4.

Notably, contamination patterns and POP concentrations differed on one side of the land-link causeway between Singapore and Malaysia in the Straits of Johore compared to the other, see Figure 17 (Bayen et al. 2005). The causeway represents a physical barrier to marine hydrodynamics around Singapore's northern coast, where there is no exchange of seawater across the causeway. Data on the levels of these POPs in seawater, sediments and twenty-four biota species at two mangrove sites in Singapore (Figure 17), to determine any differences of POP exposure in mangrove biota, are available (Bayen et al. 2005).

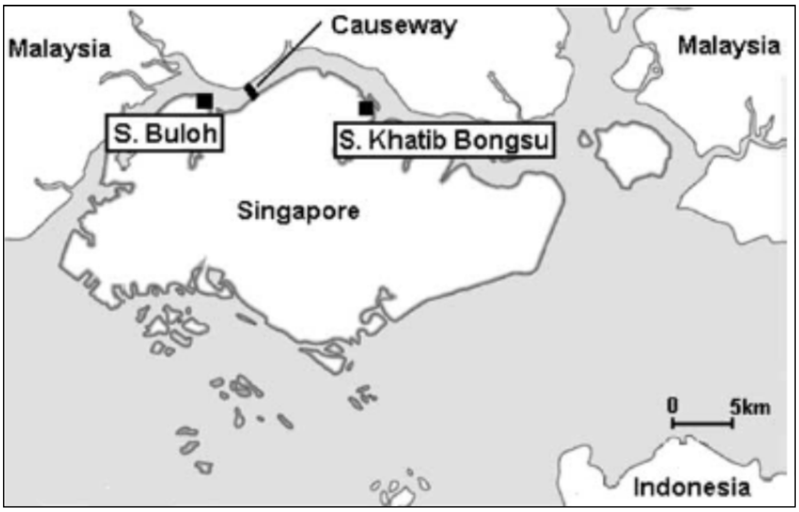

Figure 17 Location of Sungei Buloh and Sungei Khatib Bongsu mangroves in Singapore (Bayen et al. 2005).

Levels of POPs in seawater and sediments in both mangrove sites are summarized in Table 17. All POPs, except PBDEs, were detected in subsurface seawater, sea-surface microlayer and sediments. PCBs were the dominant POPs in subsurface seawater and sea surface microlayer with levels ranging from 0.1 to 6.7 ng/l and 2.4 to 26 ng/l respectively.

Table 17 Levels of POPs (range, average between brackets) in sediments, subsurface seawater and sea-surface microlayer collected from mangroves in Singapore (Bayen et al. 2005)

	POPs level in sediments ($ng\ g^{-1}$ dw)		POPs level in subsurface seawater ($pg\ l^{-1}$)		POPs level in sea-surface microlayer ($pg\ l^{-1}$)		Enrichment factor microlayer/subsurface	
	SB	SKB	SB	SKB	SB	SKB	SB	SKB
PCBs	0.59–1.14 (0.88)	0.80–1.86 (1.33)	6700–7100 (6900)	140–1500 (910)	2400–26000 (14000)	1500–7300 (4100)	0.3–3.9 (2.1)	2.3–10.9 (6.7)
PBDEs	<1	<1	<80	<80	<80	<80	n.a.	n.a.
DDTs	<0.1–0.93 (0.29)	0.56–0.85 (0.70)	18–23 (21)	3–72 (32)	21–170 (95)	27–99 (61)	1.2–33 (17)	1.4–8.3 (4.0)
HCHs	1.8–6.0 (3.9)	1.2–1.6 (1.4)	2000–2300 (2100)	110–1100 (770)	4000–9000 (6500)	880–1400 (1100)	1.7–22 (11)	0.8–8.8 (3.6)
Endosulfan	<0.2	<0.2	280–630 (450)	25–40 (30)	330–1800 (1000)	59–240 (140)	2.8	2.4–9.7 (4.9)
Chlordanes	0.01–0.04 (0.02)	0.02–0.06 (0.04)	4–8 (6)	<1–3 (2)	<1–5	<1	1.3	n.a.

The enrichment factor is calculated as the ratio of POPs levels between the subsurface water and sea-surface microlayer.
n.a.: not applicable.

Marine water samples within one kilometer of the coastline of Singapore were analysed to determine prevalent concentrations of a range of persistent organic pollutants (POPs) (Basheer et al. 2003b). Total OCP concentrations varied between 4.90 ng l^{-1} to 22.04 ng l^{-1} at surface, and 4.09 to 18.05 ng l^{-1} at mid-depth. Total PCB concentrations varied from 0.22 ng l^{-1} to 20.41 ng l^{-1} at surface and 0.4 to 10.79 ng l^{-1} at mid-depth. There concentrations are in line with the levels found at the mangrove sites (Bayen et al. 2005), as described above. In general, the distribution profile shows that the surface concentrations of POPs are higher than at mid depth. Levels of OCPs and PCBs are generally lower than reported levels for other Asian countries but higher than some levels reported elsewhere in the world (Bayen et al. 2005).

4.3.4 PAHs

Total PAH concentrations in surface water within one kilometer of the coastline of Singapore varied from 88.44 to 1419.57 ng l^{-1} at the surface, and 129.78 to 940.41 ng l^{-1} at mid-depth (Basheer et al. 2003b). Concentrations of PAHs were considered higher than reported levels for several other countries, most likely due to the presence of Singapore's extensive petroleum industry (Basheer et al. 2003b). The enrichment of PAHs in the sea-surface microlayer (SML) of Singapore (Lim et al. 2007) presents a potential threat to both marine biodiversity and commercial fisheries.

The prevalence and concentration of PAHs were also studied in marine sediments from Singapore's coastal environment (Basheer et al. 2003a). The total PAH concentration varied between 15.22 μg g^{-1} and 82.41 μg g^{-1} [4]in the northeastern region and between 13.63 μg g^{-1} and 84.92 μg g^{-1}in the southwestern region. The highest concentration of total PAH i.e. 84.92 μg g^{-1} was recorded at a site adjacent to a petrochemical refinery. Among the sixteen individual PAHs, chrysene, indeno[1,2,3-cd]pyrene and benzo[a]anthracene were most prevalent in the sediments.

The PAH content in the sediment can also be a state indicator for oil pollution of e.g. coral reefs.

4.3.5 Antifouling compounds

While stringent environmental pollution standards are in place for industrial effluents, there is currently no legislative control over pollution from antifouling paints in Singapore (Basheer et al. 2002). The concentrations of toxic antifouling agents tri, di and mono butyltin (resp.TBT, DBT and MBT), triphenyltin (TPhT) and Irgarol-1051 (2-methylthio-4-tert-butylamino-6-cyclopropylamino-s-triazine) were determined from seawater obtained from 26 locations along and off the coast of Singapore in October and November 2000 (Basheer et al. 2002). TBT concentrations in seawater ranged between 0.43 and 3.20 μg/l with a mean value of 1.40 ± 0.60 μg/l. The mean values of DBT and MBT were 1.07 ± 0.80 μg/l and 0.34 ± 0.50 μg/l respectively, while TPhT concentrations of up to 0.40 μg/l were found. Monophenyltin and diphenyltin were not detected in all samples analysed. Irgarol-1051 was found to be present at concentrations of between 3.02 μg/l and 4.20 μg/l in seawater with a mean value of 2.00 ± 1.20 μg/l.

4.4 Ecosystems

Singapore's main ecosystems are coral reefs, seagrasess and mangroves. This section describes the state of these ecosystems.

4.4.1 Coral reefs

In earlier days many island shores of Singapore were formed by vital fringing coral reefs, and these reefs had some of the highest biodiversity in the world (Bellwood, et. al., 2004). Nowadays reefs are located on the southern Islands only (Figure 18). Coral reefs in Singapore form a genetic continuum with reefs in Southeast Asia through migration of coral larvae, such that when local conditions improve, reefs may be repopulated. Reef quality in Singapore is, however, low compared to other reefs from Southeast Asia.

Main risks for reefs at Singapore are caused by coastal development (i.e. sediment related) and marine based pollution (i.e. water quality related), see Figure 19.

[4] Sediment sample was air dried. g PAH/g sediment is gram wet sediment

Cooper et al. (2009) give an overview of a selection of condition indicators applicable to monitoring programs of coral reefs. The environmental conditions included in the overview (see ANNEX 3) are mainly related to increased sedimentation/suspended solids/turbidity and nutrient enrichment.

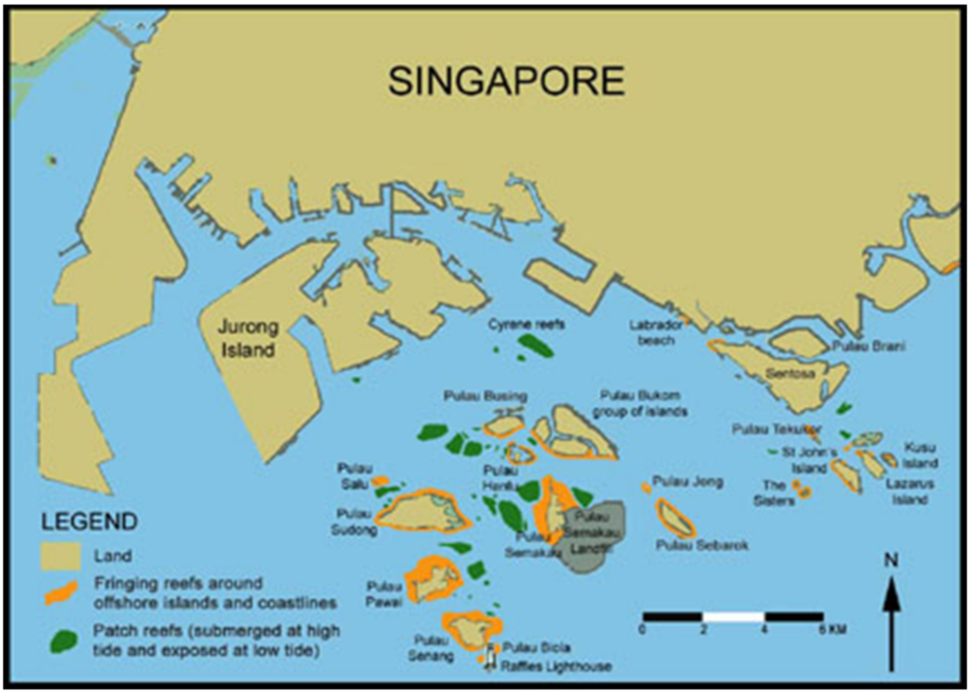

Figure 18 Location of fringing and patch reefs in Singapore (http://coralreef.nus.edu.sg/).

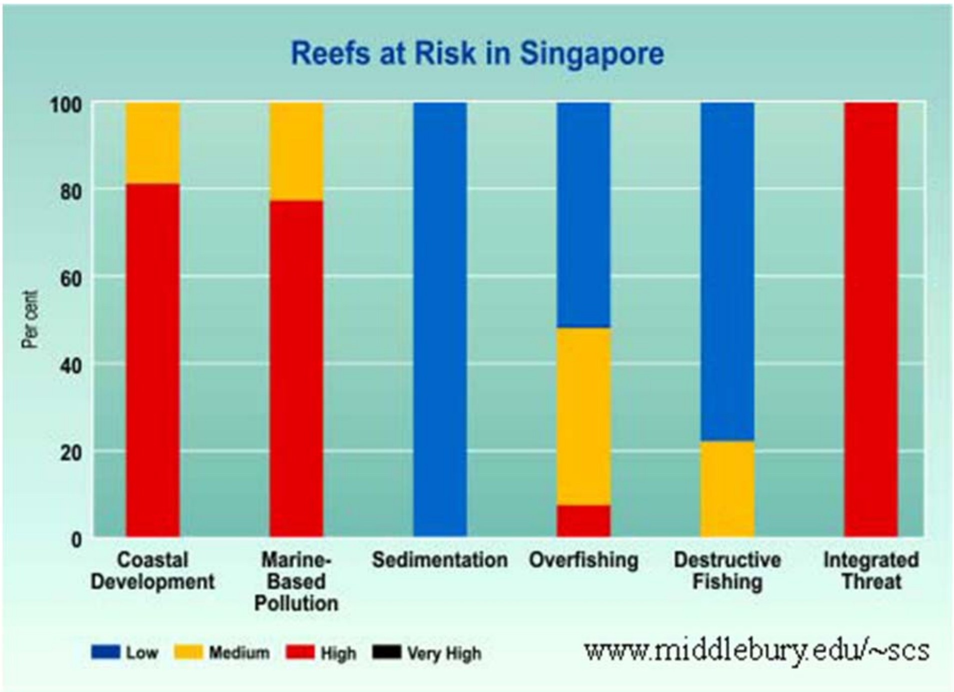

Figure 19 Reefs at risk at Singapore

4.4.2 Seagrass

There are at least 25 sites in Singapore at present known to have seagrasses, though not necessarily all in the form of dense meadows. Most sites are concentrated around the smaller islands to the south of Singapore, but there are also 7 sites along the shores of Singapore's 'mainland' (Figure 20). Some sites harbour dense meadows, most notably the extensive reef flats of Cyrene reef, west of Pulau Semakau and off Pulau Ubin.

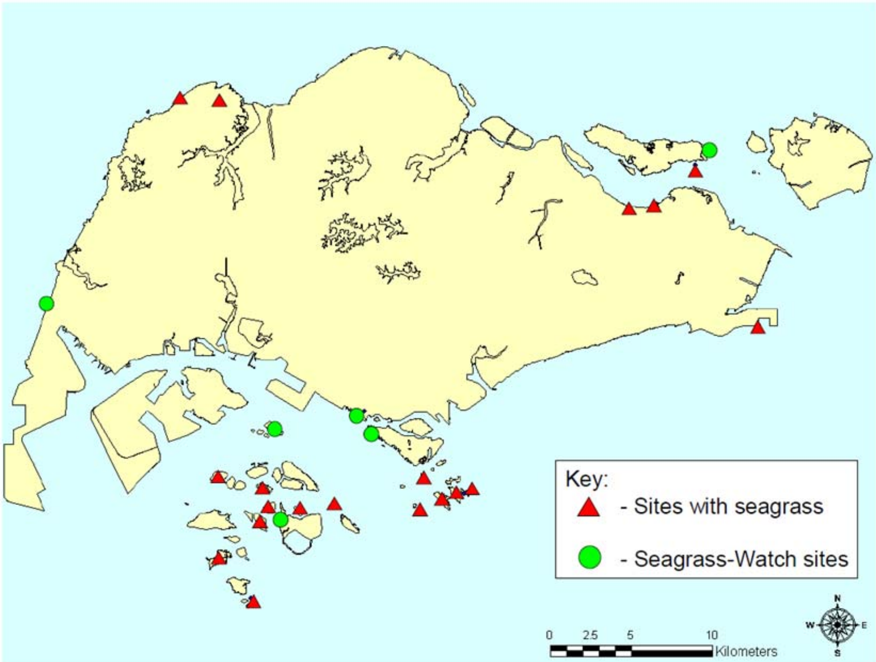

Figure 20 Seagrass sites in Singapore (Yaakub et al, 2008).

Most of Singapore's seagrass meadows are intertidal, with some (relatively sparse) subtidal Halophila ovalis and H. decipiens meadows at depths down to 8 m. There is no detailed historical data available on former depth distribution of seagrasses in Singapore, but it seems likely that the maximum depth penetration of most subtidal seagrass growth has decreased due to the marked increase in the turbidity of Singapore's coastal waters over the past few decades, similar to the decline in depth penetration reported for Singapore's corals (Chou and Tun, 2007).

4.4.3 Mangroves

The most abundant mangrove tree species in Singapore are *Avicennia alba, Sonneratia ovata, Rhizophora apiculata, Bruguiera cylindrical, Bruguiera gymnorrhiza, Ceripos, Xylocarpus, and Heritera.* Mangroves around Singapore contain several flagship species of which the long-tailed macaque monkeys is most probably the most appaeling. Other characteristic species are the Mudskipper, the spitting Archerfish and bats.

100 years ago, Singapore was covered by 13% of Mangrove area, of which only a few percent of the original cover is present today. A few remaining mangroves areas that have been preserved are relatively well protected, others are not. Except for Mandai, the mangroves have become national parks, be it with varying levels of protection. Figure 21 shows the change in mangrove area over the last 50 years.

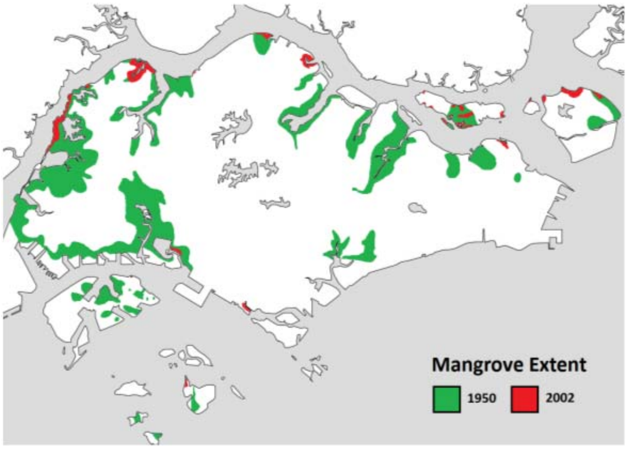

Figure 21 Qualitative impression of the change in mangrove area over the last 50 years.

4.4.4 Indicators

When selecting state indicators, the contaminant should be relevant to the species, communities and/or ecosystem of concern. We here consider corals, seagrass and mangroves. The three ecosystems differ in their structural basis (tree, macrophyte, and colonial invertebrate containing symbiotic algae, respectively) as well as in longevity (decades for mangroves, 1 year for seagrasses, centuries for corals). The valued ecological resources for these ecosystems are primary producers, those organisms that provide physical structure and food for the major communities on which other organisms, including humans, depend (Peters et al., 1997). The following resources, as selected by Peters et al. (1997), could be relevant indicators species:

- for mangrove forests, *Rhizophora* and *Avicennia spp*.;
- for seagrass beds, the turtle grass *Thalassia testudinum*; and
- for coral reefs, *scleractinian* corals.

It should be noted that, although *scleractinian* corals have economic and aesthetic value, species less valued by humans but crucial for the survival and health of reefs, such as herbivorous fishes or long-spined sea urchins, might also be useful indicator species.

4.5 Contaminants in biota[5]

The marine environment of Singapore is contaminated with a range of substances. Biota from the marine environment of Singapore have been found to contain organic pollutants (Basheer et al. 2004, Obbard et al. 2007) and heavy metals (Flammang et al. 1997, Cuong et al. 2005). In this section contaminants in biota are considered as state descriptors. However, they can also be regarded as impact descriptors (see Chapter 5.4).

Organic pollutants
Alkylphenols and bisphenol-A were detected in all seafood samples purchased from a local supermarket (Basheer et al. 2004). Up to 530.4 ng/g wet weight (w.w.) of total alkylphenols (see Figure 22) was found and between 13.3 and 213.1 ng/g w.w. of bisphenol-A in prawn, crab, blood cockle, white clam, squid, and fish (Table 18).

[5] Could be assessed as an impact as well

Table 18 Alkylphenols and bisphenol-A in seafood samples purchased from a local supermarket in Singapore (Basheer et al. 2004)

Analytes	Concentration (ng g^{-1} wet weight ± SE) ($n = 5$)					
	Prawn (*Penaeus monodon*)	Crab (*Portunus pelagicus*)	Blood cockle (*Anadara granosa*)	White clam (*Meretrix meretrix*)	Squid (*Loligo* sp.)	Fish (*Decapterus russelli*)
4-*n*-butylphenol	4.5 ± 1.1	20.0 ± 0.8	25.3 ± 6.1	23.7 ± 5.4	11.5 ± 3.7	19.3 ± 5.1
4-*t*-butylphenol	21.3 ± 17.0	24.0 ± 2.1	8.8 ± 5.6	6.5 ± 3.7	13.9 ± 13.1	19.0 ± 9.0
4-*n*-pentylphenol	3.7 ± 8.3	8.0 ± 6.0	6.3 ± 1.4	5.5 ± 1.2	5.7 ± 2.6	5.4 ± 2.1
4-*n*-hexylphenol	7.0 ± 12.2	9.0 ± 5.0	5.9 ± 0.8	4.3 ± 2.4	6.0 ± 3.3	6.0 ± 3.1
4-*n*-octylphenol	23.0 ± 18.9	4.1 ± 2.3	5.4 ± 3.3	4.5 ± 2.0	5.5 ± 1.9	3.3 ± 1.0
4-*t*-octylphenol	20.4 ± 15.8	20.2 ± 1.2	6.7 ± 2.7	44.9 ± 21.2	10.2 ± 5.4	31.4 ± 15.0
4-*n*-heptylphenol	10.2 ± 6.7	5.1 ± 2.1	6.0 ± 4.5	5.7 ± 3.3	4.1 ± 1.7	4.4 ± 1.5
4-nonylphenol	197.0 ± 13.1	103.1 ± 36.0	54.0 ± 6.1	46.6 ± 11.4	64.8 ± 13.7	60.5 ± 10.4
2,4-dichlorophenol	10.7 ± 7.5	191.0 ± 22.0	152.4 ± 37.0	139.7 ± 43.5	84.1 ± 20.2	141.2 ± 22.8
Pentachlorophenol	47.8 ± 24.5	146.0 ± 10.8	107 ± 56.1	71.4 ± 82.8	41.8 ± 47.4	37.7 ± 3.9
Bisphenol-A	13.3 ± 8.4	213.1 ± 20.2	56.5 ± 40.0	27.4 ± 29.1	118.9 ± 107.1	65.6 ± 47.4

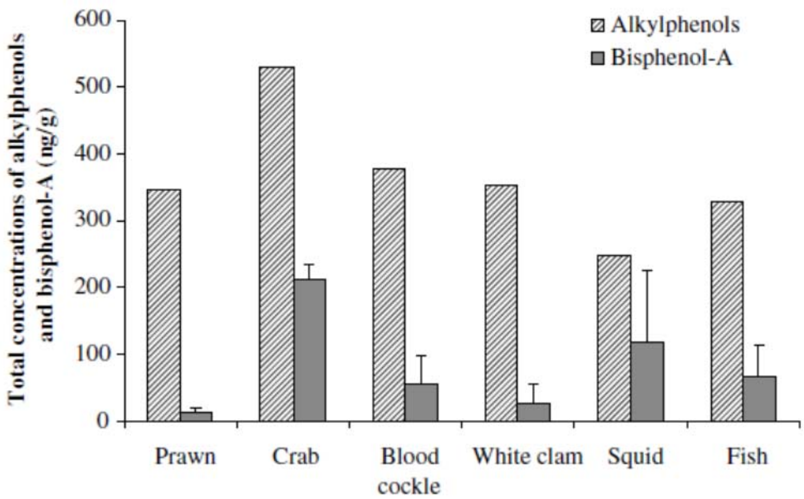

Figure 22 Total alkylphenol and bisphenol-A in seafood samples from a local supermarket (Basheer et al. 2004).

The ubiquity of POPs, including polybrominated diphenyl ethers (PBDEs), in the marine environment of Singapore was confirmed (Bayen et al. 2005). A biomagnification phenomenon was observed amongst the species collected and analysed from two mangrove sites studied. Thunder crabs and fish displayed the highest POP levels. Congener profiles of PBDEs varied amongst mangrove biota species and suggested different metabolic pathways exist for flame retardants. Similarly, crab species showed an ability to metabolize chlordane insecticide (Bayen et al. 2005). Concentrations of chlordanes, DDTs, PCBs and PBDEs, on a dry weight basis (dw), are summarized for fifteen species common to the two mangrove study sites in Figure 23. Higher concentrations of PCBs and PBDEs were generally found in biota from S. Khatib Bongsu and chlordanes in biota from S. Buloh. However, the differences between the two sites was not significant using a linear correlation analysis ($p > 0.05$).

Levels of POPs found in biota of two mangrove sites (Sungei Buloh and Sungei Khatib Bongsu) were comparable to concentrations of POPs found in the eggs of fish-eating birds, such as heron and egrets, where toxicological risks to breeding success were revealed (Bayen et al. 2005).

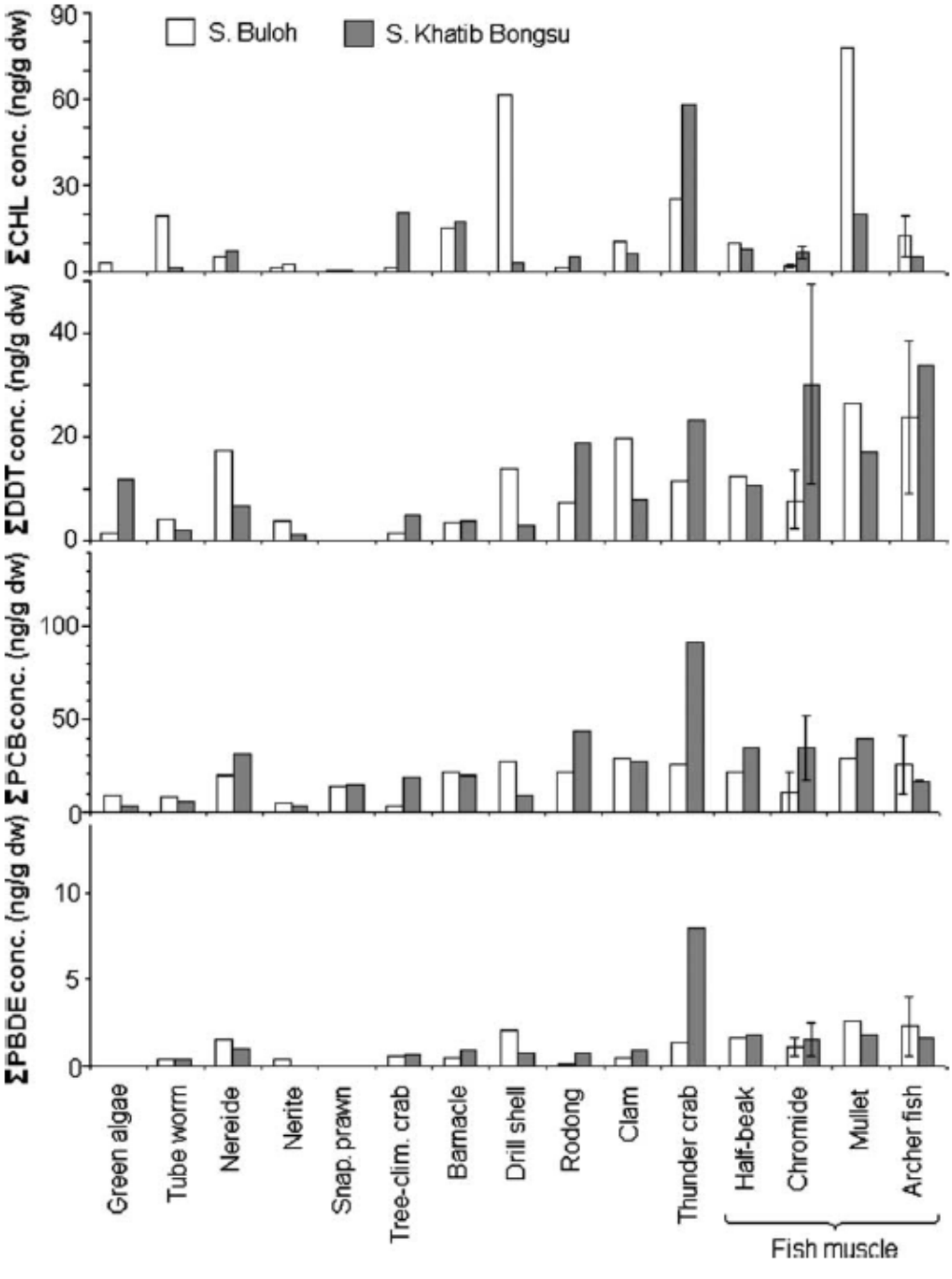

Figure 23 Concentrations of POPs in mangrove biota in Singapore (ng/g dw). (Average value obtained for duplicate analysis, except for chromide and archer fish for which three individual fish were analysed separately.) (Bayen et al. 2005).

Heavy metals in biota

Levels of heavy metals in the mangrove sediments of Singapore are presented in the context of available data from other countries in Table 19. There is no clear difference in prevailing concentrations of As, Cd, Pb and Ni between the two mangrove sites. However, levels of Cu and Zn were notably higher in S.

Khatib Bongsu than in S. Buloh (star values; see Table 19). This is consistent with the results for seawater and sediment samples.

Table 19 Concentrations of heavy metals in mangrove biota of Singapore relative to other countries (Cuong et al. 2005)

Organism	Site	%d/w	As	Cd	Cu	Ni	Pb	Zn
Nerita lineate	SB[a]	80 ± 3	2.7	0.03	7.5	2.7	0.49	31
	SKB[b]	81 ± 0	5.7	0.02	8.8	10	1.1	680*
Nerita albicilla	Taiwan			6.9 ± 1.1 dw				
	Hong Kong			1.8–2.9 dw	133–189 dw			105–130 dw
Polymesoda expansa	SB	84 ± 0	6.7	0.03	3.1	1.4	0.64	65
	SKB	87 ± 0	3.9	0.06	14*	1.1	0.28	72
Telescopium telescopium	SB	78 ± 1	12	0.05	85	7.6	0.48	340
	SKB	75 ± 2	10	0.12	140*	10	1.4	100
	Australia			Nd[c]–2.06	0.7–72	Nd–2.89	Nd–8.99	9.6–199
Thai gradate	SB	63 ± 9	4.1	0.47	52	5.4	0.91	65
	SKB	76 ± 5	10	0.37	110*	2.4	0.53	140*
Thai clavigera	Hong Kong			7.3–9.9 dw	183–310 dw			261–313 dw
	Taiwan				492 ± 132 dw			768 ± 333 dw
Myomenippe hardwicki	SB	84 ± 5	3.9	0.02	35	1.7	0.73	49
	SKB	75 ± 1	4.7	0.08	63*	2.5	0.76	60*

Levels are presented as μg/g wet weight, except where stated otherwise.
[a] SB: Sungei Buloh.
[b] SKB: Sungei Khatib Bongsu.
[c] Nd: not detected.

5 Impacts

5.1 Introduction

The previous chapters describe activities (Chapter 2), pressures (Chapter 3) and states (Chapter 4) that are related to impacts on Singapore's marine environment. In this chapter the potential impact on Singapore's marine environment is described, according to the following elements:

- Eutrophication, resulting from nutrient enrichment;
- Contamination effects, resulting from concentration levels in water, sediment and biota;
- Contaminants in biota, resulting from concentration levels in water and sediment.

5.2 Eutrophication

5.2.1 Observed effects

As described in Chapter 3.2 (pressures – nutrient enrichment), high nutrient loads in the coastal water of Singapore are mainly caused by the variable anthropogenic land-based inputs from rivers, urban runoff, domestic, industrial and agricultural sewage. Such nutrient influxes may stimulate primary production that in turn may lead to an increase in phytoplankton biomass and sustain elevated levels of phytoplankton standing crop. Further nutrient increase can lead to the formation of Harmful Algal Blooms (HABs) and oxygen depletion (Chia, 2000).

Increased phytoplankton biomass

In the enriched waters of Johor Strait, frequent algal blooms were observed with chlorophyll-*a* levels up to 60 µg l^{-1}. These occurrences of the blooms seemed not to depend on seasonality, but were more likely related to variations in anthropogenic inputs and subtidal conditions (Wolanski, 2006). Even higher concentrations of Chlorophyll-*a* of up to 92.0 µg l^{-1} were determined in the centre of the strait decreasing to 70 µg l^{-1} close to Kuala Johor. Yew-Hoong Gin et al. (2002) found on average comparable results with chlorophyll-*a* levels fluctuating widely ranging from 0.5 to 139 µg l^{-1}.

On the contrary, Singapore Strait has generally lower chlorophyll-*a* concentrations, with the highest values being lower than 4 µg l^{-1} (Wolanski, 2006; Delft hydraulics, 2007; Yew-Hoong Gin et al., 2002).

Harmful Algal Blooms (HABs)

The occurrence and increased frequency of HABs, commonly known as red tides, have been noted during monitoring of the phytoplankton composition in Singapore and Johor Straits (Khoo and Wee, 1996). The rich coastal waters of the Straits around Singapore stimulate the growth of a variety of dinoflagellates. The most predominant species causing the red-tide phenomenon are *Noctiluca scintillans* and *Hornellia marina* (Choo et al., 1994). The occasional blooms of these organisms are reported to cause fish and shrimp mortality as a result of oxygen depletion.

Furthermore, HABs causing Paralytic Shellfish Poisoning (PSP) were known to occur in the coastal waters of Singapore since the mid 90's. Occasionally, people have reportedly been hospitalized with PSP-like symptoms (Anton et al. 1995). The dinoflagellates which caused PSP were identified as *Alexandrium tamiyavanicii* (Norhana and Nahar, 1996). The occurrence of the marine blue-green algae, *Trichodesmium erythraeum* in Singapore coastal waters was reported as early as 1974 (Khoo and Wee, 1996). In later years, two other dinoflagellates (Cochlodinium sp and *Gymnodinium catenatum* and Chattonella sp) which may cause PSP were also reported.

Oxygen depletion
Oxygen concentrations were measured in the two main Straits. Yew-Hoong Gin et al. (2000) observed DO levels between 6 and 8 mg l^{-1} in Singapore Strait, with higher values near the surface due to reaeration from the atmosphere and photosynthesis. Other studies (Chou et al., 2004; Delft Hydraulics, 2007, Gin *et al*., 2002) show that in Singapore Strait oxygen levels do not drop below 4.0 mg l^{-1}, while in Johor Strait they can decrease down to 2-3 mg l^{-1} (Cheong et al., 2001;). There, highest concentrations (11 mg l^{-1}) were observed during the rainy season and lowest (2 mg l^{-1}) at the end of a long rainy season. Oxygen stratification is observed in the central part of the Strait, and it is attenuated along the direction to Kuala Johor.

5.2.2 Coral reefs

There is a strong variation in effect of nutrient enrichment on coral reefs. A wide range of nutrient impacts have been reported, from little or no impacts to major changes in coral reef community structure (Naim, 1993; Lapointe, 1997; Koop et al., 2001; Szmant, 2002). Some authors proposed threshold nutrient levels above which coral reefs would become degraded (Lapointe, 1997) but complex local factors often determine the magnitude and extent of the impacts of nutrient enrichment.

Nutrient enrichment is generally considered to be mainly an indirect stress, as it first influences benthic and planktonic algae (Lapointe, 1997). Consequently elevated phytoplankton populations reduce light penetration which may in turn affect coral nutrition, growth, and survival (Kinsey and Davies,1979). Reduced water clarity causes reduction in photosynthesis and growth in corals (Rogers, 1983; Telesnicki and Goldberg, 1995), consequently restricting the depth range within which corals can survive (Loya, 1976; Yentsch et al., 2002; Anthony and Fabricius, 2000). Increased production in the water column often favors the growth of benthic filter-feeders which may out compete corals for space (Birkeland, 1977). Benthic algae increase in biomass, colonize coral skeletons and overgrow and kill living corals by forming thick mats which kill all underlying organisms by blocking light and trapping sediment (Mc Cook, 1999; Mc Cook et al., 2001).Certain algae such as *Enteromorpha spp.* (Fong et al., 1993) or *Dictyosphaeria cavernosa* (Stimson et al., 2001) have been reported to significantly develop in response to anthropogenic nutrient inputs. The foliose macroalgae *Sargassum spp*. is also known to have a high nutrient demand and to use a large range of nutrient sources (Schaffelke and Klump, 1998; Schaffelke, 2001). Such species with physiological capabilities to overgrow coral reefs in the presence of nutrient inputs can be considered as indicator of water quality.

The indirect effects of nutrients on coral reef systems are complex. Although coral reef condition indicators, such as hard and soft coral diversity, reef growth, bio-erosion, coralline algal abundance, coral recruitment and recruit survivorship, can be correlated with nutrients the actual nature of the interaction causing reef degradation is complex and still poorly understood (Moss et al., 2005). The interactions between macroalgal growth, grazing pressure on the algae, nutrient enhancement of algal growth and hence coral-algal competition for space on coral reefs, however, has been studied extensively and is currently relatively well understood (McCook, 1999; McCook et al., 2001; Miller, 1998; Lapointe, 1997; Hughes et al., 1999; Stimson and Larned, 2001). Another well studied nutrient-related interaction on reefs of the Indo-Pacific is that between the coral-eating crown of thorns starfish (*Acanthaster planci*) and reef condition. *A. planci* outbreaks seem associated with broad scale nutrient enrichment from land runoff and subsequent phytoplankton blooms leading to enhanced survivorship of *A. planci* larvae, this happens when chlorophyll concentration are above 0.5–0.8lgl-1 (Brodie et al., 2004). To minimize *A. planci* outbreaks limits for chlorophyll concentration can be set at 0.5lgl-1 in the larval period of *A. planci* (November to February).

The direct effects of dissolved inorganic nutrients, such as nitrate, ammonium and phosphate, on adult corals are also complex as indicated by the variable responses of elevated nutrients on corals in studies investigating this relation. In some studies increased nutrient concentrations increased coral growth, but reduced skeletal density, while in others high concentrations had the opposite effect. Some workers found that at high nutrient concentrations the density of zooxanthellae in the coral is increased which changes the balance of energy, CO2 and nutrients between zooxanthellae and coral (Muscatine et al., 1989; Marubini and Davies, 1996; Ferrier-Pages et al., 2001). Furthermore reproduction of corals is negatively affected by nutrients as shown by Cox and Ward (2002) who found decreased larval production at slightly elevated ammonium concentrations.

Bioerosion is the process of erosion of substrata by biological activity, and comprises both internal bio-erosion (i.e. micro- and macro-bioeroders) and external bio-erosion (i.e. grazers) (Hutchings 1986; Bellwood 1995). Macro-bioeroders are predominantly sponges, polychaetes, sipunculans, barnacles and bivalves. Rose and Risk (1985) found an increased abundance of the boring sponge *Cliona delitrix* on reefs associated with an increase in nutrients added to the system by discharge of untreated sewage. An increase in the abundance of macro-bioeroders and distance from the coast was found in *Acropora formosa* and massive colonies of Porites. This was attributed primarily to a greater exposure to terrestrially derived nutrients on nearshore reefs on the Great Barrier Reef (Sammarco and Risk 1990; Risk et al. 1995;). Abundances of macro-bioeroders have been shown to have a high specificity and slow-response period to spatial differences in water quality (Cooper et al. 2008b), and hence provide a useful time-integrated measure of water-quality changes. For this reason, abundance of macro-bioeroders ranked a high-priority bioindicator for use in long-term monitoring, but had medium priority for short-term monitoring because of the slow-response period (Table 20). The abundance of macro-bioeroders can be determined with counts of external bore holes occurring in quadrates placed on the surface of living massive corals.

Table 20 Overview of bio-indicators and corresponding response period (A selection after Cooper et al, 2009).

Response	Method	Response time
Coral growth	Gamma densitometry	Months
Skeletal elemental and isotopic composition	Mass spectrometry	Days to months
Partial mortality	Visual estimate	Days to months
Mucus production	Visual estimate	Immediate to weeks
Population measures		
Population structure	Quantify colony size	Months to years
Coral diseases	Visual estimate	Weeks
Abundance of macro-bioeroders	Visual estimate, quadrats	Months to years
Community measures		
Micro- and meiobenthic bioindicators	Sediment or rubble samples, deployment of glass slides	Days to months
Coral larval supply	Larval traps, settlement plates	Days to weeks
Coral recruitment	Counts along transects, quadrats	Weeks to years
Benthic cover corals and octocorals	Video or photo transects	Days to years
Benthic cover macroalgae	Video or photo transects	Months
Community structure	Taxonomic inventories	Days to years
Taxonomic richness	Taxonomic inventories	Months to years
Max. depth coral-reef development	Visual estimate	Months to years (?)

Living coral coverage, sometimes associated with the ratio of living/dead coral coverage, or the ratio between algal/living coral coverage are the most commonly used descriptor of nutrient enrichment impact on coral populations. However, no detailed case-studies were conducted to validate the robustness and usefulness of these potential indicators (Fichez et al., 2005).

5.2.3 Seagrass and mangroves

Local information on the impact of nutrient enrichment on seagrasses and mangroves in Singapore were not found in literature. A general description of impact is given instead.

(Burkholder et al. 2007)reviewed the consequences of eutrophication's on seagrasses. Seagrass decline can occur under nutrient over-enrichment. Nutrient enrichment stimulates high-biomass algal overgrowth of epiphytes and macroalgae in shallow coastal areas, and of phytoplankton in deeper coastal waters. This results in light reduction and reduced growth of seagrass. Direct physiological responses such as ammonium toxicity and water-column nitrate inhibition through internal carbon limitation may also contribute. Seagrass decline under nutrient enrichment appears to involve indirect and feedback mechanisms, and is manifested as sudden shifts in seagrass abundance rather than continuous, gradual changes (Burkholder et al. 2007).
A decrease in water-column light penetration adversely affects seagrass photosynthesis rates (Longstaff & Dennison 1999). Longstaff (2003) have defined the long-term quantity of light required for sea grass survival (Table 21).

Table 21 Minimum light requirements for three species of sea grass (long-term: 10 or more weeks) (Moss et al., 2005)

Long-term (>10 weeks) minimum light requirements for three species of seagrass

	Halophila ovalis	*Halodule pinnifolia*	*Zostera capricorni*
Molphoton $m^{-2} d^{-1}$	<5 (7.5)[a]	<10 (15)	10 (15)
% surface light	~6% (10%)	~20% (30%)	~30% (45%)

[a] Numbers in brackets are suggested guideline values based on Longstaff's data.

Indirect effects on trophic structure can also be critically important, for example, the loss of herbivores, through increased hypoxia/anoxia and other habitat shifts, that would have acted as "ecological engineers" in promoting seagrass survival by controlling algal overgrowth; and shifts favoring exotic grazers that out-compete seagrasses for space (Burkholder et al 2007).

Seagrasses can be considered as "long-term" integrators (days to weeks) of nutrient availability, especially through analyses of their tissue content, and of activities of enzymes such as nitrate reductase and alkaline phosphatase.
The ratio of leaf nitrogen content to leaf mass has also shown promise as a "nutrient pollution indicator" for the seagrass Zostera marina, with potential application to other species (Burkholder et al 2007).

Mangrove ecosystems are susceptible to nutrient enrichment as well. Studies have shown that growth of intertidal mangrove forests is accelerated with enhanced nutrient availability (Lovelock et al 2009) . However, nutrient enrichment favours growth of shoots relative to roots, thus enhancing growth rates but increasing vulnerability to environmental stresses that adversely affect plant water relations. Two such stresses are high salinity and low humidity, both of which require greater investment in roots to meet the demands for water by the shoots.

5.3 Contamination effects

5.3.1 Observed effects

Toxicity effects have been observed in the marine environment of Singapore which could be attributed to different contaminants, such as heavy metals, petroleum compounds and organotin compounds.

Heavy metals
Toxicity effects (e.g. decreased phytoplankton production and decreased autotrophic bacteria counts) of heavy metals concentrations found in in Ponggol Estuary, Singapore have been observed (Nayar et al. 2004a). Nayar et al. (2004a) exposed phytoplankton and bacteria in mesocosms to previously measured environmental levels of heavy metals from Ponggol Estuary. Intensive dredging activity during the monitoring period may have led to the resuspension and bioavailability of particulate metals (Nayar et al. 2004a). The results showed significant copper toxicity to phytoplankton and autotrophic bacteria, followed by nickel and lead at all concentrations tested. Production of exposed phytoplankton varied from appr. 2% (Cu) to 25% (Sn) in relation to controls. Enhanced rates of heterotrophic bacterial production (varied from appr. 300% (Cu) to 1500% (Cd) in relation to controls) and total bacterial abundance (up to appr. 500% (Sn) in relation to controls) were observed in treatments with higher metal concentrations. The study showed that phytoplankton was inhibited by the background concentrations of heavy metals that were biologically available from the sediments resuspended by dredging, while bacterial heterotrophs were not negatively affected (Nayar et al. 2004a).

Phenols

A common group of surfactants collectively known as alkylphenol ethoxylates (e.g. octylphenols, nonylphenols and pentachlorophenols) can cause adverse changes in the reproductive health of humans and animals (Basheer et al. 2004). These substances have been found in coastal waters and supermarket seafood from Singapore. No studies on impact were conducted.

Hydrocarbons

Harmful effects from petroleum hydrocarbons to soft-bottom macrobenthic communities have been observed at locations in the northeast area and the southwest area, Singapore (Lu 2005). Total petroleum hydrocarbons were significantly negatively correlated with species number, abundance and diversity, suggesting harmful effects from petroleum hydrocarbons on macrobenthic communities in Singaporean waters. Nayar et al. (2004b) found effects from petroleum hydrocarbons on the periphytic algal biomass. A reduction in periphytic algal biomass (with respect to controls) of 68–93% was observed for various treatments exposed to diesel (Nayar et al. 2004b). Bacteria and phytoplankton were also affected by exposure to environmentally measured concentrations of petroleum hydrocarbons in Ponggol estuary, using diesel fuel as the source of contaminant (Nayar et al. 2005). Results showed inhibition of phytoplankton, as seen from the decrease in phytoplankton production, chlorophyll a concentrations and cell counts.

POPs

Response of aquacultured oysters to POP's has been studied at Sungei Buloh and Sungei Khatib Bongsu, Singapore (Bayen et al. 2007). Growth rates differed significantly at the two sites, revealing that marine water quality can have potentially adverse effects for the oyster aquaculture industry in Singapore. The oysters from the uncontaminated site grew from 11 to 68mm over 230 days. In contrast, the oysters from the contaminated site grew relatively slowly, from 11 to only 20mm over 230 days. The levels of all POPs (PCBs, DDTs, Chlordanes, Heptachlor, PBDEs) in subsurface seawater, except for PBDEs, were higher at the contaminated compared to the uncontaminated site. PBDEs were not detected at either site. There were no significant differences with respect to temperature, salinity, dissolved oxygen, chlorophyll a and total organic carbon between the two sites. Shell abnormalities (chambering) were observed for juvenile and mature oysters at the contaminated site (Bayen et al. 2007).

Singapore's marine sediments (north-eastern and south-western coastal regions of Singapore) can be classified as moderately contaminated with probable ecotoxicological impacts to marine organisms (Wurl & Obbard 2005c). Significant levels of selected organochlorine pesticides, PCBs and PBDEs have been found in the surface sediments.

Antifouling compounds

A study on the levels of antifouling substances in the coastal environment of Singapore (Basheer et al. 2002) describes effects from some of these substances, cited from several studies. Irgarol-1051 is highly toxic to non-target marine algae (Table 22) and is sufficiently stable to reach toxic concentrations in the environment. The mode of action is based on the inhibition of photosynthetic electron transport in chloroplasts. Irgarol-1051 inhibits photosynthesis at concentrations lower than 1 µg/l. It is feared that Irgarol-1051 might inhibit the growth of algae along shorelines, changing biological communities and altering the ecology of coastal areas (Basheer et al. 2002).

Imposex in snail species (the masculinisation of females of certain marine snails in response of the exposure to TBT) has been observed as a localized effect from the presence of organotins at Johor Straits (Tan 1999).

Table 22 Recent toxicity data of Irgarol 1051 for several species of the aquatic environment (Konstantinou & Albanis 2004). EC_{50}^{a}= effect concentration LC_{50}^{b} = lethal concentration (µg/l) $NOEC^{c}$= No observed effect concentration (µg/l) $LOEC^{d}$ =lowest observed effect concentration (µg/l)

Class	**Test organism**	**Toxicity index**	**EC_{50}^{a}/LC_{50}^{b}**	**$NOEC^{c}/LOEC^{d}$**
Corals	*Madracis mirabilis*	-	-	0.063^{d}
phytoplankton	*Various species*	EC50	0.441-0.647	$0.025\text{-}0.647^{d}$
bacteria	*Virbio fischeri*	15 min EC50	50800 ± 7800	10000 ± 1900^{d}
crustacean	*Artemia salina*	24 h LC50	>4*10^4	
Sea urchin	*Anthocidaris crassispina*	32 h	-	10^{c}

5.3.2 Coral reefs

Laboratory studies have identified several effects of oil on corals, as summarized by Haapkyla et al. (2007), such as decreased growth rate and histopathological effects. Furthermore, field studies have shown exposure to oil can significantly decrease coral cover and that the size of gonads is a suitable measure of long-term (>3 years) sub-lethal effects of oil on reproduction (Haapkyla et al., 2007).

5.3.3 Seagrass and mangroves

Inputs of toxic chemicals, e.g. in catchment runoff are known to cause species-specific effects in mangroves, resulting in dieback or damage of species sensitive to toxic chemicals (Schaffelke et al. 2005). Table 23 shows an overview of effects of pollution on seagrasses and mangroves. Peters et al (1997) report that mangroves act as a sink for heavy metals and are relatively insensitive to heavy metal pollution.

Table 23 Summary of reported effects of water pollutants and physical disturbance on macrophytes in the Great Barrier Reef region, Australia (Schaffelke et al. 2005). Arrows indicate positive ↑ or negative ↓ effects on macrophyte health and production, black for strong, grey for weaker effects

	Macrophyte community type					
	Mangroves		Seagrasses		Macroalgae	
Nutrient availability	↑↓	Correlation of tissue nutrient content and availability Increased growth Increased epiphyte cover on roots Threshold effect?	↑↓	Correlation of tissue nutrient content and availability Increased growth Increased epiphyte cover on leaves Threshold effect?	↑↓	Correlation of tissue nutrient content and availability Increased growth Increased epiphyte cover Threshold effect?
Sediments/suspended solids	↓	Burial, smothering	↓	Burial, smothering Decreased light availability	↑↓	Burial, smothering Decreased light availability Potential nutrient source
Herbicides	↓	Local mortality of sensitive species	↓	Limited data Inhibition of photosynthesis	↓	Limited data Inhibition of photosynthesis, synergism with sediment
Heavy metals	↓	Limited data on tissue metal content Species and site-specific tolerance?	↓	Limited data on tissue metal content Inhibition of photosynthesis in exposure experiments Species and site-specific tolerance?	↓	Limited data Low tissue levels
Oil spills	↓	Mortality/damage by smothering of breathing roots	↓	Mortality by smothering Inhibition of photosynthesis by toxic effects of oil and dispersants	?	No data
Reclamation/alteration of habitat	↓	Mortality/damage by removal and coastal development	↓	Mortality/damage by removal Slow recolonisation (years) after transient disturbance	↓	Mortality/damage by removal Quick recolonisation (months) after transient disturbance

5.3.4 Indicators

Although the concentrations of contaminants give an indication of the state of the environment regarding chemical pollution, as described in Chapter 4.3, effect- or impact indicators are required to measure the impact of the pollution. Effects can occur at every level of biological organization, so a variety of indicator species and appropriate biomarkers might give advance warning of the bioavailability of the contaminants and potential effects prior to the loss of significant habitat (Peters et al., 1997). An overview of available biomarkers in tropical marine organisms is presented in Annex 3.

5.4 Contaminants in biota

Contaminants in biota can be addressed in two ways:

- as a state descriptor, potentially leading to contamination effects (see also Chapter 4.4.4), or;
- as an impact of contamination in water and sediment, through bioaccumulation.

As described in Chapter 4.4.4, biota from the marine environment of Singapore have been found to contain organic pollutants (Basheer et al. 2004, Obbard et al. 2007) and heavy metals (Flammang et al. 1997, Cuong et al. 2005). This could lead to contamination effects. Concentrations of POPs found in the eggs of fish-eating birds, for example, revealed toxicological risks to breeding success (Bayen et al. 2005). It was recommended that the risk for organisms at higher trophic levels in the mangroves of Singapore, including mammals and birds, should be evaluated, particularly for organisms cultured locally and destined for human consumption (Bayen et al. 2005).

6 Interviews

6.1 Introduction and summary

In February 2010 interviews were held with researchers of NUS (Prof. Chou Loke Ming, Dr Peter Todd, Dr James Guests, Dr Tedd Web, Dr Dan Friess, Jani Tanzil, Siti Maryam) and TMSI (Dr Sin Tsai Min, Dr Pavel Tkalich). The interviewed researchers are active in the field of water quality or coral reef-, mangrove- and sea grass ecology.
The aim of the interviews was to gain insight in whether water quality (e.g. nutrients, heavy metals and other toxic compounds) is seen as an important factor influencing the three marine ecosystems coral reefs, sea grass beds and mangroves. Furthermore we were interested to gain insight in the causes of decline in these ecosystems, and their protection in Singapore.

In general turbidity and sedimentation are assumed to be the most important factors influencing coral reefs and sea grass meadows viability. Mangrove forests decline as a result from a unbalance of fine sediments; input is lower than outflow. Water quality issues (nutrients, heavy metals and other toxic compounds) are considered less important but an overview of concentrations of pollutants and their effects is lacking such that conclusions cannot easily be made. Water quality is monitored in Singapore by agencies (e.g. National Environmental Agency) and institutes (e.g. TMSI has been monitoring over a long time span) but given confidentiality these data are not publically available.

Protection of the three ecosystems is not organized centrally but depends on their geographical location, e.g. when in the area governed by NParks mangroves may be relatively well protected, whereas if governed by another agency protection may be of less importance.
Coastal protection is the most important, generally accepted, ecosystem services provided by mangroves, sea grass beds and coral reefs.

6.2 Water quality

Experts Dr. Sin Tsai Min and Dr Pavel Thalich.
Water quality studies have been ongoing in TMSI for a long time (over 10 years). TMSI research includes monitoring, experiments and modelling approaches. Water quality aspects monitored are hydrodynamics, eutrophication, salinity, temperature and other standard environmental parameters.

The resulting data and the conclusions based on the data are not publically available since TMSI works as a consultant for the government. Projects run by TMSI are directed at e.g. the impact of desalination plumes, drain discharge resulting from spills, oil spills and heavy metal spills from old dump sites. There is no national strategy on water quality in the marine environment.

Nutrients and eutrophication are considered important factors changing biodiversity. Algal blooms are currently more prevalent and macro algae more abundant. These phenomena may interact with El Niño, since the last results in an increase in forest fires in the neighbouring counties and by that more atmospheric deposition of nutrients in Singaporean waters.
The general assumption for most pollutants is that concentrations will quickly dilute in the coastal zone. This is especially the case for sewage which is discharged, after treatment, at 1.4 km offshore at the south east of Singapore at a site were water currents are strong. Pharmaceuticals are not monitored in coastal waters PCB's and POP's only in specific projects.
Singapore has been one of the first nations to ban the use of TBT, concentrations of TBT are now much lower compared to those reported by Basheer et al. 2003. It is unclear what the impact is of the new

antifouling products and its components such as Copper that are used to replace TBT. These compounds may form a water quality risk in near future in Singapore coastal waters.
Possible local water quality issues are pollution from the backwashing of filters in desalination plants. These filters may catch all kinds of compounds but their backwashing is not regulated.

The main pressures on corals, sea grass and mangroves are considered change in hydrodynamics, loss of habitat due to land reclamation, and disruption of settlement of coral larvae due to high levels of sedimentation. Also eutrophication may be an important issue for coral reefs in Singapore, especially in combination with high temperatures (hypothesis of Dr. Tkalich).

6.3 Mangroves

Experts Tedd Web and Dan Friess.
Mangroves generally fall under the authority of the State Land Authority (SLA) and are not formally protected. Economic developments may result in loss of mangroves. Those mangrove forests that are situated in the parks managed by NParks are relatively well protected.
Mangroves are located at the northern part of Singapore. Probably only those species that can tolerate high levels of stress are still present. Given the absence of environmental conditions that are considered vital for viable mangrove forests, being sites where sediments can settle that have low erosion levels and the possibility for mangrove forests to expand to the sea, opportunities to improve mangrove forests are meagre in Singapore. Only at Paulau Tekong, a military training site closed for the public, mangroves seem in a healthy state. Given high dynamics, both in natural and anthropogenic factors, mangroves are considered transient in Singapore.

Mangroves provide ecosystem services by coastal protection (e.g. stabilizing sediments). The provision by mangroves of a nursery function for fish is small since there is almost no commercial fishery in Singapore.

Major threats to mangroves are:

- Wave energy from e.g. shipping resulting in erosion
- Lack of sediment input in the system. At het Northern side of Singapore the remaining estuaries where mangroves are present are dammed such that sediment input from the main sediment supplier the Johor River is cut-off.
- Land reclamation works.

Climate change is a potential threat (in relation to sea-level rise may result in erosion).
Water quality (e.g. elevated nutrient levels) is not expected to be a very important factor for the sustainability of adult mangrove threes. Elevated nutrient levels, however, may impact seedlings, but scientific information on this issue is lacking.

6.4 Coral reefs

Experts professor Chou Loke Ming, Peter Todd, James Guests and Jani Tanzil.
Protection of coral reefs is not organized centrally in Singapore. Only at Labrador park, a stretch of 6km fringing reef is under protection. This is the only natural coral reef shoreline left in Singapore.

Most coral reefs in Singapore are fringing reefs located at the southern island of Singapore.
Reef quality between 0 and 4 m depth is regarded as fair. Below 4 m light levels are low and restrict coral survival. Species composition is different from other sites, only light-limited and sedimentation

tolerant species are present in Singapore. Coral cover is currently about 20-30% suggesting that availability of space is not a limiting factor for recruitment. Also settling of larvae seems not to be an issue, survival of settled larvae, especially in their first life stages (as inferred from settled larvae in situ on tiles), however, does seem to be a bottleneck in coral recruitment. Another issue is that algal species may compete for space with corals.
Coastal protection is the most important ecosystem service provided by coral reefs.

Ranking different pressures threatening coral reefs in Singapore sedimentation is of overarching importance on the viability of coral reefs. Turbidity reducing light penetration, smothering and abrasion are the main impacts of sedimentation. Especially high turbidity has a stronger impact on coral reef viability. Limited light penetration restricts coral growth to a maximum depth of 6 m. Smothering and abrasion strongly reduces the survival of the early life stages of coral recruits.
Based on sediment traps background sedimentation in Singaporean waters is considered to be at $15 mg/cm^2/day$. Dredging related sedimentation can be up to $40 mg/cm^2/day$. Sediment caused turbidity decreases with distance from the shore.
High sediment loads and high turbidity can have resulted from many causes including runoff from the land as a consequence of the lack of natural vegetation. Most of Singapore is nowadays vegetated with exotic species, and ecosystems are disrupted resulting, among others, lower sediment stabilizing capacity, higher erosion and thus increased runoff.
Habitat destruction by land reclamation is the second most important factor reducing coral reef variability in Singapore.

Other threats are rising water temperature, nutrient loads, heavy metals, freshwater input, boating, anchorage and grounding by ships and tramping by tourists.
Bleaching is very water temperature dependent, and coral growth declines with water temperature (result research of Jani Tanzil).
Eutrophication is an issue in Singapore as can be inferred from more frequent occurrence of algal blooms, however, causal relations of eutrophication with coral reef viability is lacking (Prof. Chou). From the fact that near the outlet of the Johor river (which waters are considered to contain large amounts of nutrients) coral reefs are still viable, it can be hypothesized that high nutrient levels alone are not limiting coral reefs. Epiphytes and Saragassum are species that may prevent coral larvae to settle. Therefore indirectly high nutrients levels may impact corals by enhancing algal growth. Also macro algae seem to negatively influence fecundity of corals. James Guests refers to a small experiment that showed that Sargassum covered corals showed lower fecundity that those that were not covered.
Unclear, however, remains if and to what extend nutrient levels in Singaporean waters are elevated. Algae densities (such as sargassum) are relatively high in Singapore, this may correspond to the presence of nutrients but also the absence of algae grazers such as parrot fish and rabbit fish. Low fish levels are not a consequence of commercial fishing pressure but recreational fishing is taking place and may have a large impact.
Little information is available on species composition of other groups than corals (e.g. fish) given low visibility strongly reduces monitoring of these species.
Freshwater input is a local problem for the viability of coral reefs and prevalent especially in the northern part of Singapore. Generally toxicological stress (heavy metals, PCB's and other pollutants) are not reported as major factors in Singapore.

Damage caused by boating of small ships, anchorage, grounding of larger ones is considered a minor issue with the exception of flat bottom ships used for construction works. Given the fact that coral reefs in Singapore are very shallow and surface at low tide tramping by tourists may be an issue when tourist levels increase.
Micro plastics which smother the reefs may be an increasing problem.

6.5 Sea grass

Expert Siti Maryam
Sea grass meadows are not officially protected in Singapore

Most Sea grass meadows in Singapore are intertidal and are found at the southern island. A few sea grass meadows can be found at the western and eastern part of the island. In Singapore most sea grass meadows are in a transient state and relative few sea grass meadows reach the climax state. Sea grass is generally multiplying vegetative by budding in Singapore, flowering plants are relatively scarce.

Coastal protection by reducing wave erosion is the most important ecosystem service provided by sea grass meadows.
The major threats to sea grass meadows are turbidity caused by high sediment load in the coastal waters. These high sediment loads result in lower light availability for the plants. Fine sediments re-suspend as a result form wave action and human activities like dredging and shipping. Like in case of coral reefs, also the depth range where sea grass can grow is limited by light and species normally growing deeper in other areas are only found in at low depth, in the intertidal, in Singapore. Apart from turbidity temperature is the most important factor influencing sea grass viability. Nutrients may play a role by enhancing epiphyte growth on sea grass blades further restricting light penetration to the chloroplasts in the sea grass. Already epiphyte cover is over 50% in Singaporean sea grass. Siti uses epiphyte cover as a proxy for nutrient load. Direct measures of nutrients are unavailable and the sources of the nutrients are unknown.
Other factors do not seem to play a role on the viability of sea grass in Singapore. Given the sheltered locations where sea grass can be found, wave action seems to have little impact. Pollutants like heavy metals and herbicides may have a minor impact, but information on concentrations is missing and agriculture is almost absent in Singapore such that impact of herbicides may be low. Tramping by tourists may have a negative impact, but tourism in the areas where sea grass grows is low.

7 Assessment of the eutrophication status of Singaporean area

7.1 Introduction

During the past decades it has become clear that eutrophication is a significant problem in many Singaporean estuaries and coastal zones. High nutrient loads in the coastal waters around Singapore by the anthropogenic land-based inputs from rivers, urban runoff, domestic, industrial and agricultural sewage, and aquacultural effluents are causing a series of nuisances that have far-reaching consequences.
Due to chronic nutrients enrichments of coastal and estuarine waters increased influxes have already lead to the occurrence of symptoms like:

- elevated levels of chlorophyll a (Wolanski, 2006; Yew-Hoong Gin et al., 2002),
- periodic events of anoxia and hypoxia (Chia, 2000),
- reports of harmful and toxic algal blooms in several areas (Chia, 2000; Khoo and Wee, 1996; Wolanski, 2006).

Nutrient enrichment of coastal areas may have far-reaching consequences, such as fish-kills (Choo et al., 1994), impairment of shellfish aquaculture (Choo et al., 1994; Joint et al., 1997), loss or degradation of sea grass beds (McGlathery, 2001) and smothering of bivalves and other benthic communities (Chou et al, 2004). These modifications are likely to have significant economic and social costs.

Eutrophication in estuaries and coastal zones has historically been assessed using the classical freshwater approach (e.g. Carlson, 1977), i.e. through the measurement of variables such as transparency, nutrients and chlorophyll a and the establishment of nutrient-based classification systems. However, in the last decades it has been recognized that estuarine and coastal eutrophication may manifest itself, e.g. through the appearance of algal nuisance, or changes in the composition or even die-off of intertidal and sub-tidal benthic communities that in turn may consequently lead to a loss in habitat. It has become apparent that nutrient concentrations may not be a robust diagnostic variable: high concentrations are not an obligatory indicator of eutrophication, and low concentrations do not necessarily indicate absence of eutrophication (Cloern, 2001). In fact, there are many other factors that determine the ultimate level and type of expression of eutrophic symptoms within an estuary including tidal exchange, freshwater inflow, hydrodynamical regimes, etc. (NRC, 2000).

Increase in research effort and discussion on coastal eutrophication processes has advanced our understanding of the problems, and produced recommendations for remediation and proposed research (NRC, 2000, OSPAR, 2001 and 2003).

Nowadays, the cause - effect variables of the phenomena related to eutrophication are well defined and the dynamics have been reasonably well understood. However, the quantitative assessment of eutrophication in terms of threshold values for nutrients, chlorophyll a or dissolved oxygen is not straightforward. Although the parameters involved can be easily measured on a routine basis, there are a number of shortcomings related to the problem of quantifying eutrophic conditions (Primpas and Karydis, 2009) that concern the:

- difficulty to discriminate between the nutrients of the system and nutrients from human activities i.e. discrimination between natural and anthropogenic sources
- Interrelationship between variables such as nitrate, nitrite, ammonia, phosphate, chlorophyll-a, phytoplankton biomass, water transparency and Dissolved Oxygen (as impact) that are used to describe the phenomena

- variable distribution that deviates from normality
- wide overlapping ranges of parametric values induced by the annual cycle of nutrients, phytoplankton and Dissolved Oxygen induces

Despite these concerns, the need for evaluating the eutrophication status of estuarine and coastal systems, in order to support policy definition, has led to the development of different methods which use symptoms-based multiparameter assessment. Well-known examples are the United States National Estuarine Eutrophication Assessment (NEEA) (Bricker et al., 1999) and the OSPAR Comprehensive procedure (OSPAR, 2001 and 2003).

The OSPAR approach uses an integration or combination of 4 categories of symptoms to derive an overall eutrophication classification of the impacted areas (ranging from non-problem to potential problem to problem area). Through the establishment of Ecological Quality Objectives (EcoQOs) for the main elements of the 4 categories, the main drivers, pressures, state and impacts and their underlying causal relationships are technically evaluated and described (Figure 24). EcoQOs include the establishment of "threshold" and/or "background" values for nutrients, chlorophyll a, oxygen deficiency, phytoplankton indicator species, changes or kills in zoobenthos and algal toxins.

The NEEA approach uses a combination of primary and secondary symptoms to derive an Overall Eutrophic Condition (OEC) index, which is then associated with a measure of Overall Human Influence (OHI) and the Definition of Future Outlook (DFO). This approach contains the essential components of a Pressure (OHI)-State (OEC)-Response (DFO) model, although the OHI also reflects aspects of the state of the system, since it includes a susceptibility metric (Figure 25).

Here we describe and apply an integrated methodology for the Assessment of Estuarine Trophic Status (ASSETS), which may be applied comparatively to rank the eutrophication status of several Singaporean estuaries and coastal areas based on the available information, and to address management options. The methodology we use here is based on the assessment approach used and developed by NEEA (Bricker et al., 1999). Comparison with the approach of OSPAR (2001) is made. Both the approaches may include quantitative and semi-quantitative components, and uses field data, models and expert knowledge on the Pressure-State-Response (PSR) indicators.

7.2 Methodologies

7.2.1 OSPAR- EcoQO

OSPAR established a set of EcoQOs (Ecological Quality Objectives) for categorical assessment of nutrients and eutrophication effects. They were developed in parallel to, and derived from the Comprehensive Procedure assessment parameters and their respective assessment levels (see Table 24). The suggested categories for assessment should be viewed in a sequence of cause/effect relationship, according to the harmonised assessment parameters and their respective assessment levels, in the assessment step, the integration step, and the overall area classification step under the Comprehensive Procedure (Figure 24). Additional criteria may be developed but their development strongly depends on the progress that can be made in establishing their respective assessment levels. A candidate for eutrophication is macrophytes, for which area specific assessment levels and criteria are in advanced progress (OSPAR 2005). The scores for each of the parameters in Table 1 is the departing point for the second step in the classification process.

The scores attained from the application of the assessment parameters in Table 24 are integrated in a table with the criteria categories and the area classes for an initial area classification (step 2) (cf. Table 25 for guidance). Table 25 provides examples of the actual integration step.

Table 24. Harmonised assessment parameters and related elevated levels within the OSPAR. Those corresponding to the EcoQOs for eutrophication are underlined [6].

Category I: Degree of nutrient enrichment

1) Riverine inputs and direct discharges2 (area-specific): Elevated inputs and/or increased trends of total N and total P (compared with previous years)
2) Nutrient concentrations (area-specific): Elevated level(s) of winter DIN and/or DIP
3) N/P ratio (area-specific): Elevated winter N/P ratio (Redfield N/P = 16)

Category II: Direct effects of nutrient enrichment (during growing season)

1) Chlorophyll a concentration (area-specific): Elevated maximum and mean level
2) Phytoplankton indicator species (area-specific): Elevated levels of nuisance/toxic phytoplankton indicator species (and increased duration of blooms)
3) Macrophytes including macroalgae (area-specific): Shift from long-lived to short-lived nuisance species (e.g. Ulva). Elevated levels (biomass or area covered) especially of opportunistic green macroalgae).

Category III: Indirect effects of nutrient enrichment (during growing season)

1) Oxygen deficiency: Decreased levels (< 2 mg/l: acute toxicity; 2 - 6 mg/l: deficiency) and lowered % oxygen saturation
2) Zoobenthos and fish: Kills (in relation to oxygen deficiency and/or toxic algae) and Long-term area-specific changes in zoobenthos biomass and species composition
3) Organic carbon/organic matter (area-specific): Elevated levels (in relation to III.1) (relevant in sedimentation areas)

Category IV: Other possible effects of nutrient enrichment (during growing season)

1) Algal toxins: Incidence of DSP/PSP mussel infection events (related to II.2)

It follows from *Table 24* that it is initially appropriate to classify an area as potential problem area if the area shows an increased degree of nutrient enrichment (Category I). On occasion, data on direct, indirect/other possible effects are not sufficient to enable an assessment or are not fit for this purpose (as indicated by '?' in Table 25). In such a situation section 3.2(b) of the OSPAR Eutrophication Strategy applies (OSPAR 2001 and 2003). It requires urgent implementation of monitoring and research in order to enable a full assessment of the eutrophication status of the area concerned within five years of its classification as potential problem area with regard to eutrophication. In addition, it calls for preventive measures to be taken in accordance with the Precautionary Principle.

7.2.2 OSPAR: Assessing eutrophication parameters

The EcoQO eutrophication is an integrated set of five area-specific EcoQOs belonging to 4 categories considered for assessment. A background document that assesses all important elements of the variables

[6] Note: Parameters found at levels above the assessment level are considered as "elevated levels". For concentrations, the "assessment level" is defined as a justified area-specific % deviation from background not exceeding 50%.

for Singapore is presented in Annex 4. The information is organised in such manner it responds to the eutrophication indicator and other requirements set.
Due to lack of data only the overall eutrophication EcoQO is given. Ideally, for all separate elements of this QO a comprehensive background document should be constructed in order to be conclusive. The back ground document indicates where the major gaps in data and area-specific knowledge lie and can be used to tackle the uncertainties that hamper quantitative analyses of the eutrophication status.

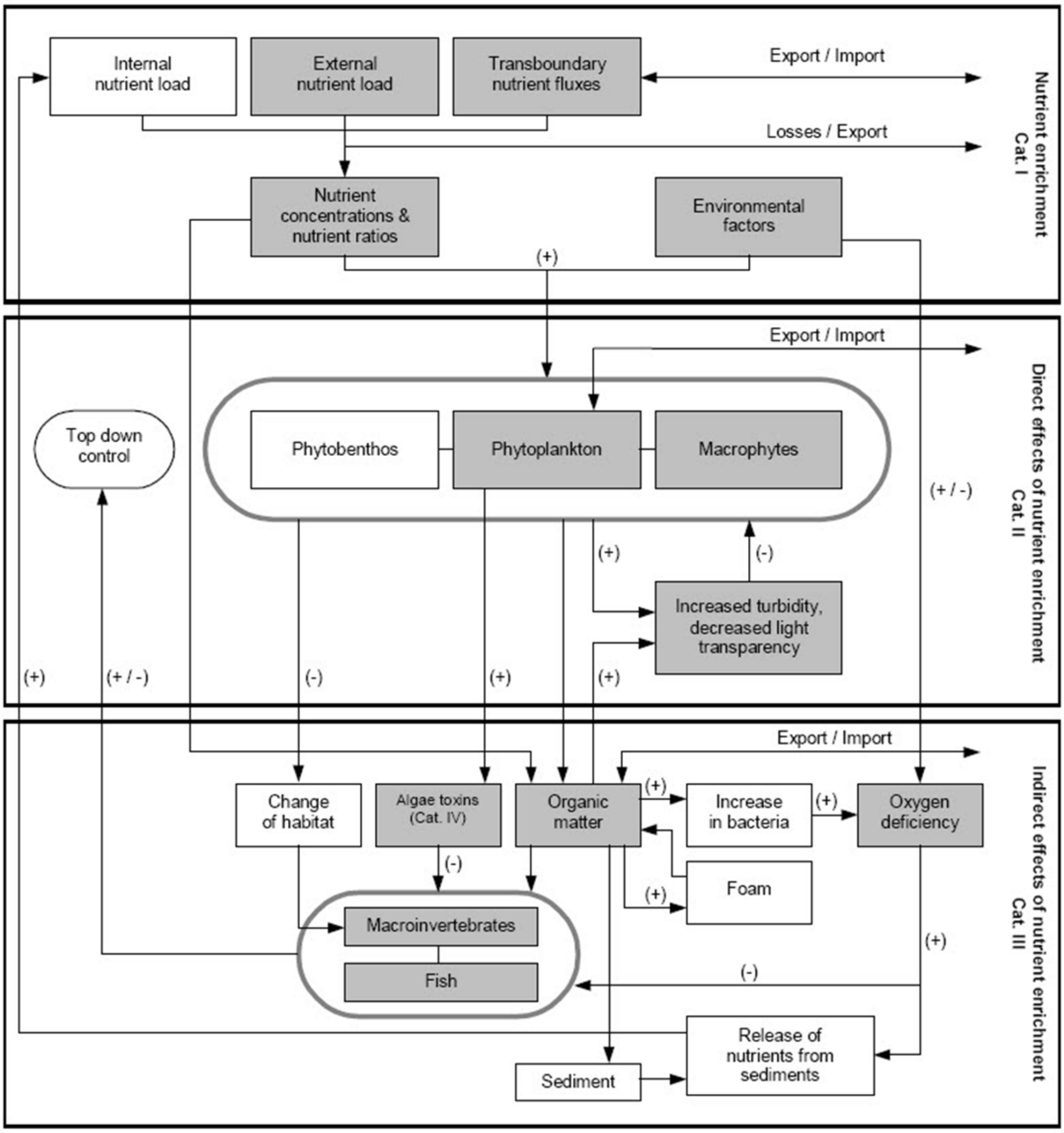

Figure 24 Generic conceptual framework of OSPAR used to assess eutrophication in all categories of surface waters. The Shaded boxes indicate components relevant for the Comprehensive Procedure. '+' indicate enhancement; '–' indicate reduction. Cat. I = Category I. Degree of nutrient enrichment (causative factors), Cat. II = Category II. Direct effects of nutrient enrichment, Cat. III = Category III. Indirect effects of nutrient enrichment, Cat. IV = Category IV. Other possible effects of nutrient enrichment

It should be pointed out that, despite large anthropogenic nutrient inputs and high nutrient concentrations, an area may exhibit few if any direct and/or indirect effects. However, countries should take into account the risk that nutrient inputs may be transferred to adjacent areas where they can cause detrimental environmental effects and countries shall recognise that they may contribute significantly to so called 'transboundary affected' problem areas and potential problem areas with regard to eutrophication outside their national jurisdiction.

Table 25 Examples of the integration of categorised assessment parameters (see Table 24) to give an initial classification. The eutrophication EcoQOs are indicated in bold.

	Category I Degree of nutrient enrichment Nutrient inputs **Winter DIN and DIP** Winter N/P ratio	Category II Direct effects **Chlorophyll *a*** **Phytoplankton indicator species** Macrophytes	Categories III and IV Indirect effects/other possible effects **Oxygen deficiency** Changes/**kills in zoobenthos**, fish kills Organic carbon/matter Algal toxins	Initial Classification
a	+	+	+	problem area
	+	+	-	problem area
	+	-	+	problem area
b	-	+	+	problem area[3]
	-	+	-	problem area[3]
	-	-	+	problem area[3]
c	+	-	-	non-problem area[4]
	+	?	?	potential problem area
	+	?	-	potential problem area
	+	-	?	potential problem area
d	-	-	-	non-problem area

(+) = Increased trends, elevated levels, shifts or changes in the respective assessment parameters

(-) = Neither increased trends nor elevated levels nor shifts nor changes in the respective assessment parameters

? = Not enough data to perform an assessment or the data available is not fit for the purpose

Note: Categories I, II and/or III/IV are scored '+' in cases where one or more of its respective assessment parameters is showing an increased trend, elevated level, shift or change.

7.2.3 NEEA (ASSETS method)

The NEEA approach aims at deriving an Overall Eutrophic Condition (OEC) index, which is then associated with Overall Human Influence (OHI) and the Definition of Future Outlook (DFO). This approach contains the overall Pressure (OHI)-State (OEC)-Response (DFO) model, although the OHI also may reflect on the system state (*Figure 29*). The initial start is the setup of the flow chart connecting underlying relations in a pressure, state and response environment.

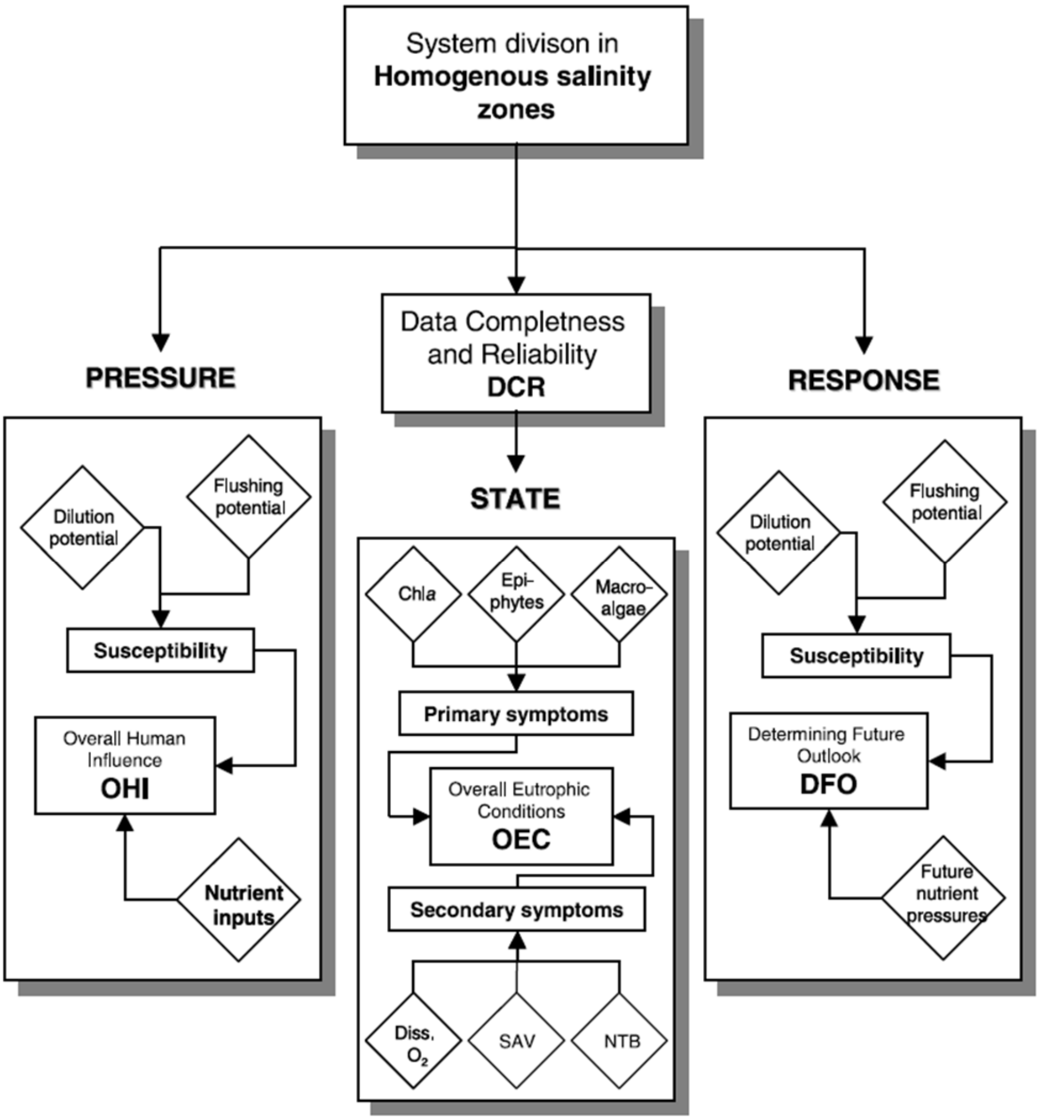

Figure 25 Flow chart of the ASSETS methodology

Background information on 16 nutrient related water quality parameters should be considered including information on frequency of occurrence, trend detection, shifts, concentrations and contributing or limiting factors. Issues of concern for analyses are here:

1. Chlorophyll a. Surface concentrations, Hypereutrophic (>60 ug l−1), High (>20, ≤60 ug l−1), Medium (>5, ≤20 ug l−1), Low (>0 and ≤5 ug l−1), Limiting factors to algal biomass (N, P, Si, light, other), Spatial coverage, months of occurrence, frequency of occurrence
2. Turbidity. secchi disk depths High (<1m), Medium (≥1, ≤3m), Low (>3 m), Spatial coverage, months of occurrence, frequency of occurrence
3. Suspended solids, Concentrations, Problem (significant impact upon biological resources), No problem (no significant impact), Months of occurrence, frequency of occurrence
4. Nuisance algae. Occurrence
5. Toxic algae. Toxic algae Problem (significant impact upon biological resources) .No problem (no significant impact), Dominant species, Event duration (hours, days, weeks, seasonal, other), Months of occurrence, frequency of occurrence.
6. Macroalgea. Abundance

7. Epiphytes. Problem (significant impact upon biological resources), No problem (no significant impact), Months of occurrence, frequency of occurrence.
8. Nitrogen. Maximum dissolved surface concentration, High (≥1mg l−1), Medium (≥0.1, <1mg l−1), Low (≥0 and <0.1 mg l−1), Spatial coverage, months of occurrence.
9. Phosphorus. Maximum dissolved surface concentration, High (≥0.1 mg l−1), Medium (≥0.01, <0.1 mg l−1), Low (≥0 and <0.01 mg l−1), Spatial coverage, months of occurrence
10. Anoxia. Dissolved oyxgen concentration
11. Hypoxia Observed
12. Biological stress. Not observed, Stratification (degree of influence and High Medium Low). Not a factor then Water column depth, Surface, Bottom, Throughout the water column, Spatial coveraged, months of occurrence, frequency of occurrence
13. Primary production. Dominant primary producer: pelagic, benthic, other
14. Planktonic community. Dominant taxonomic group (number of cells): diatoms, flagellates, blue-green algae, diverse mixture, other
15. Benthic community. Dominant taxonomic group (number of organisms): Crustaceans, Molluscs, Annelids, Diverse mixture, other
16. Submerged Aquatic vegetation (SAV). Spatial coverage

For determining the human pressures the ASSETS methodology has applied a simple model to combine human pressure and system susceptibility. Equations for the determination of OHI may be derived based on a simple “Vollenweider” mass balance model, modified to include the dispersive exchange between an estuarine black box and the open sea (Ferreira, 2000). Only dissolved inorganic nitrogen (DIN) is considered, and non-conservative terms are neglected since only the relative proportions of DIN derived from anthropogenic and ocean sources are of interest in the evaluation of pressure see Bricker et al., 2003 for more information).`

Then, a subset of six parameters from the set of 16 here above was selected to provide an index of state, expressed as overall eutrophic condition. These are divided into two groups, indicative of primary (early) and secondary (advanced) symptoms of eutrophication. Chlorophyll a, macroalgae and epiphytes are considered to be primary symptoms—excessive concentration or abundance is considered to diagnose early stages of an eutrophication problem. Low dissolved oxygen (DO), losses of SAV, and occurrence of nuisance and/or toxic algal blooms are considered to be secondary symptoms, i.e. indicators of well-developed eutrophic conditions (Figure 26). In NEEA, a method was developed to combine results for this subset of symptoms (parameters) into an indicator of overall eutrophic condition based on the concentration, spatial coverage, and frequency of occurrence of extreme or problem occurrences. No formulation was developed, but rather a logic stepwise decision method was used to determine the weighted expression value for all the separate elements (Brickland et al., 2003). In *Figure 27* an overview is provided on the determination of overall eutrophication conditions based on primary and secondary symptoms.

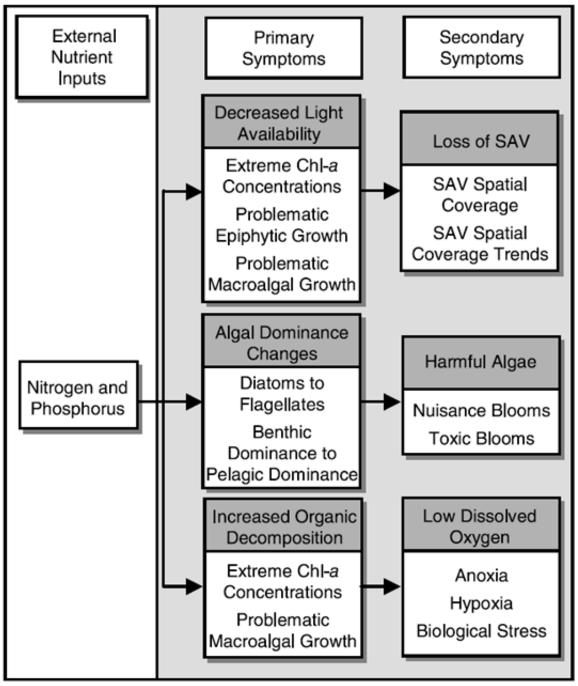

Figure 26. Conceptual model of primary and secondary symptoms of eutrophication.

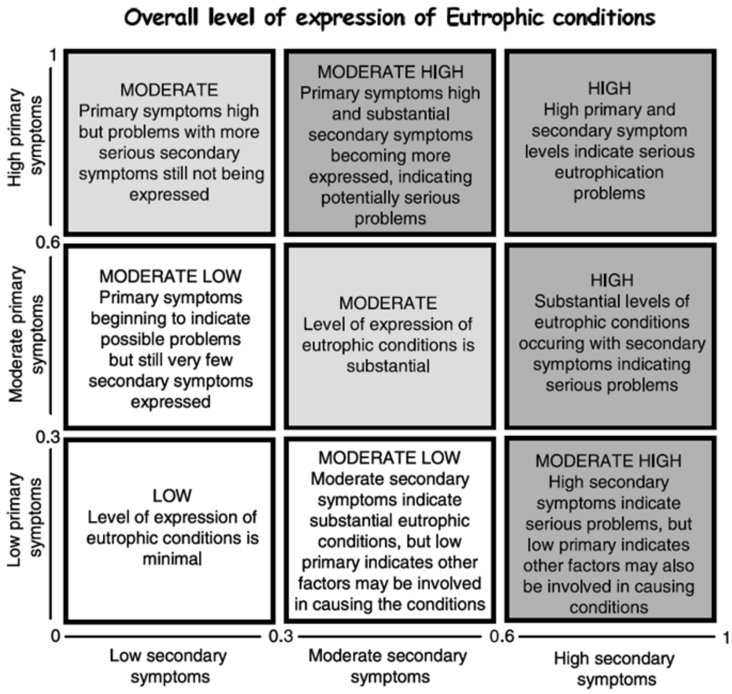

Figure 27. Determination of overall eutrophic condition based on primary and secondary symptoms.

7.2.4 ASSETS: Assessing eutrophication parameters

Due to a lack of data only a relatively small available set of field and modelled data could be used to gain for the eutrophication assessment. In total the data of 8 published works were included in the

assessment of the parameters. Of these works only 6 contained field measurements, the remaining 2 contained mostly data from modelling exercises. The parameters values as organised in the DPSIR context are presented in previous chapters. Other information is found in the background document of the OSPAR approach for analysing eutrophication status around Singapore in Annex 4.
Also, the 8 works (Cloern et al., 2001; Gin et al., 2002; Chou et al., 2004; Wolanksi, 2006; Palani., 2008 and 2009 and the modelling works: Delft hydraulics, 2007; DHI, 2004) are all published during the last decade. This hampers the establishment of trends and natural background levels for the parameters.

7.3 Aggregation of data

Due to lack of relevant coverage of the eutrophication assessment variables in time and space we needed to aggregate the sparse field data into three main systems surrounding Singapore (West and East Johor strait and Singapore Strait) to allow the application of both the OSPAR and ASSETS approaches. It must be noted though that even with the clear separation in regions eutrophication is a process rather than a state.
The modelling work of Tkalich et al. (2003) provided information on Bathymetry (Figure 28) and gave some information on the vertical water column structures and tidal action together with the basin-wide modelling exercise of DHI (2004) we managed to gain rough insights into total run-off, the basin volumes, hydrodynamics and flushing rates.
The field data and the modelled data were pooled per region and because median values per variable could not be calculated they were arranged along a worst to best ordination and consequently per scenario set (thus 3 regions with 2 sets each) treated by the 2 approaches.

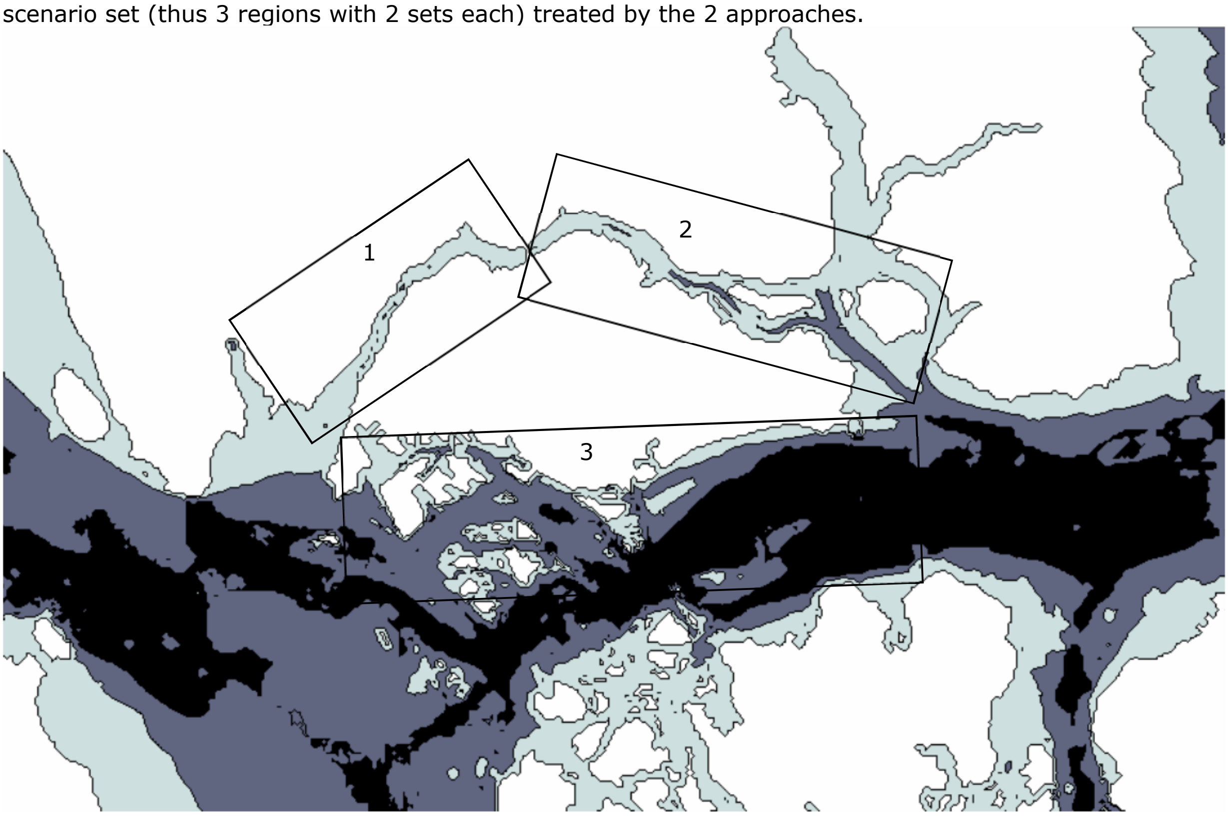

Figure 28. Bathymetric map Singapore and surroundings. Colour white represents land, light grey: 0-15m depth, dark grey: 15-30 and black: depth >30m. Three sets of data are used for computing the bathymetry, namely the Electronic Navigation Chart (ENC) of Singapore, Navigation Chart 202 (of 1998) by Maritime Port Authority of Singapore (MPA) and MPA's digital map in isoline form (See Tkalich et al., 2003). Indicated are analysed systems 1: West Johor Strait (up to causeway connecting Malaysia and Singapore), 2: East Johor Strait and 3: Singapore Strait.

7.4 Results and discussion

7.4.1 Assessment results

For both the OSPAR and ASSETS approaches, the underlying DPSIR reasoning and inclusion of key variables seemed valuable in assessing the eutrophication status. However, since the OSPAR approach only includes 4 categories containing 5 variables the total data to work with for Singapore region still remained insufficient to make an assessment beyond a qualitative level (initial classification, see Table 25).
However, and although not all variables exist or were measured for all the three systems, the suite used by ASSETS containing information on 16 variables seemed broad enough to assess most common types, with emphasis on the magnitude, timing, and predictability of extreme conditions of various indicators observed.

Given the elevated concentrations found for both N and P compounds, the reported occurrence of HABS (*Chatonella marina* and *Cochlodimium spp*), elevated Chlorophyll a (up to 140 ug/l) both West and East Johor Strait classify as problem area according to the OSPAR approach. OSPAR draws data on nutrient concentrations measured in winter. This is hard to adapt to Singaporean conditions with seemingly low variation in water temperature and seasonal monsoons. However, the year-round elevated nutrient level seemed for most of the available data clearly way above levels that are commonly reported in very eutrophied and enriched areas.

For Singapore Strait nutrient levels were lower and mostly closer to natural background concentrations although a few elevated concentrations were recorded (see chapter 4). However, in this region there have been reports on lowered Dissolved oxygen concentrations (4-6 mg/l in Gin et al., 2002; and Wolanksi, 2006). Only because of the latter, the Singapore Strait classifies initially as a potential problem area.
The ASSETS approach resulted in more details in the final eutrophication score of the different regions (Table 26)

Table 26 Overal score table of West and East Johor and Singapore straits. Results from the ASSETS analyses. Low and High scenario indicates separate ASSETS analyses on best situation (low nutrients and high oxgen etc) and worst situation (high nutrients, oxygen depletion, etc.)

System	Pressure (OHI)	State (OEC)	Respons (DFO)	Scenario
West Johor Strait	Moderate high	Low	Improve low	Low
	High	Low	Improve low	High
East Johor Strait	Moderate high	Low	Improve low	Low
	Moderate high	Low	Improve low	High
Singapore strait	Low	Moderate	Worsen low	Low
	Moderate	Moderate	Worsen low	High

For the constructions of Table 26 predominantly the influencing factors like lowered salinity, elevated nitrogen concentrations and the basin characteristics seemed sufficient to score the pressures (OHI) for the three regions. According to the analyses West and East Johor Strait score rather equal to the highest pressures to be expected in West Johor. This most likely results from the nutrient input from the Malaysian river systems.

The analyses of the eutrophic condition (state) in terms of elevated chlorophyll a concentrations as well as the occasional occurrence of nuisance or toxic algae blooms, generally low dissolved oxygen concentrations and an affected submerged aquatic vegetation (Singapore region in whole is characterised by strongly impoverished SAV). The latter and the lowered oxygen levels classify Singapore strait as in moderate state regardless the much lower nutrient levels.

For the whole of the Johor Strait susceptibility for eutrophication remains high and even with projected changes in agricultural and population pressures and increased sewage treatment the overall eutrophication status is expected to improve slowly. Contrary, Singapore Strait is likely to worsen according to the analyses. Although susceptibility is much lower for this region (due to size and higher currents), a relative increase in nutrients originating from a much larger region and numerous river systems is to be expected. This may slowly worsen the eutrophication response initially. Only when these pressures (over a much wider area than Singapore region) are reduced and natural biological communities can recover the situation will improve.

7.4.2 Monitoring needs

The availability of an existing body or time-series of data to allow a realistic setting of objectives is a prerequisite for the establishment of the eutrophication status. International guidelines for these regions seem to be available, at times even providing some adequate monitoring data, including supporting environmental information.

However, monitoring should be performed in a coherent way, to reflect the cause/effect relationship. The risk of misinterpretation of the causes of direct and indirect effects is substantially reduced when all categories (nutrient enrichment, direct effects, and indirect effects) as well as supporting environmental information are monitored and assessed together.

Given the current unknown status of the area a regular, coherent and integrated mandatory monitoring of nutrients in conjunction with the direct and indirect effect parameters is required to assess the status and facilitate evidence based management.

8 Risk evaluation of contaminants in the marine environment of Singapore

8.1 Introduction

Typical marine ecosystems (coral reefs, seagrass meadows) in Singapore have decreased in range and species diversity over the last century. Coral reef cover decreased with 60% ((Hamid et al. 2009)). Most often this decrease is attributed to land reclamation works and associated increase of sedimentation and turbidity. High sedimentation and turbidity levels occur regularly near land reclamation works ((Hamid et al. 2009)).
However, as already noted in the introduction of this report, other stressors may have an influence as well on the marine environment of Singapore.

Our hypothesis is that the level of contaminants in the marine environment of Singapore may have attributed to the degradation of marine ecosystems. The research question to answer was:

- Do measured concentrations of contaminants as described in chapter 4 pose a threat to the marine ecosystems of Singapore?

The risk evaluation of contaminants in the marine environment of Singapore was performed using a first tier risk assessment method called the PEC/PNEC approach. Where possible, spatial variation of the environmental risk was taken into account by aggregating the available data into 4 defined regions of Singapore (North East, North West, South West, South East) see *Figure 29*.

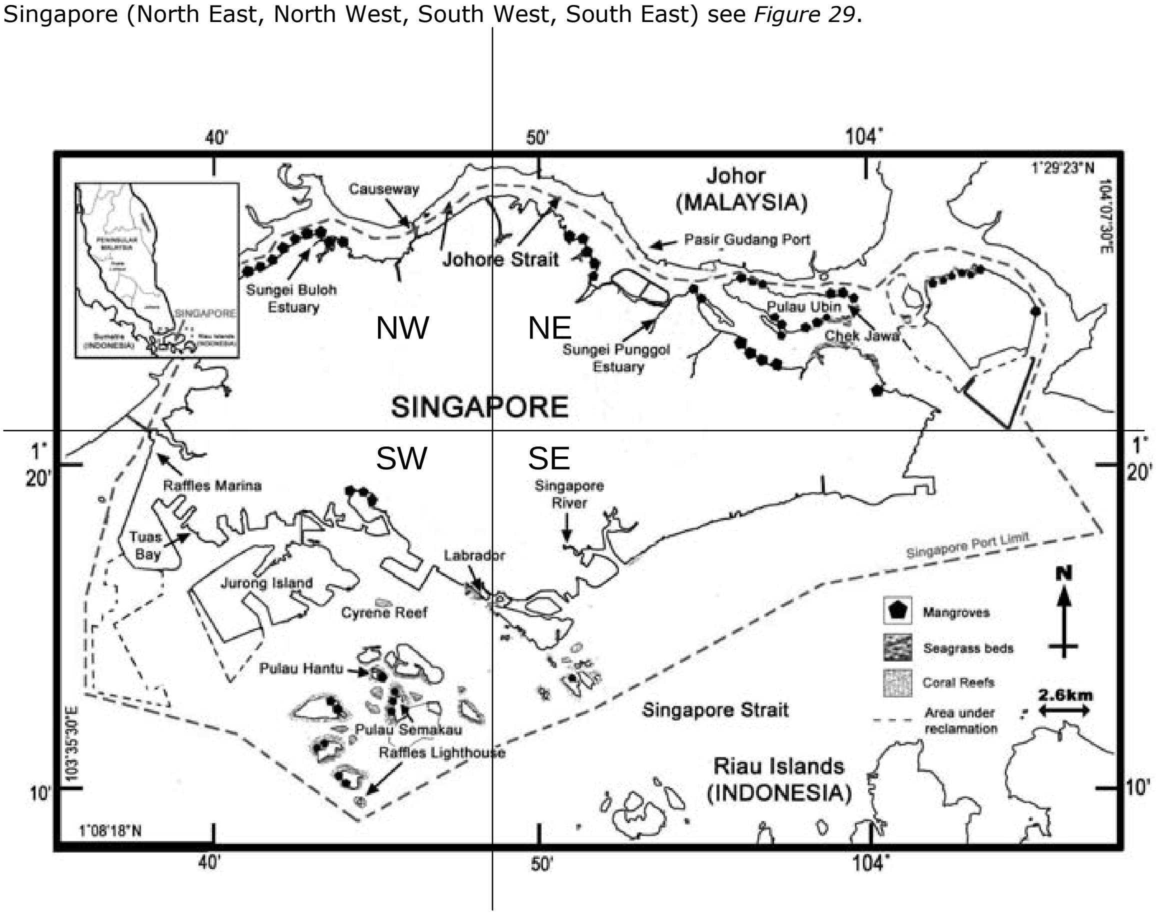

Figure 29 Map of Singapore showing the four sections used for spatial differentiation.

8.2 Methodology

8.2.1 PEC PNEC appraoch

The EU Technical Guidance Document (EU-TGD) on risk assessment (EC 2003) defines the PNEC as the concentration below which unacceptable effects on organisms will most likely not occur. The ratio between the Predicted Environmental Concentration (PEC) and the PNEC can then be used as an indication of the likelihood of adverse effects to occur.

Certain assumptions are made concerning the aquatic environment, which allow an extrapolation to be made from single-species short-term toxicity values to ecosystem effects, expressed as the Predicted No Effect Concentration (PNEC). It is assumed that:

- ecosystem sensitivity depends on the most sensitive species, and;
- protecting ecosystem structure protects community function as well.

These two assumptions have important consequences. By establishing which species is the most sensitive to the toxic effects of a chemical in the laboratory, extrapolation can subsequently be based on the data from that species. Furthermore, the functioning of any ecosystem in which that species exists is protected provided the structure is not distorted to such a degree that it causes an imbalance.

It is generally accepted that protection of the most sensitive species should protect structure, and hence function. For most substances, the pool of data from which to predict ecosystem effects is very limited as, in general, only short-term toxicity data are available. In these circumstances, it is recognized that, while not having a strong scientific validity, empirically derived assessment factors must be used. Assessment factors have also been proposed by the US-EPA and the OECD.
In applying such factors, the intention is to take into account the uncertainties in the information to predict a concentration below which an unacceptable effect will most likely not occur. It is not guaranteed to be a level below which the chemical is considered to be safe. However, it is likely that an unacceptable effect will not occur (EC 2003).

The PNEC can be derived from laboratory NOEC (No Observable Effect Concentration) and/or L(E)C50 (50% Lethal or Effect Concentration) values by applying an assessment factor. The magnitude of the assessment factor depends on the amount of suitable toxicity data. The highest assessment factor (10,000) is applied when only a limited set of acute toxicity values is available. The lowest assessment factor (10) is applied when chronic NOECs are available for three trophic levels (usually algae, crustaceans and fish) and at least two additional marine taxonomic groups (EC 2003). The assessment factors applicable on taxonomic groups of fresh water organisms ((EC 1996)) are a factor 10 lower than the marine assessment factors and are less refined ((EC 2003)). The EU TGD is a widely accepted document and has for instance been adopted in REACH guidelines for chemical safety analysis (ECHA 2008).

The PEC PNEC ratio is also known as the Risk Characterisation Ratio 'RCR'. Ratio values above 1 indicate potential risk from the compound towards the environment. The scale of the risk can be crudely measured by considering this ratio – a figure of 1 to 10 is of lower concern, between 10-100 additional data are needed. Over 100 is of major concern, and action to reduce the risk to the environment should be required [EC, 2003].

8.2.2 PNEC values

In previous chapters in this report the results of a literature review on contaminants in the marine environment of Singapore are described. Only limited information was found on the local impact of these contaminants (see chapter 5). Besides limited local information on impacts, general data of toxicology on tropical species is limited as well ((Kwok et al. 2007)). Our own quick scan in the EPA toxicity database revealed that (varying on the substance) very limited information is available on toxicity data on tropical species (scan was on corals, anemone, mangrove, seagrass, not on individual species). In *Table 27* a brief overview is provided in which for each substance the total number of records is given as well as the proportion of these based on tests with tropical species. Substances were chosen as a benchmark. The proportion of tropical data within the EPA database depends on the substance and varies between 0.2% and 4.6%. This is a very limited proportion given the fact that tropical biodiversity is assumed to be higher than temperate.

Table 27 Quick scan results from EPA database. Total records per substance relative to number of records including coral, seagrass, anemone or mangrove species.

Substance	total records	Number of coral/seagrass/ anemone/mangrove	%
Diuron	1536	70	4.6%
cadmium nitrate	638	2	0.3%
dichlorvos	1025	2	0.2%
pentachlorophenol	2610	10	0.4%
Copper chlorine	5176	72	1.4%
petroleum	963	11	1.1%

From this quick scan, it could be concluded that data availability was not sufficient to calculate PNEC values for each habitat, i.e. seagrass, mangrove, coral reefs. Instead generic PNEC values for the marine environment are assessed. In the present study most of the applied Predicted No Effect Concentrations (PNECs) were calculated following the EU Technical Guidance Document on risk assessment (EC, 2003). In *Table 28* an overview of PNEC values is given, based on a literature review and requirements by the TGD requirements by Holthaus et al 2005. The PNEC values for specifically alkylphenols by Hotlhaus et al 2005 were reviewed by De Vries et al. in 2009. The PNEC of butylphenol was adjusted to 0.69 µg/l, based on availability of additional data. Other values were did not need adjustment.

PNEC values found in literature might vary among studies due to several reasons. Different databases on toxicological data can be retrieved, or in different periods, but also due to the application of the safety factors, and incorporation of the revised TGD standards (as provided in EC, 2003). PNECS before 2003 will not have taken into account the more strict standards for derivation of marine PNECs. A variety of PNEC values for alkylphenols (*Table 29*) were used in this evaluation to set the PNEC values of Holthaus et al. 2005 and (De Vries et al. 2009) in perspective.

Table 28 PNEC values for the marine environment (Holthaus et al. 2005)

Group	**Compound**	**PNEC (µg/l)**
Metals	Cd	0.028
	Cu	0.07
	Ni	0.6
	Pb	0.1
	Zn	0.56
PAH	Naphthalene	1.5
	Phenanthrene	0.13
	Anthracene	0.011
	Fluoranthene	0.1*
	Pyrene	0.00248 **
	Benzo[a]pyrene	0.005
Alkylphenols	butylphenol	0.074
	pentylphenol	0.006
	octylphenol	0.002
	heptylphenol	0.06
	nonylphenol	0.001

* PNEC fluoranthene with UV enhanced toxicity is 0.0001

** PNEC pyrene with UV enhanced toxicity is 0.000023

Table 29 Various PNEC values for alkylphenols

PNEC	butylphenol	pentylphenol	octylphenol	heptylphenol	nonylphenol	Reference
1		0.36	0.032	0.19	0.04	(Frost 2002)
2					0.33	EU, 2002
3	0.64					EU, 2008
4			0.0122			EU, 2005
5			0.001		0.003	(Maggi et al. 2008)
6	0.074	0.006	0.002	0.06	0.001	Holthaus et al 2005
7	0.69	0.006	0.002	0.06	0.001	De Vries et al 2009

The PNEC for TBT is set on 3.55 ng/L based on findings of Leung et al 2007.

8.2.3 PEC

Available concentrations from literature have been taken as input for this risk study. These include measured concentrations of heavy metals, alkylphenols and PAHs from different locations around Singapore (Table 30, *Table 31*and Table 32 respectively). To demonstrate spatial variation for this risk study, the locations have been divided into four parts: Northwest; Northeast; Southeast; and Southwest. Average PEC values presented are often accompanied with very large standard deviations (see tables).

Average concentrations of TBT could not be calculated. Only ranges were provided by Basheer et al 2002. TBT concentration sin the NE region are 1.4-2.4 µg/l, 1.9 (SE), 0.43-3.2 (SW) and 0.5-1.4 in NW region. The overall mean TBT concentration among 26 locations was 1.44 µg/l.

Table 30 PEC Metals in µg/l (Cuong et al. 2005). Average (standard deviation) N=2

Location	**Section**	**Cd**	**Cu**	**Ni**	**Pb**	**Zn**
Mangrove water, S. Buloh	NW	0.16 (0.1)	0.28 (0.02)	0.27 (0.02)	0.19 (0.11)	1.58 (0.1)
Mangrove water, S. Khatib Bongsu	NE	0.05 (0.01)	0.66 (0.14)	0.48 (0.08)	0.10 (0.09)	1.38 (0.41)
Coastal water, Seletar	NE	0.25 (0.05)	0.64 (0.02)	0.51 (0.02)	0.98 (0.02)	3.73 (0.16)
Coastal water, Kranji	NW	0.02 (0.005)	0.17 (0.006)	0.23 (0.01)	0.006 (0.008)	2.37 (0.17)

Table 31 Average PEC PAHs in ng/l with (sd) (Obbard et al. 2007) N=6 (NE), 9 (SW)

Section	**Naphthalene**	**Phenanthrene**	**Anthracene**	**Fluoranthene**	**Pyrene**	**Benzo[a]pyrene**
NE	2.15 (0.77)	5.55 (3.0)	38.71 (21.4)	36.15 (82.3)	8.44 (5.9)	2.15 (2.3)
SW	1.28 (1.0)	3.62 (1.8)	21.45 (9.7)	3.18 (1.2)	13.56 (7.1)	1.28 (2.7)

Table 32 PEC average levels of Alkylphenols in µg/l with (sd) based on data from (Basheer et al. 2004).

Average (standard deviation) N= 5 (NW), 10 (SE), 10 (SW), 3 (NW)

Section	**Butyl-phenol**	**Pentyl-phenol**	**Octyl-phenol**	**Heptyl-phenol**	**Nonyl-phenol**
NE	1.04 (1.66)	0.17 (0.2)	0.34 (0.41)	1.08 (1.36)	1.03 (0.66)
SE	0.35 (0.62)	0.28 (0.62)	0.18 (0.24)	0.21 (0.52)	1.11 (0.84)
SW	0.40 (0.90)	0.16 (0.34)	0.21 (0.44)	0.14 (0.02)	0.69 (0.50)
NW	0.06 (0.01)	0.02 (0.01)	0.03 (0.02)	0.01 (0.00)	1.15 (0.31)

8.3 Results and conclusions PEC/PNEC

8.3.1 Presentation of results

Calculated risk is presented in tables per compound group. Color schemes are used to provide a quick overview of the severness of the risk. The scale of the risk can be crudely measured by considering this ratio as already discussed in the introduction of PEC/PNEC.
Green = no risk (0-1)
Yellow= low risk (1-10)
Orange= moderate risk (10-100)
Red = high risk (>100)

8.3.2 Heavy metals

In Table 33 an overview of PEC/PNEC ratios for metals is given. Data show that for Nickel the PEC/PNEC value is below 1, other metals which were detected occur at concentrations which result in a PEC/PNEC above 1. Highest ratios for Cadmium, Copper and Lead were found in the north east region, being the eastern Yohor straits, near Seletar. Ratios of 1-10 indicate low risk to the environment.

Bio-availability of metals was not taken into account in this evaluation. Metals can be less bio-available due to interactions with e.g. organics and salt. It is, therefore, expected that the risk will be lower than suggested in Table 31.. Furthermore, the PNEC values are based on temperate species. For most metals it is known that temperate species tend to be more sensitive than their tropical counterparts ((Kwok et al. 2007)). Cadmium, copper, lead, nickel and zinc are amongst these metals. Metal concentrations as reported by Cuong et al. in 2005 pose only a very low or no risk to the marine environment, based on this first tier risk evaluation.

Table 33 PEC/PNEC ratios for metals, green indicating no risk, yellow indicating low risk to the environment.

Location	Section	Cd	Cu	Ni	Pb	Zn
Mangrove water, S. Buloh	NW	5.7	4.1	0.5	1.9	2.8
Mangrove water, S. Khatib Bongsu	NE	1.8	9.4	0.7	1.0	2.5
Coastal water, Seletar	NE	9.1	9.1	0.8	9.8	6.7
Coastal water, Kranji	NW	0.5	2.4	0.4	0.1	4.2

8.3.3 PAHs

In *Table 34* an overview of PEC/PNEC ratios for PAHs is given. Data show that Anthracene and Pyrene both have an average ratio above 1. The other PAHs have ratios below 1, and no risk to the environment is expected based on these single concentrations.

No information is available on the difference in sensitivity to PAHs between temperate and tropical species. (Kwok et al. 2007) recommend the application of an extrapolation factor of 10 when surrogate temperate values are used for tropical or subtropical regions, or when a priori knowledge on the sensitivity of tropical species is very limited or not available.
This means that the ratios presented in Table 34 should be multiplied by 10 in order to account for sensitivity of tropical species. Instead of ratios of 1-9, ratios of 10-90 than appear, indicating a serious concern, and additional monitoring is required to evaluate the actual risk and impact of PAHs.

Table 34 PEC/PNEC ratio's for PAHs, for the Northeast and Southwest sections. Green indicates no risk, orange indicates serious concern of the compound. Color was adjusted to orange because of risk multiplier of 10 as suggested by (Kwok et al. 2007)

Section	Naphthalene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Benzo[a]pyrene
NE	0.00	0.04	3.52	0.36	3.40	0.91
SW	0.00	0.03	1.73	0.03	5.47	0.71

8.3.4 Alkylphenols

PEC/PNEC ratios were calculated for each alkylphenol-PNEC that was found in literature. These values are presented per literature reference in Table 35, *Table 36*, *Table 37* and *Table 38*. Large variation on the ratios and its consequences for risk evaluation can be observed among the different references used. Generally, no risk of butylphenol is to be expected as the calculated ratios are around 1.

The PNEC values for which the revised TGD criteria were taken into account ((De Vries et al. 2009), Holthaus et al, 2005 and (Maggi et al. 2008)), are generally lower, leading to higher ratios, indicating high ecological risk for the marine environment of Singapore. Nonylphenol is the compound with highest calculated risk. Ratios vary between 231 and 1150. Octylphenol ratios vary between 16.67 in the NW, and 342 in the NE region. The NE region in generally the region with highest risk resulting from alkyphenols, however, the order depends on the specific alkylphenol.

The used PNEC values are based upon temporate species, as no toxicity data for tropical species were available for these compounds. Kwok et al 2009 suggests to apply an extrapolation factor of 10 to account for the uncertainty in sensitivity due to lack of tropical data. The extrapolation of the factor to the alkylphenol data results in extreme high ratio's, indicating that alkylphenols are a mayor concern to the marine environment.

*Table 35 Ratios according to PNECs of De Vries et al (2009 (covers PNEC values of Holthaus et al 2005, except for butylphenol)**

	butylphenol	pentylphenol	octylphenol	heptylphenol	nonylphenol
NE	1.51	29.00	171.00	17.93	1028.00
SE	0.51	46.00	90.00	3.44	1113.00
SW	0.58	25.83	104.50	2.29	694.00
NW	0.09	2.78	16.67	0.17	1150.00

*Ratios for butylphenol based upon Holthaus et al 2005 are as follows: 14.0 (NE); 4.77 (SE), 5.45 (SW), 0.86 (NW).

Table 36 Ratios according to PNECs of (Maggi et al. 2008). No PNEC values for butylphenol, pentylphenol and heptylphenol were given.

	butylphenol	pentylphenol	octylphenol	heptylphenol	nonylphenol
NE	-	-	342.00	-	342.67
SE	-	-	180.00	-	371.00
SW	-	-	209.00	-	231.33
NW	-	-	33.33	-	383.33

Table 37 Ratios according to PNECs of (Frost 2002). No PNEC values for butylphenol and heptylphenol were given.

	butylphenol	pentylphenol	octylphenol	heptylphenol	nonylphenol
NE	-	0.48	10.69	-	25.70
SE	-	0.77	5.63	-	27.83
SW	-	0.43	6.53	-	17.35
NW	-	0.05	1.04	-	28.75

Table 38 Ratios according to PNECs retrieved from EU RAR documents. No PNEC values for pentylphenol and heptylphenol were given.

	Butylphenol#	pentylphenol	Octylphenol^	heptylphenol	Nonylphenol**
NE	1.62	-	28.03	-	3.12
SE	0.55	-	14.75	-	3.37
SW	0.63	-	17.13	-	2.10
NW	0.10	-	2.73	-	3.48

#: based on Eu, 2008, revised TGD criteria taken into account

^: based on Eu, 2005, revised TGD criteria most probably taken into account

**: Based on EU, 2002, revised TGD criteria not set yet.

8.3.5 TBT

PEC PNEC ratios for TBT were 419 (mean), 930 (maximum value in SW region), 125 (minimum value in SW region). In general the NW region had the lowest ratio varying from 145-419. Based on these data, TBT poses a high risk to the marine environment.

8.4 Discussion

8.4.1 Application of additional safety factor

A proper risk assessment of substances discharged to aquatic environments relies on data derived predominately from ecotoxicity tests (OECD 1995). Most of these data are generated by developed western countries and are based on temperate and coldwater species endemic to Europe and North America (Dyer et al. 1997; Kim et al. 2001). Toxicity data for tropical species are often lacking for ecological risk assessment (Kwok et al 2007). Consequently, the assessment in this study used PNEC values derived from temperate species. The question arises whether tropical species have the same sensitivity as temperate species as tropical environments and related habitats differ in both their physicochemical and biological characteristics. Biodiversity in tropical ecosystems is higher than in temperate zones, and potentially more species could be affected due to pollution (Kwok et al. 2007).

Various laboratory studies suggest that the risk of toxicity to an aquatic organism appears to increase with temperature (Brecken-Folse et al. 1994; Willis et al. 1995; Lydy et al. 1999; Kwok and Leung 2005). Species in these studies are however not all strict tropical species, but mostly temperate species tested under various, elevated temperatures. Their increased sensitivity can be attributed to the fact that the species were exposed outside or at the limits of their normal physiological state. It can thus be questioned whether tropical species under their normal environmental conditions experience increased sensitivity.
This question was partly answered by Kwok et al. 2007 who compared the sensitivities of tropical and temperate species to the same chemicals at their normal conditions. The results of their study indicated that the relative sensitivities of tropical and temperate species are noticeably different for some of the chemicals they looked into. Temperate species tend to be more sensitive than their tropical counterparts for most metals. However, for un-ionized ammonia, phenol, and some pesticides (e.g., chlorpyrifos), tropical species are probably more sensitive. Kwok et al 2009 recommend that when a priori knowledge on the sensitivity of tropical species is very limited or not available and surrogate temperate values are used for tropical or subtropical regions an extrapolation factor of 10 should be applied to the outcome of the risk assessment and related Water Quality standards. In the specific result sections this factor was taken into account.

8.4.2 Q10

Sensitivity to toxicants between tropical and temperate species might differ due to differences in physiology. It can be hypothesized on the basis of the metabolic principle (Q10), that tropical aquatic species should be more sensitive to toxic chemicals than their temperate counterparts (Castillo et al. 1997).

Furthermore, the solubility of the toxicant in water and the rates of uptake and circulation in the test organism are higher at elevated temperatures. Indeed ectothermic aquatic organisms experience the double bind of reduced dissolved oxygen and increased metabolic rates as water temperature increases (Cairns et al. 1975; Rathore and Khangarot 2002). This might increase the amount of energy expended to meet their respiratory gas exchange requirements, which could ultimately exacerbate toxic effects. In

contrast, as metabolic rate increases, biochemical detoxification and elimination of the chemical might also increase with temperature, which could eventually reduce chemical toxicity (Howe et al. 1994).
To which extent this factor contributes to the risk assessment is not to say, but should be taken into consideration as a factor potentially increasing or lowering the risk.

8.4.3 Spatial variation of environmental risk in Singapore

Given data density, data did not allow complete spatial coverage of concentrations of toxicants in coastal water. Therefore a more pragmatic approach was chosen by dividing the waters of Singapore in 4 quarters. Based on the calculated risk, the environment of the north east region of Singapore is at most risk facing environmental impact due to deteriorated water quality. The north west region seems to be at lowest risk in general, but given the risk of nonylphenol this region should be considered to be at high risk facing environmental impact as well. The number of data points to retrieve PEC data in this region was low (n=3) and a more detailed study is therefore recommended.
It should be emphasized that spatial variance between near shore and off shore locations was not taken into account in the environmental risk assessment.

Industries that may be responsible for the risk are widespread in the marine environment of Singapore. As pressure data are lacking, no adequate assessment can be given on which industry is highly responsible and which is less. Typically, alkylphenols are natural constituents of petroleum oil and may be found in produced water discharged from offshore oil and gas installations. The three alkyl phenols– nonylphenol (NP), octylphenol (OP) and butylphenol– are used as intermediates in the production of other chemicals. NPs are used to produce NP derivates, especially ethoxylates, with end uses as emulsifiers, dispersive agents, surfactants and/or wetting agents in various industrial and domestic products. OP is mainly used to produce phenol/formaldehyde resins with various end uses (tackifier in rubber for tyres, water-based paints, pesticide formulations, and recovery of oil in offshore processes). Butylphenol may be used in the production of antioxidants for rubber and plastic and as an additive to fuel or lubricants (OSPAR, 2010).

Sources of heavy metals in general include mining, industrial production (foundries, smelters, oil refineries, petrochemical plants, pesticide production, chemical industry), untreated sewage sludge and diffuse sources such as metal piping, traffic and combustion by-products from coal-burning power stations.

The introduction of PAHs into the marine environment comes via different processes such as atmospheric deposition, sewage and industrial discharges, and oil spillages.
Concentrations of PAHs in Singapore's coastal zone were considered higher than levels reported for several other countries, most likely due to the presence of Singapore's extensive petroleum industry (Basheer et al., 2003b).

TBT introduction to the marine environment is assumed to be low now-a-days due to the world-wide ban on TBT containing antifouling paints.

8.4.4 From risk to impact

Based on the first tier risk assessment we conclude that the marine environment of Singapore faces a high risk to be affected by water quality as reported in various scientific references. A note should be made that the PEC data used came from single measurements performed mid-2000, and the present water quality may be different.

The actual impact (or effect) from the compounds for which a high risk was concluded, shall vary among the considered species and habitat. As impactstudies have been performed on a limited base, we hereafter provide an overview of possible indications of impact of contamination.

Impact on corals resulting from contamination varies from metallothionein production to bleaching and reduced recruitment. Impact indicators for exposure and/or effects of contaminants on corals found in literature are summarized in Table 39. It should be noted that some are actual established indicators and others are only observed effects.

Table 39 Impact indicators for corals (after Cooper et al 2009)

Contaminants	**Indicator**	**Reference**
Metals	Metallothionein in reef fish	(Peters et al. 1997)
Oil compounds	Cytochrome P450 in reef fish and coral	(Peters et al. 1997)
	Glutathione-S-transferase in coral	(Peters et al. 1997)
	The size of gonads is a measure of long-term (>3 years) sub-lethal effects of oil on reproduction	(Haapkylä et al. 2007)
	Decrease in coral cover	(Haapkylä et al. 2007)
Pesticides	Bleaching	
	Bleaching in coral	(Peters et al. 1997)
	Expulsion of the symbiont (bleaching)	Jones and Kerswell (2003); Jones et al (2003)
	Mucus production in coral	(Peters et al. 1997)
	Reduced photosynthesis	
	Toxic effect by restricting electron transfer within the photosynthetic chloroplast of the target plant or alga, leading to a decrease in photosynthetic efficiency	(Jones 2005)
	Loss of fitness in the host coral due to reduced photosynthesis of symbiotic dinoflagellates	Jones et al (2003)
	Depression of photosynthetic activity in juvenile and adult coral symbionts	(Negri et al. 2005)
	Inhibition of photosynthesis in crustose coralline algae	(Harrington et al. 2005)
	Increases inhibition of photosynthesis in comnination of herbicide and sediment stress	(Harrington et al. 2005)
	Less coral recruitment as crustose coralline algae are a critical settlement inducer for many coral species	Heyward and Negri (1999)

Impact on seagrass from contamination varies from acute mortality to depressed photosynthesis. Impact indicators for exposure and/or effects of contaminants on seagrass found in literature are summarized in Table 40. It should be noted that some are established indicators and others are observed effects.

Table 40 Impact indicators for seagrass

Contaminants	Indicator	Reference
Metals	Decrease in abundance of benthic invertebrates (e.g. *Cymadusa* and *Crepidula*)	(Peters et al. 1997)
	Reduced photosynthesis	(Peters et al. 1997)
Oil compounds	Acute mortality from physical impacts	(Peters et al. 1997)
	Decreasing growth rates	(Peters et al. 1997)
Pesticides	Depressed photosynthesis	Haynes et al. (2000); McMahon et al. (2005)

Impacts of contaminants on mangroves vary from growth stimulation, deformation or reduced productivity. Impact indicators for exposure and/or effects of contaminants on mangroves found in literature are summarized in Table 41. It should be noted that some are actual established indicators and others are only observed effects.

Table 41 Impact indicators for mangroves

Contaminants	Indicator	Reference
Metals	Not relevant (impacts are minor to non-existent)	(Peters et al. 1997)
Oil compounds	Growth stimulation at very low oil concentrations	(Peters et al. 1997)
	Damage to pneumatophores (can take a year or more to become noticeable)	(Peters et al. 1997)
	Deformed or abnormal aerial roots	(Peters et al. 1997)
	Reduced productivity	(Peters et al. 1997)
	Lower rates of litter production	(Peters et al. 1997)
	Lower seedling survival	(Peters et al. 1997)
Pesticides	Mortality by herbicides (breakdown of cell walls in both roots and leaves)	(Peters et al. 1997)
	Decreased fiddler crab populations at normal application rates of Temepos	(Peters et al. 1997)

9 Conclusions and perspectives

Water quality of the marine waters around Singapore is a key factor to the health of the ecosystem elements. Human activities lowering water quality, might potentially impact marine ecosystems, and are therefore important to identify. The importance of the actual water quality of Singapore towards ecosystem performance is thus important to be discussed in order to place measures as "Building with Nature" in context. The aim of this study was to assess the present impact of water quality as a consequence of human activities on local coastal ecosystems in order to assess its relevance in relation to marine infrastructure developments as reclamation and associated dredging.

In this report an overview is given on driving forces and pressures affecting water quality (nutrients and contaminants). Furthermore the actual state on nutrients and contamination level is given, as well as the state of the ecology. The impacts related to current state of the water quality are described. As limited information on local impacts was available, extrapolation was performed from the state descriptions.

9.1 Impact of water quality in Singapore

The assessment of the nutrient status of the coastal waters and its impact on eutrophication is discussed in chapter 7, the assessment of the contamination status and its consequential risk to cause environmental impact is discussed in chapter 8. Both assessments indicate that impacts of water quality are likely in Singapore and are possible more widespread or frequently occurring than the limited observations as described in chapter 5 (impacts) suggest.

9.1.1 Water quality: nutrients

The evaluation of the risk caused by eutrophication in Singapore marine environments, is strongly restricted due to limited data availability.
Using two evaluation approaches, it can be concluded that for whole of Johor Strait the susceptibility for eutrophication remains high. Even with projected changes in agricultural and population pressures and improved sewage treatment the overall eutrophication status is expected to only slowly improve. In contrast the Singapore Strait is likely to worsen according to the analyses. Although susceptibility is much lower for this region (due to size and stronger currents that will strongly dilute inflow of nutrients), a relative increase in nutrients originating from a much larger region and numerous river systems is to be expected. This may increase the impact of eutrophication. Only when the pressures (over a much wider area than the Singapore region alone) are reduced and natural biological communities recover the situation may improve.

9.1.2 Water quality: Contaminants

Based on the first tier environmental risk assessment we conclude that the marine environment of Singapore faces a high risk to be affected by water quality as reported in various scientific references. Especially the alkylphenol concentrations are of serious concern as calculated risk factors are extremely high. No risk of heavy metals is to be expected, and PAHs are as well of minor concern. TBT risk factors are high as well, but due to the ban on TBT containing paints, this risk will phase out with time. Substitution to TBT will however eventually arise.
A note should be made that not only for TBT, used PEC data came from single measurements performed mid-2000, and the present water quality may be different. This might include lower PEC as is the case for TBT, but might as well mean higher PEC are present.

9.1.3 Cumulated impact and relation to sediment

This report focuses on the water quality aspects nutrients and contaminants, sediment is not taken into account. Due to the scope of the "Building with Nature|" program, a short discussion on the interaction between sediment and contamination is added in this chapter.

Field conditions comprise a mixture of sediment, nutrients and multiple contaminants which can lead to additive, synerchistic or antagonistic interactions between these factors. Additive interaction means that the combination of factors may result in the sum of each single effect. Synerchistic interaction is when factors together lead to greater effects than each single effect, Antagonistic interaction means, factors together show less effect than the sum of each single factor. It should be emphasized that ecological effects of contaminants are often not distinguishable from effects of other stress factors such as sedimentation, nutrient loading, and habitat destruction (Peters et al., 1997). An overview of indicators of contamination and specific tropical environmental endpoints were therefore taken into account in this report (chapter 8).

Chemical contaminants might result in sublethal chronic, as well as acute, direct and indirect impacts on mangrove, seagrass, and coral reef organisms (Peters et al., 1997). Bioaccumulation of toxicants and synergistic effects are also possible (Cooley et al., 2006). Little is known about the interactions of contaminants with calcareous sediments and bioavailability, the influence of light availability and temperature, microbial degradation in the tropics, and food web bioaccumulation. Nayar et al. (2004a) points to a possible large-scale negative impact of dredging on the estuarine biota, especially on the algae and plants as seagrasses through resuspension and bioavailability of particulated metals. This resuspension of contaminated sediments resulted in measurable toxicity at the dredged sites (Nayer et al., 2004). Furthermore, finer contaminated sediments also may have been transported to adjacent straits, posing further environmental risk to the biotic communities there (Nayar et al. 2004a). Our assessment however indicated that the risk of metals is very limited at the locations for which data were available, such that impacts caused by resuspension of heavy metals for these sites can be expected to be low.

9.2 Recommendations

9.2.1 Monitoring

Most studies used in this report and those referred to in the review of Obbard et al. (2007) present data on chemical and environmental state based on short term monitoring periods. These studies are usually stand alone and do not relate to incentives for long term monitoring. Furthermore, most studies are performed within the last decade.

This indicates that trend analysis on the presence of contaminants and nutrients in the coastal surroundings of Singapore cannot be performed. Therefore no indication on future concentrations or translocations across compartments can be given based on chemical history. In the absence of specific preventative measures, an increase in intensity of human activities in and around Singapore may result in an increased influx of chemicals. Persistent compounds, such as POPs and heavy metals, may then accumulate to higher levels in ecosystem components.

The risk of misinterpretation of the causes of direct and indirect effects is substantially reduced when all categories (emissions of contaminants, nutrient enrichment, concentrations in the environment, direct effects, and indirect effects) as well as supporting environmental information are monitored and assessed together.

The availability of studies reporting both pressure and impact is very limited for the Singapore marine environment. Based on the results from this report it seems highly recommendable to invest in such environmental research. Monitoring of both contaminants and nutrients related issues should be performed in a coherent way, to reflect the cause/effect relationships.

9.2.2 DSPIR- Response

Concerning the DPSIR framework, we have not addressed the Response element in this report .
The Response element deals with questions such as "What are we doing about it, or what can be done about it?" and reflects the societal and political response to the previous element in the framework.

When analysing the available data needed to prepare this report, it became clear that limited data was available in scientific public databases and reports from local governmental departments. From the interviews with local experts we learned that environmental studies are being performed in Singapore, but that these reports are confidential and therefore cannot be used.

In our opinion the DPSIR framework is only a useful instrument if all aspects of the framework can be analysed and discussed implying data is available. The limited availability of data on pressures and impacts does not give an overview of all relevant pressures, states and impacts of water quality aspects in Singapore. The societal response to the issue of water quality aspects towards better regulation is herewith hampered.

However, a recent proposal by civil society for the integrated and balanced conservation of Singapore's Marine Heritage, the so-called Blue Plan, recommends continued effective prevention, containment and make measures for marine pollution operational through stringent pollution controls and adherence to International Maritime Organisation (IMO) Conventions (Blue Plan, 2009). Better enforcement to reduce and manage marine litter and the input of endocrine disrupting chemicals (incl. TBT) should also be considered. Accidental oil spills in Singapore's marine waters remain an ever-present threat to the remaining critical marine ecosystems in these waters, calling for appropriate oil spill contingency planning (Blue Plan, 2009).

9.2.3 Building with Nature

In the scope of Building with Nature programs, the lack of data on water quality issues is a concern. Measures taken in the scope of Building with Nature aiming at positive effects on the environment may be hampered by low water quality such that the desired effect of the measures taken is not reached.

In order to fully exploit the potential of "Building with Nature" measures it can be beneficial to consult governmental departments and other economic sectors involved in water quality issues, to rise awareness and to combine efforts aiming at improving water quality and thus better ecosystem performance.

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Quality assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 57846-2009-AQ-NLD-RvA). This certificate is valid until 15 December 2012. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Environmental Division has NEN-AND-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

Justification

Report C179/10
Project Number: 430.61110.52

The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of Wageningen IMARES.

Approved: Dr. R.H. Jongbloed
Scientist

Signature:

Date: 30 May, 2011

Approved: J.H.M. Schobben MSc.
Head of Department

Signature:

Date: 30 May, 2011

ANNEX 1. Identified DPSI in Singapore

Annex 1a: Drivers, Pressures, States and and/or Impacts related to water quality, pollution, and/or nutrients identified in Singapore. Non-shaded cells are suggested data or relationships and shaded cells contain observed data or identified relationships

Driver	Pressure	State	Impact	Reference
-	-	Alkylphenols and bisphenol-A in coastal waters and seafood	-	(Basheer et al. 2004)
petrochemical industry	Introduction of petroleum/oil	POP's in seawater	Adverse effects on marine wildlife	(Basheer et al. 2003b)
Unknown (via atmospheric deposition)	Introduction of petroleum/oil	POP's in seawater	Adverse effects on marine wildlife	(Basheer et al. 2003b)
land reclamation	Resuspension from sediment	POP's in seawater	Adverse effects on marine wildlife	(Basheer et al. 2003b)
petrochemical industry	Introduction of petroleum/oil	POP's in seawater	Adverse effects on marine wildlife	(Basheer et al. 2003b)
wastewater treatment plant discharge	-	POP's in seawater	Adverse effects on marine wildlife	(Basheer et al. 2003b)
shipping	Resuspension from sediment	POP's in seawater	Adverse effects on marine wildlife	(Basheer et al. 2003b)
shipping	Introduction of petroleum/oil	POP's in seawater	Adverse effects on marine wildlife	(Basheer et al. 2003b)
Docking	Introduction of petroleum/oil	POP's in seawater	Adverse effects on marine wildlife	(Basheer et al. 2003b)
shipping	Introduction of petroleum/oil	POP's in sediment	Adverse effects on marine wildlife	(Basheer et al. 2003a)
petrochemical industry	Introduction of petroleum/oil	POP's in sediment	Adverse effects on marine wildlife	(Basheer et al. 2003a)
shipping	Introduction of antifouling	Organotin and Irgarol-1051 in coastal waters	Highly toxic to organisms	(Basheer et al. 2002)
shipping	-	PCB's and polybrominated diphenyl ethers in Green Mussels	-	(Bayen et al. 2003)
land-based input (rivers, runoff)		PCB's and polybrominated diphenyl ethers in Green Mussels	-	(Bayen et al. 2003)
-	-	POP's in aquacultured oysters	Response of aquacultured oysters to POP's	(Bayen et al. 2007)

Driver	Pressure	State	Impact	Reference
-	-	POP in sediments, seawater, and twenty-four biota species (mangrove)	-	(Bayen et al. 2005)
landfill	Changes in turbidity	Ambient sediment load, live coral cover, species diversity, beds of seagrass	Effect of landfill on coral reef	(Chou & Tun 2007)
-	-	Levels of heavy metals in representative mangrove habitats	-	(Cuong et al. 2005)
land-based input (rivers, runoff)	Introduction of heavy metals	Metals in sediment	-	(Cuong & Obbard 2006)
other	-	-	-	(EIA 2007)
offshore oil and gas	-	-	-	(EIA 2007)
-	Introduction of heavy metals	Heavy metals in Diadema setosum	-	(Flammang et al. 1997)
shipping	pollution general	-	Coastal environmental impacts: 1960s-1990s	(Hesp 1995)
land reclamation	pollution general	-	Coastal environmental impacts: 1960s-1990s	(Hesp 1995)
land reclamation	Changes in turbidity		Effect on coral reef and mangroves	(Hesp 1995)
shipping	Introduction of petroleum/oil	-	Coastal environmental impacts: 1960s-1990s	(Hesp 1995)
Unknown (via atmospheric deposition)	Introduction of heavy metals	-	-	(Hu & Balasubramanian 2003)
coastal reconstruction	Changes in turbidity	survival and growth of Giant clam	Effect of light levels and sedimentation	(James et al. 2008)
coastal reconstruction	Changes in turbidity	survival and growth of Giant clam	Effect of light levels and sedimentation	(James et al. 2008)
other	pollution general	Water quality (suspended sediment, nutrient and inorganic variables)	-	(Lim 2003)

Driver	Pressure	State	Impact	Reference
other	pollution general	Water quality (suspended sediment, nutrient and inorganic variables)	-	(Lim 2003)
Unknown (via atmospheric deposition)	Introduction of Pahs	PAHs in SML and subsurface water	-	(Lim et al. 2007)
land-based input (rivers, runoff)	Introduction of Pahs	PAHs in SML and subsurface water	-	(Lim et al. 2007)
shipping	Introduction of Pahs	PAHs in SML and subsurface water	-	(Lim et al. 2007)
ports	-	Soft-bottom macrobenthic communities and environmental variables	harmful effects from petroleum hydrocarbons	(Lu 2005)
shipping	-	Soft-bottom macrobenthic communities and environmental variables	harmful effects from petroleum hydrocarbons	(Lu 2005)
petrochemical industry	-	Soft-bottom macrobenthic communities and environmental variables	harmful effects from petroleum hydrocarbons	(Lu 2005)
wastewater treatment plant discharge	pollution general	-	-	(Meiyappan 2004)
ports	-	-	-	(MPA 2009)
shipping	-	-	-	(MPA 2009)
land reclamation	Introduction of heavy metals	Heavy metal concentration in sediment	toxicity to phytoplankton and autotrophic bacteria	(Nayar et al. 2004a)
dredging	Introduction of heavy metals	Heavy metal concentration in sediment	toxicity to phytoplankton and autotrophic bacteria	(Nayar et al. 2004a)
coastal reconstruction	Introduction of heavy metals	Heavy metal concentration in sediment	toxicity to phytoplankton and autotrophic bacteria	(Nayar et al. 2004a)
shipping	Introduction of heavy metals	Heavy metal concentration in sediment	toxicity to phytoplankton and autotrophic bacteria	(Nayar et al. 2004a)
shipping	Introduction of petroleum/oil	distribution of petroleum hydrocarbons	effects on the periphytic algal biomass	(Nayar et al. 2004b)

Driver	**Pressure**	**State**	**Impact**	**Reference**
ports	Introduction of petroleum/oil	distribution of petroleum hydrocarbons	effects on the periphytic algal biomass	(Nayar et al. 2004b)
petrochemical industry	Introduction of petroleum/oil	distribution of petroleum hydrocarbons	effects on the periphytic algal biomass	(Nayar et al. 2004b)
petrochemical industry	Introduction of petroleum/oil	Hydrocarbon concentrations in water and sediment	effects on bacteria and phytoplankton	(Nayar et al. 2005)
shipping	Introduction of petroleum/oil	Hydrocarbon concentrations in water and sediment	effects on bacteria and phytoplankton	(Nayar et al. 2005)
ports	Introduction of petroleum/oil	Hydrocarbon concentrations in water and sediment	effects on bacteria and phytoplankton	(Nayar et al. 2005)
land reclamation	Introduction of heavy metals	Heavy metal concentration in particulate and dissolved fraction and in sediments	Effects on Periphytic algae	(Nayar et al. 2003)
dredging	Introduction of heavy metals	Heavy metal concentration in particulate and dissolved fraction and in sediments	Effects on Periphytic algae	(Nayar et al. 2003)
coastal reconstruction	Introduction of heavy metals	Heavy metal concentration in particulate and dissolved fraction and in sediments	Effects on Periphytic algae	(Nayar et al. 2003)
shipping	Introduction of heavy metals	Heavy metal concentration in particulate and dissolved fraction and in sediments	Effects on Periphytic algae	(Nayar et al. 2003)
shipping	pollution general	Prevalence of POPs in the seawater, sediments, biota and mangrove habitats of Singapore, biomagnification	-	(Obbard et al. 2007)

Driver	Pressure	State	Impact	Reference
Docking	pollution general	Prevalence of POPs in the seawater, sediments, biota and mangrove habitats of Singapore, biomagnification	-	(Obbard et al. 2007)
petrochemical industry	pollution general	Prevalence of POPs in the seawater, sediments, biota and mangrove habitats of Singapore, biomagnification	-	(Obbard et al. 2007)
pharmaceutical industry	pollution general	Prevalence of POPs in the seawater, sediments, biota and mangrove habitats of Singapore, biomagnification	-	(Obbard et al. 2007)
land reclamation	pollution general	Prevalence of POPs in the seawater, sediments, biota and mangrove habitats of Singapore, biomagnification	-	(Obbard et al. 2007)
Unknown (via atmospheric deposition)	pollution general	Prevalence of POPs in the seawater, sediments, biota and mangrove habitats of Singapore, biomagnification	-	(Obbard et al. 2007)
Docking	Introduction of heavy metals	Metal concentrations in sediment cores.	-	(Orlic & Tang 1999)
petrochemical industry	Introduction of heavy metals	Metal concentrations in sediment cores.	-	(Orlic & Tang 1999)
other	Introduction of heavy metals	Metal concentrations in sediment cores.	-	(Orlic & Tang 1999)
tourism	Introduction of antifouling	Presence of organotins	Imposex in snail species / Localized effects	(Tan 1999)
shipping	Introduction of antifouling	Presence of organotins	Imposex in snail species / Localized effects	(Tan 1999)

Driver	Pressure	State	Impact	Reference
Docking	Introduction of antifouling	Concentrations of metallic pollutants in the marine sediments	-	(Tang et al. 1998)
shipping	Introduction of antifouling	Concentrations of metallic pollutants in the marine sediments	-	(Tang et al. 1998)
wastewater treatment plant discharge	change in oxygen	Trace metal concentrations and sediment properties	Anoxic sediment, increased Pb and Zn	(Wood et al. 1997)
Construction of dam	Water/tidal flow changes	Trace metal concentrations and sediment properties	Anoxic sediment, increased Pb and Zn	(Wood et al. 1997)
other	pollution general	Levels of selected organochlorine pesticides , PCBs and PBDEs in the surface sediments	Singapore's marine sediments can be classified as moderately contaminated with probable ecotoxicological impacts to marine organisms	(Wurl & Obbard 2005c)
shipping	pollution general	Levels of selected organochlorine pesticides , PCBs and PBDEs in the surface sediments	Singapore's marine sediments can be classified as moderately contaminated with probable ecotoxicological impacts to marine organisms	(Wurl & Obbard 2005c)
wastewater treatment plant discharge	pollution general	Levels of selected organochlorine pesticides , PCBs and PBDEs in the surface sediments	Singapore's marine sediments can be classified as moderately contaminated with probable ecotoxicological impacts to marine organisms	(Wurl & Obbard 2005c)
agriculture	pollution general	Levels of selected organochlorine pesticides , PCBs and PBDEs in the surface sediments	Singapore's marine sediments can be classified as moderately contaminated with probable ecotoxicological impacts to marine organisms	(Wurl & Obbard 2005c)
shipping	Introduction of petroleum/oil	Levels of selected chlorinated pesticides and polychlorinated biphenyls (PCBs). In SML and seawater	toxic response in fish larvae	(Wurl & Obbard 2005a)

Driver	Pressure	State	Impact	Reference
shipping	Nutrient enrichment	Levels of selected chlorinated pesticides and polychlorinated biphenyls (PCBs). In SML and seawater	toxic response in fish larvae	(Wurl & Obbard 2005a)
Docking	pollution general	Levels of selected chlorinated pesticides and polychlorinated biphenyls (PCBs). In SML and seawater	toxic response in fish larvae	(Wurl & Obbard 2005a)
ports	pollution general	Levels of selected chlorinated pesticides and polychlorinated biphenyls (PCBs). In SML and seawater	toxic response in fish larvae	(Wurl & Obbard 2005a)
land-based input (rivers, runoff)	pollution general	Levels of selected chlorinated pesticides and polychlorinated biphenyls (PCBs). In SML and seawater	toxic response in fish larvae	(Wurl & Obbard 2005a)
aquaculture	pollution general	Levels of selected chlorinated pesticides and polychlorinated biphenyls (PCBs). In SML and seawater	toxic response in fish larvae	(Wurl & Obbard 2005a)
agriculture	pollution general	Levels of selected chlorinated pesticides and polychlorinated biphenyls (PCBs). In SML and seawater	toxic response in fish larvae	(Wurl & Obbard 2005a)
Unknown (via atmospheric deposition)	pollution general	Levels of selected chlorinated pesticides and polychlorinated biphenyls (PCBs). In SML and seawater	toxic response in fish larvae	(Wurl & Obbard 2005a)
Unknown (via atmospheric deposition)	Introduction of PCB's	Organochlorine compounds in the marine atmosphere	-	(Wurl & Obbard 2005b)

Driver	Pressure	State	Impact	Reference
land-based input (rivers, runoff)	pollution general	Organochlorine compounds in the sea-surface microlayer, water column and sediment	-	(Wurl & Obbard 2006)
Unknown (via atmospheric deposition)	pollution general	Organochlorine compounds in the sea-surface microlayer, water column and sediment	-	(Wurl & Obbard 2006)
wastewater treatment plant discharge	pollution general	Organochlorine compounds in the sea-surface microlayer, water column and sediment	-	(Wurl & Obbard 2006)
-	Resuspension from sediment	Organochlorine compounds in the sea-surface microlayer, water column and sediment	-	(Wurl & Obbard 2006)
land-based input (rivers, runoff)	Nutrient enrichment	chlorophyll levels	potential for eutrophication and the incidence of harmful algal blooms	(Yew-Hoong Gin et al. 2002)
urban and storm water runoff, rivers, wastewater treatment plant discharge	Nutrients enrinchment	Nitrogen has been found as the limiting nutrient in coastal zone.	potential fo eutrophication and DO depletion causing distress to fish life.	Cheong et al., 1999
land-based input (rivers, runoff)	Nutrients enrinchment	high nitrogen and phosporous load in the effluents	fish kills. The causes are attributed to pollution, eutrophication and Harmfull algal blooms. The bloom of Noctiluca scintillansc caused shrimp and fish mortality in the East Johor Strait in 1983 and 1985	Choo et al.
Agriculture (pig farms)	Nutrients enrinchment	high oxygen demand and cause eutrophiication.	fish kills. The causes are attributed to pollution, eutrophication and Harmfull algal blooms. The bloom of Noctiluca scintillansc caused shrimp and fish mortality in the East Johor Strait in 1983 and 1986	Choo et al.

Driver	Pressure	State	Impact	Reference
all	pollution general	Description of the genaral status of marine ecosystem in Singapore, pollution and strategies for the conservation of biodiversity	-	Chou et al., 1997
-	-	-	Impacts of harmful algae in the Asian Pacific Areas. It describes the different types of HAB (PSP, DSP, ASP, TTX, Ciguatera), the toxins produced and their effects. Between 1934 and 1994 there had been reported 3164 cases of human poisoning and 148 deaths.	Corrales and Maclean, 1995
land-based input (rivers, runoff)	Nutrient enrichment	T, S DO, TN and TP, chlorophyll	Potential for eutrophication and harmful algal blooms	Gin et al.,2002
urban and storm water runoff, rivers, wastewater treatment plant discharge	Nutrients enrinchment	-	Production of toxins by marine dinoflaggellates species that can accumulate through the food chains and cause human poisoning (DPS): No cases of DSP occurred yet in Singapore.	Holems and Theo, 2002
shipping	Introduction of non-native species and translocations	-	Gymnodium catenatum produces PSP-toxins. It has been found in Singapore waters since 1997, though is generally associated with temperate waters.	Holmes et al. 2002
-	-	Four species of dynopsoid dinophlagellate	Potential of production of DSP toxins from this (not demonstrated) from Dinophysis caudata	Holmes et al., 1999
dredging	Changes in turbidity	-	a shift in the relative dominance of one size phytoplancton fraction on another	Nayar et al., 2005
-	-	Prediction of water quality parameters (Temperature, salinity, PH, DO, NH4, NO2, TN, PO4,TP, Chl-a)	-	Palani et al., 2008
urban and storm water runoff, rivers, wastewater treatment plant discharge	Nutrients enrinchment	Description of the eutrophication model for Singapore with baseline data	Potential for eutrophication and harmful algal blooms	Tkalich and Sundarambal, 2003

Driver	Pressure	State	Impact	Reference
urban and storm water runoff, rivers, wastewater treatment plant discharge	Nutrients enrinchment	Posphate and nitrogen levels	potential for eutrophication	Wolanski, 2006
urban and storm water runoff, rivers, wastewater treatment plant discharge	Nutrients enrinchment	phytoplancton abundance, algal blooms with elevated chlorophyll concentrations	algal blooms and eutrophication	Wolanski, 2006
storm water runoff, rivers, wastewater treatment plant discharge	Nutrients enrinchment	oxygen level, small fish kills	oxygen depletion, marine organisms kills	Wolanski, 2006
urban and storm water runoff, rivers, wastewater treatment plant discharge	Nutrients enrinchment	-	dinoflagellate species blooms which produces toxins that kill small marine organisms.	Wolanski, 2006

Annex 1b

Drivers, Pressures, States and and/or Impacts related to sedimentation, litter, noise, introduction of non-native species and conversion/destruction identified in Singapore. Non-shaded cells are suggested data or relationships and shaded cells contain observed data or identified relationships

Driver	Pressure	State	Impact	Reference
Construction of dam	reduction in sedimentation	geomorphic history and vegetation dynamics	Reduction in coverage (land clearance). Reduction in sediment supply, led to erosion and retreated mangrove	(Bird et al. 2004)
land reclamation	reduction in sedimentation	geomorphic history and vegetation dynamics	Reduction in coverage (land clearance). Reduction in sediment supply, led to erosion and retreated mangrove	(Bird et al. 2004)
landfill	Sedimentation	Ambient sediment load, live coral cover, species diversity, beds of seagrass	Effect of landfill on coral reef	(Chou & Tun 2007)
land reclamation	-	Marine life	Habitat loss, habitat degradation and habitat modification	(Chou 2006)

Driver	Pressure	State	Impact	Reference
shipping	-	Marine life	Habitat loss, habitat degradation and habitat modification	(Chou 2006)
other	-	Marine life	Habitat loss, habitat degradation and habitat modification	(Chou 2006)
land reclamation	Sedimentation	Environmental conditions, benthic communities, coral recruitement	Effect of chronic exposure to high sediment load	(done & van Woesik 2006)
dredging	Sedimentation	Environmental conditions, benthic communities, coral recruitement	Effect of chronic exposure to high sediment load	(Dikou & van Woesik 2006)
-	-	Dynamics and size structure of phytoplankton	-	(Gin et al. 2000)
-	-	Fish species composition, density, spatial and seasonal variations, environmental variables	Relation of environmental variables with fish assemblages	(Hajisamae & Chou 2003)
-	-	feeding ecology and trophic organization of 32 fish species	-	(Hajisamae et al. 2003)
land reclamation	Sedimentation	-	Effect on coral reef and mangroves	(Hesp 1995)
land reclamation	conversion/destruction		Effect on marine habitats	(Hesp 1995)
shipping	Introduction of noise	-	Coastal environmental impacts: 1960s-1990s	(Hesp 1995)
land reclamation	Introduction of noise	-	Coastal environmental impacts: 1960s-1990s	(Hesp 1995)
dredging	Sedimentation	survival and growth of Giant clam	Effect of light levels and sedimentation	(James et al. 2008)
dredging	Sedimentation	survival and growth of Giant clam	Effect of light levels and sedimentation	(James et al. 2008)
Shipping	Introduction of non-native species and translocations	-	-	(Joachimsthal et al. 2004)
Shipping	Introduction of microbial pathogens	-	-	(Joachimsthal et al. 2004)
dredging	Sedimentation	Sediment granulometry, sediment nutrients and sediment organic carbon	Alteration of bottom characteristics	(Nayar et al. 2007)
tourism	Introduction of litter	presence and abundance of microplastics (>1.6 µm) in beach sediments and seawater (surface microlayer and subsurface layer)	transfer medium for toxic substances, ingestion by marine organisms	(Ng & Obbard 2006)

Driver	Pressure	State	Impact	Reference
shipping	Introduction of microbial pathogens	presence and abundance of microplastics (>1.6 μm) in beach sediments and seawater (surface microlayer and subsurface layer)	transfer medium for toxic substances, ingestion by marine organisms	(Ng & Obbard 2006)
other	Introduction of litter	presence and abundance of microplastics (>1.6 μm) in beach sediments and seawater (surface microlayer and subsurface layer)	transfer medium for toxic substances, ingestion by marine organisms	(Ng & Obbard 2006)
tourism	Introduction of litter	Marine litter	Animals choke or become poisoned when they eat trash, and drown when they become entangled in bags, ropes, and old fishing gear.	(Ocean Conservancy 2009)
other	Introduction of litter	Marine litter	Animals choke or become poisoned when they eat trash, and drown when they become entangled in bags, ropes, and old fishing gear.	(Ocean Conservancy 2009)
shipping	Introduction of litter	Marine litter	Animals choke or become poisoned when they eat trash, and drown when they become entangled in bags, ropes, and old fishing gear.	(Ocean Conservancy 2009)
fisheries	Introduction of litter	Marine litter	Animals choke or become poisoned when they eat trash, and drown when they become entangled in bags, ropes, and old fishing gear.	(Ocean Conservancy 2009)
land-based input (rivers, runoff)	Introduction of litter	Marine litter	Animals choke or become poisoned when they eat trash, and drown when they become entangled in bags, ropes, and old fishing gear.	(Ocean Conservancy 2009)

Driver	Pressure	State	Impact	Reference
aquaculture	conversion/destruction	-	During construction: loss of habitats and nursery areas; coastal erosion; reduced biodiversity; reduced catch yields of commercially important species; acidification; and alteration of water drainage patterns. Saline soil production and alteration of water drainage pattern and alteration of water drainage pattern	(PÁEz-Osuna 2001)
Construction of dam	Water/tidal flow changes	Trace metal concentrations and sediment properties	Anoxic sediment, increased Pb and Zn	(Wood et al. 1997)

ANNEX 2 Overview of activities and pressures in the coastal waters of Singapore

Summary table on activities (column) and related pressures (rows) in the coastal waters of Singapore. This table is not limited to water quality.

pressure/activity	dredging	landfill	dumping of sludge	coastal construction works	surface mining off shore	ports	maritime transportation	docking	aquaculture	fisheries	unknown (via atmospheric deposition)	tourism	land-based input (rivers, runoff)	cooling water discharge & intake	wastewater treatment plant discharge	petrochemical industry	pharmaceutical industrial discharge	surface mining on shore
Changes in pH									x		x		x	x	x	x	x	x
Changes in salinity													x	x	x			
Changes in turbidity	x	x	x	x	x		x		x			x	x		x			x
change in oxygen	x			x	x				x				x	x	x	x	x	
Introduction of antifouling						x	x	x	x			x		x	x	x	x	
Introduction of heavy metals		x	x			x	x	x	x		x		x	x	x	x	x	x
Introduction of microbial pathogens		x	x				x		x	x			x		x			
Introduction of PAHs		x	x			x	x	x			x		x		x	x	x	
Introduction of PCB's		x	x			x	x	x			x		x		x	x	x	
Introduction of pesticides									x		x		x		x			
Introduction of petroleum/oil			x			x	x	x					x			x		
Introduction of radio nuclides		x	x										x			x		
Nutrient enrichment	x	x	x	x	x				x	x	x	x	x		x	x	x	x
Organic enrichment	x	x	x	x	x				x	x			x		x	x	x	x
pollution general	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x
Resuspension from sediment	x		?	x	x		x											
Non- selective extraction of species	x				x				?	x				x				
Selective extraction										x								
Abrasion	x			x	x		x		x	x		x						
Sealing			x	x					x									
Smothering	x	x	x	x	x				x									x
Conversion/destruction	x	x	x	x	x				x									
Sedimentation	x	x	x	x	x				x									x
Erosion	x			x	x													
Reduction in sedimentation				x														
Selective extraction of species									x	x								
Introduction of non-native species and translocations				x			x		x			x						
Introduction of litter		x	x			x	x	x	x	x		x	x					
Introduction of noise	x	x	x	x	x	x	x	x	x	x		x						
Migration barrier				x			x											
Water/tidal flow changes	x	x	x	x	x													

ANNEX 3 Overview of indicators

Condition indicators for coral reefs under different environmental conditions (after Cooper et al., 2009).

Bioindicator	Stressor	Response	Source
Genetic/colony measures			
Coral growth	Light limitation, nutrient availability	Massive *Porites*: mean skeletal density (g cm^{-3}, ±SD): Central GBR nearshore 1.35 ± 0.21, offshore 1.57 ± 0.16. Mean extension rate (mm $year^{-1}$, ±SD): nearshore 13.56 ± 3.5, offshore 8.22 ± 1.02. Mean calcification rate (g cm^{-2} $year^{-1}$, ±SD): nearshore 1.77 ± 0.26, offshore 1.28 ± 0.12	(Lough and Barnes 1992)
Coral growth	Dissolved inorganic nutrients	*S. pistillata*: growth rates (mg day^{-1}) decreased by 25–60% during long-term nutrient exposure	(Ferrier-Pages et al. 2000)
Partial mortality	River exposure	More colonies with >50% partial mortality adjacent to river mouths than sites distant from riverine discharge	(Nugues and Roberts 2003)
Bioindicator	Stressor	Response	Source
Population measures			
Population structure	Field water quality gradient	High Island (high exposure to flood plumes) low colony density (0.13 m^{-2}), similar proportion across size classes. Fitzroy Island (low exposure to flood plumes) greater colony density (2.46 m^{-2}), population dominated (>73%) by juvenile size classes.	(Smith et al. 2005)
Coral diseases	Dissolved inorganic nutrients	Nutrient enrichment associated with increased aspergillosis of *Gorgonia ventalina* and yellow band disease of *Montastraea annularis* and *M. franksii*	(Bruno et al. 2003)
Coral diseases	Dissolved organic carbon	Species-specific responses in mortality of *Montastrea annularis*, *Agaricia tenuifolia* and *Porites furcata* exposed to different sources of DOC. Mortality increased over time suggesting chronic exposure is potentially more deleterious than acute exposure	(Kuntz et al. 2005)
Coral diseases	Dissolved organic carbon	Mortality of *M. annularis* fivefold greater, and microbial production rates one order of magnitude greater, in DOC enriched treatments than in controls	(Kline et al. 2006)
Bioerosion	Terrestrial runoff	Total internal bioerosion of *Acropora* highly variable with nearshore ~4%, mid-shelf ~12%, outer reefs ~1%.	(Risk et al. 1995)
Bioerosion	Terrestrial runoff	Internal bioerosion in living *Porites* 11% on nearshore reefs, 1.3% on outer reefs.	(Sammarco and Risk 1990)
Community measures			
Micro- and meiobenthic bioindicators	Field water quality gradient	Change in benthic foraminifera along water quality gradients. Heterotrophic rotaliids and a species retaining plastids (*Elphidium sp.*) characteristic of low light, higher nutrient conditions on turbid nearshore reefs with larger symbiont-bearing taxa *Amphistegina* spp. and *Calcarina hispida* abundant on clear-water outer reefs in the Whitsunday Region of GBR	(Uthicke and Nobes 2008)
Larval supply and recruitment	Sedimentation	Larval survival and settlement reduced in experimental treatments of high (100 mg l^{-1}) and low (50 mg l^{-1}) sediments compared with controls (0 mg l^{-1})	(Gilmour 1999)
Larval supply and recruitment	River exposure	Recruitment greater on reefs distant from a river in the northern GBR compared with those adjacent to river discharge	(Smith et al. 2005)
Benthic cover	Dredging	Coral cover decreased by 30% adjacent to a dredging operation. Recovery of coral cover within 22 months	(Brown et al. 1990)
Benthic cover	Field water quality gradient	Increasing distance from two rivers, Central GBR: From reefs near the river to those >80 km, macroalgae cover decreased from 70 ± 10% to 0%, octocoral cover increased from 1 ± 1% to 19 ± 10%, and hard coral cover increased from 4 ± 2% to 31 ± 14%	(van Woesik et al. 1999)
Community structure	Field water quality gradient	Increasing distance away from two rivers, Central GBR: 24 hard coral taxa at reefs near rivers, 64 hard coral taxa at reefs >80 km away from rivers	(van Woesik et al. 1999)
Taxonomic richness	Field water quality gradient	Regional and gradient analysis of water quality on GBR, taxonomic richness of hard corals 50% lower in region with high nutrient and sediment loads; decreased octocoral richness but increased macroalgae richness along water quality gradients from low to elevated levels of nutrients and sediments	(Fabricius et al. 2005)
Max. depth of coral-reef development	Field water quality gradient	Maximum depth of coral reef development increased from 5.0 m at coastal reefs to 25 m at offshore reefs in the Whitsunday Region of GBR	(Cooper et al. 2007)

ANNEX 4 OSPAR criteria eutrophication

An evaluation of the suitability of OSPAR eutrophication Ecological Quality Objective and underlying background information.

a	**Criteria**	**Background information and status**
	Relatively easy to understand by non-scientists and those who will decide on their use	Yes, there seems to be a growing awareness about the importance of nutrient levels and their related effects in ecosystems (seeing the agreements on increased sewage treatment in the region).
	Sensitive to a manageable human activity (in relation to measures)	Yes, the underlying mechanisms and variables for eutrophication are interrelated, following a cause/effect relationship where the cause is linked to anthropogenic inputs of nutrients (mostly riverine or run-off). Since other environmental factors and human activities may be contribute to the response as well, the risk of misinterpretation of this cause/effect relationship is substantially reduced when a coherent monitoring is performed of all relevant parameters involved.
	Relatively tightly linked in time to that activity (in relation to measures)	The response is more direct and more tightly linked for the direct effect variables. The links between nutrient input and direct and indirect effects of eutrophication may, however, be spatially and temporally separated through transboundary effects and basin characteristics. Ecosystem or environmental factors (e.g. nutrient dynamics in sediments) may cause time lags.
	Easily and accurately measured, with a low error rate (monitoring)	Not likely, the needed elements do not seem to be part of a operational monitoring programme even though guidance is available for accurate measurement, including monitoring of the relevant supporting environmental factors (such as salinity, and temperature). Monitoring of direct and indirect effects should be performed in a coherent way, and with appropriate frequency and area coverage.
	Responsive primarily to a human activity with low responsiveness to other causes of change (in relation to measures)	Yes, whereby an integrated monitoring and assessment of the cause/effect related parameters is needed in order to relate the response to human activities, taking into account environmental factors and (local) ecosystem and basin properties.
	Measurable over a large proportion of the area to which the classification is to apply	Yes, all variables for eutrophication metrics are measurable in all areas.
	Based on an existing body or time series of data to allow a realistic setting of objectives (monitoring)	No. There are no time-series available. For most areas, there is insufficient information on the variables for determining eutrophication status for nutrients, phytoplankton indicator species, oxygen deficiency and changes/kills in zoobenthos and SAV. Furthermore, frequency and spatial coverage of monitoring is very low.
b	Ecological relevance/basis for the metrics	Both approaches and underlying knowledge is adoptable, and although region specific, the ecological relevance is high.
c	Current and historic levels (including geographic areas)	No, some recent region specific levels are available through seemingly ad hoc Monitoring Programmes and other sources of information. Historic levels on most of the elements are not available for most regions.

a	**Criteria**	**Background information and status**
d	Reference level (= area-specific background concentrations)	No, area-specific reference values cannot be derived, neither by the basis of historic levels, offshore levels, or by following the salinity-dependent approach. The setting of area specific reference levels are needed for comprehensive analyses allowing management. From ASSETS some thresholds were established in waters surround the USA, Caribbean. E.g., Hypereutrophic: >60 ug Chla/l. High: >20 but ≤60 ug Chl a/l Medium: >5 but ≤20 ug Chl a/l Low: >0 but ≤5 ug Chl a/l Justification: Estuaries with highest annual Chl a less than 5 ug/ l appear unimpacted (Nixon and Pilson, 1983), however, this level is detrimental to survival of corals (Lapointe and Matzie, 1996). At 20 ug/l, SAV shows declines (Stevenson et al., 1993) and community shifts from diverse mixture to monoculture (Twilley et al., 1985). At 60 g l^{-1} high turbidity and low bottom water dissolved oxygen are observed (Jaworski, 1981).

a	**Criteria**	**Background information and status**
e	Limit points (area-specific assessment levels)	Kills of zoobenthos and the demise of SAV are ultimate “limit points” and there is some physiological basis for the limit for oxygen. For the other variables is generally no clear “limit point” (assessment level) except perhaps for some area-specific nuisance and toxic phytoplankton indicator species. *Zoobenthos* status ranges are not clear. Detrimental impact is to be expected from nuisance and harmful algae blooms on filter feeding bivalves and fish. *For Dissolved oxygen:* Generally, Anoxia: 0 mg/l, Hypoxia: >0 but ≤2mg/l Justification: bottom water concentrations of 2mg l^{-1} or less, may significantly reduced benthic life forms and success of trawling for demersal species (Rabalais and Harper, 1992). Biologically stressful: >2 but ≤5mg/l. Laboratory observations have also shown oxygen stress responses in invertebrate and fish fauna at these concentrations (Rabalais and Harper, 1992). *For SAV spatial coverage* one may apply ranges: High: ≥50 and ≤100%, Medium: ≥25% but <50%, Low: ≥1% but <25% and Very low: ≥0 but <10% Justification Submerged vascular plants play a vital role in the ecology of nearshore environments These plants attenuate variable inputs of nutrients and sediment, and are thought to be invaluable nursery areas. In relatively pristine waterbodies, SAV thrive while die-off and absence of SAV is generally believed to be an indication of an eutrophic condition, associated with high turbidity caused by increased nutrient and Chl a concentrations (Orth and Moore, 1984; Stevenson et al., 1993; Boynton et al., 1996). Additionally, high nutrient concentrations may cause an imbalance in nutrient supply ratios leading to die-off of SAV (Burkholder et al., 1992a,b). Furthermore, macroalgae above 100 g dry wtm^{-2} are known to cause SAV die-off (Dennison et al., 1992). Also epiphyte colonizing SAV at a dry weight equal to the dry wt cm^{-2} of the host plant may cause die-off of the host plant (Dennison et al., 1992).
f	Time frames	Seen form other areas worldwide, detectable changes are estimated to be demonstrated in five to ten years. Some level of eutrophication is, however, acceptable as long as areas are classified as non-problem areas. The latter is seemingly not the case for whole of Singapore area.
g	Monitoring regimes	Monitoring of the variables for eutrophication is not yet established in any Monitoring Programme. Monitoring must include estuaries, coastal and offshore areas, and has therefore a broader scope. For most (sub)areas, spatial and temporal coverage should be improved. In problem areas, and potential problem areas, monitoring should include all variables for eutrophication and accompanying environmental factors every year.

a	Criteria	Background information and status
h	Management measures to achieve better eutrophication status	In general: Reduction of all nutrient discharges have not been clearly decided upon (regardless the projected increase in sewage treatments). When measures will be implemented, it has to be evaluated if this reduction in nutrient inputs will lead to achievement of the overall objective. For Singapore region, attention should be paid to reduction of inputs through agriculture, industries, households, and sewage treatment plants. Tools are available through the international recommendations and Directives. Although phosphorus reductions have been successful, nutrient enrichment may still be relevant as a result of sediment releases. Alternative measures may be considered to reduce the impacts from nutrient releases, e.g. by creating marsh areas on the fresh-marine interface that store or process nutrients.

EcoShape is een consortium bestaande uit