Project SI 4.1 – Phase 2

A quick-scan of literature and available numerical models

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Preliminary

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EcoShape

Project SI 4.1 - Phase 2

A quick-scan of literature and available numerical models

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Abstract

The Joint Singapore Marine Program (JSMP) is a result of cooperation between the Singapore Delft Water Alliance (SDWA) and EcoShape, Building with Nature (BwN). Most research projects of the JSMP require data and /or model studies, including measurement campaigns, monitoring and modelling of ecological processes and parameters as well as physical ones. A main objective of the supportive project SI 4.1 is to provide and disclose the results of a coordinated inventory and collation of :

- required and accessible, existing data of field measurements and monitoring,
- scientific and grey literature and existing numerical models,

forming a basis for developing new measurement and monitoring plans and model studies, thereby facilitating an efficient start of the whole JSMP.

This report describes the results of a quick-scan of literature and an inventory of available numerical models. The objective of this report is to provide an accessible introduction to everybody who is interested and/or involved in the research topics addressed in the JSMP. As such, it does not pretend to give an in depth scientific literature review; this will be done within the scientific (SDWA) research projects. It does however summarise the general characteristics, management issues, data and knowledge gaps (as identified in the SDWA projects so far) for the following topics:

- The Physical system (Chapter 2)
- Water quality of the coastal waters of Singapore (Chapter 3)
- Human activities in the coastal waters of Singapore (Chapter 4)
- Coral reefs around Singapore (Chapter 5).
- Sea grass meadows around Singapore (Chapter 6)
- Mangroves around Singapore (Chapter 7)
- Modelling inventory (Chapter 8)

References

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Appendices

1 Introduction

1.1 The Joint Singapore Marine Program

With the help of Dutch expertise, the tropical nation of Singapore has invested extensively in land reclamation and the creation of new coastline. Whilst sufficient space and up-to-date coastal and marine infrastructure are necessary to maintain economic growth, sustainable ecological development of the coastal and marine environment is essential to maintain the country's aesthetic value. In addition, adaptation to the effects of climate change becomes increasingly important during the coastal development. Climate change will manifest itself in more severe storms, higher extreme water levels and increased wave attack, thereby raising a need for innovative protection of coastal areas against sedimentation, erosion, and flooding.

Turbid waters
There is a growing concern about increased turbidity levels in the Singapore coastal waters and its effect upon coastal habitats (e.g. coral reefs, mangroves, sea grasses, rocky shores and beaches).

Natural shorelines
How do we protect existing valuable habitats, enhance or restore affected habitats, and stimulate the development of new habitats? What opportunities do these habitats offer for an innovative adaptation to climate change?

The Joint Singapore Marine Programme (JSMP, see textbox) will investigate these issues and will address the causes of deteriorated water quality, the response and interactions of sensitive ecosystems, and the opportunities that these ecosystems offer for sustainable coastal and marine development. More specifically, the programme aims to:

1. Establish science-based criteria and early warning indicators for turbidity and sedimentation in marine infrastructure development (planning, construction and use). Early warning indicators allow ecosystem responses to be monitored and predicted, whereas criteria provide guidelines to support the design and construction of marine infrastructure.
2. Establish science-based protocols, tools and small-scale field pilots for developing natural soft and hard coastlines in tropical environments by utilising habitats and organisms (eco-engineers) and by enhancing the ecological potential of artificial building blocks.
3. Development of an opportunity map for eco-dynamic design together with stakeholders and end-users, to ascertain how JSMP results and products will be used in practice.

The **Joint Singapore Marine Programme (JSMP)** is a result of cooperation between the Singapore Delft Water Alliance (SDWA) and EcoShape, Building with Nature (BwN). The JSMP combines projects of Building with Nature – case Singapore - and SDWA Marine into one coherent programme. The primary goal of SDWA is scientific capacity building and strengthening of fundamental research activities in Singapore. The primary goal of BwN is to develop a green perspective for water-related infrastructure by providing tools and knowledge for sustainable design of such works.

To achieve these goals, research is carried out along five thematic lines (Figure 1.1):

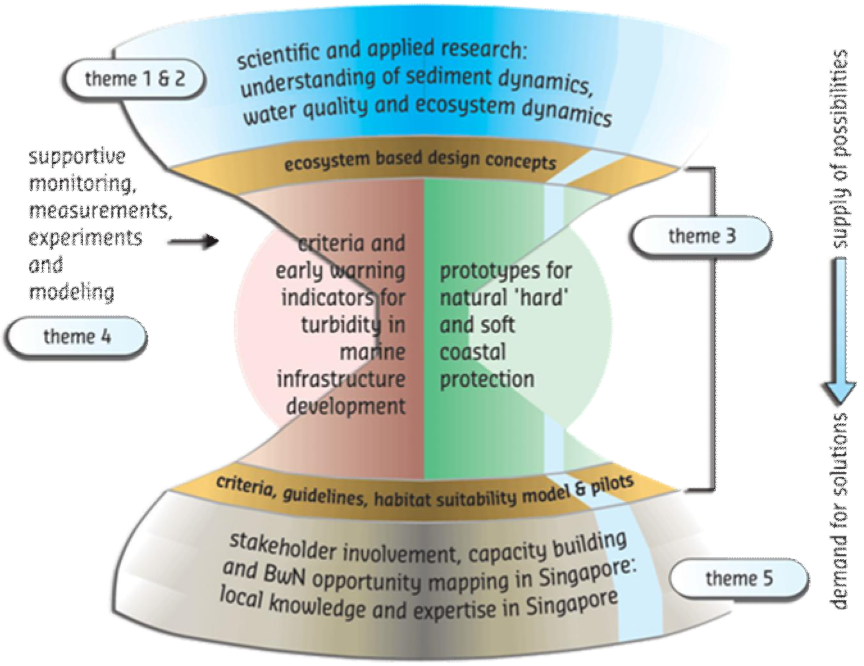

Figure 1.1 *Coherence between different research themes of the Joint Singapore Marine Programme.*

Theme 1 & 2: Scientific research focusing on sediment dynamics, water quality and ecosystem dynamics. To a large extent, this is research carried out within SDWA - Marine. This research will increase our understanding of:

- the causes and background risks of the deteriorated water quality (increased turbidity) of the coastal waters around Singapore;
- the effect of deteriorated water quality on the response of sensitive ecosystems (e.g. corals and sea grass meadows);
- interactions between corals, sea grass meadows and mangroves (self-facilitating processes) and the services that these ecosystems provide in attenuating hydrodynamic energy and in stabilizing the seabed.

Theme 3: Combining existing and new knowledge generated in Themes 1 & 2 into the practice of eco-dynamic design. This requires the development of:

- measurable and predictable criteria and early warning indicators for turbidity, sedimentation and ecosystem response;
- designs and pilots for bio-diverse coastal protection.

Theme 4: Supporting monitoring, field measurements, field and laboratory experiments and mathematical modelling for the scientific and applied studies in the other themes.

Theme 5: Involving stakeholders, especially responsible government agencies, to ensure that the knowledge and concepts that are generated in the programme can and will be put into practice. This will be achieved by training (capacity building) and by mapping opportunities in Singapore in close co-operation with the stakeholders. This theme ensures that the supply of solutions generated in the programme matches with the stakeholders' demand for solutions.

The JSMP consists of twelve coherent research projects, divided over five themes and each contributing to one or two of the applied research projects in theme 3 (Figure 1.2).

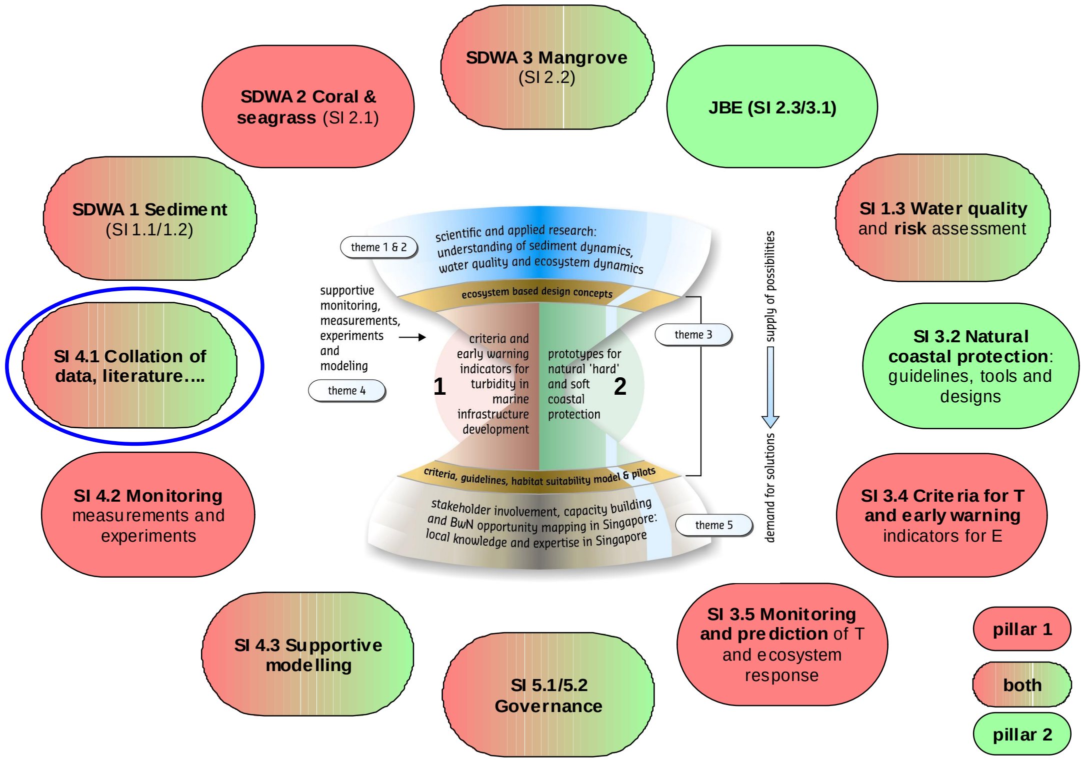

Figure 1.2 *The 12 research project of the JSMP and their coherence. JSMP objectives 1 (red) and 2 (green) represent the applied research pillars in theme 3.The colour of each project indicates which applied research pillar it contributes to, i.e. red is contribution to development of science-based criteria and early warning indicators, green is contribution to design and prototypes of natural shoreline, red/green contributes to both. The first number in the SI project code indicates the to which research theme (1 to 5) a project belongs. There are three 'SDWA projects' forming the SDWA marine Program, all other projects represent the case Singapore of Building with Nature. JBE is a BwN project that will be carried out under the umbrella of SDWA.*

1.2 The BwN project SI 4.1 of the JSMP

Most research projects of the JSMP require data and /or model studies, including measurement campaigns, monitoring and modelling of ecological processes and parameters as well as physical ones. A main objective of the supportive project SI 4.1 is to provide and disclose the results of a coordinated inventory and collation of :

- required and accessible, existing data of field measurements and monitoring,
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forming a basis for developing new measurement and monitoring plans and model studies, thereby facilitating an efficient start of the whole JSMP.

Within specific projects, a substantial effort will be made to collect new dedicated field observations and carrying out state-of-the-art modelling to address the various specific research questions and to meet the overall objectives of the JSMP. In phase 1 of this project, more general data needs have been identified, i.e. field or model data that are needed for more than one project and/or data that most likely already exists and could be obtained from governmental agencies or other stakeholders. The existence and accessibility, as well as the collection, review and disclosure of this general data in a data base will be assessed in early 2010.

This report describes the results of a quick-scan of literature and an inventory of available numerical models. The objective of this report is to provide an accessible introduction to everybody who is interested and/or involved in the research topics addressed in the JSMP. As such, it does not pretend to give an in depth scientific literature review; this will be done within the scientific (SDWA) research projects. It does however summarise the general characteristics, management issues, data and knowledge gaps (as identified in the SDWA projects so far) for the following topics:

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- Modelling inventory (Chapter 8)
- Key points summary from Chapters 2-8 (Chapter 9)

For reference purposes, appendix A summarizes the collected literature references in two ways: 1) a total, alphabetically ordered reference list and 2) and alphabetically ordered reference lists per topic. The collected literature (pdf-files) will be actually disclosed as a next activity (2.4) of Phase 2.

2 The physical system

2.1 Hydrodynamic regime in the coastal waters around Singapore

2.1.1 Tides and monsoon currents

The large-scale currents in the South China Sea are generated by the annual variation of the monsoon winds and by tides with a pronounced spatially varying dominance of semi-diurnal and diurnal constituents.

<u>Monsoon winds</u>
The monsoon winds are generated by a combination of the trade winds and the seasonal variation of the position of the sun. Near the equator, the trade winds generate a persistent system of easterly winds. The resulting pressure gradient between the western Pacific and the eastern Indian Ocean drives a net westward flow through the South China Sea. The equatorial pressure trough moves according to the position of the sun, crossing the equator twice each year, generating a north-south component of the wind direction. November to April is dominated by the Northeast monsoon (north of the equator) and the Northwest monsoon south of the equator (between 0^o and 10^oS). May to October is dominated by the Southeast monsoon (south of the equator) or the Southwest monsoon north of the equator (between 0^o and 10^oN) (Wyrtki, 1961). As a result, the sea level near Singapore fluctuates over 40 cm annually, with lowest levels in June-July and a peak in November (Wyrtki, 1961). East of Singapore, in the waters in-between Malaysia/ Sumatra and Borneo, the residual flow strongly fluctuates in strength and direction. It is directed southward from September to May (with peak current velocities in February and December of 15-20 cm/s, and northward from May to September (with current velocities generally between 15 and 20 cm/s (Wyrtki, 1961). The flow in the Singapore Strait is generally westward throughout most of the year, with velocities of 10-15 cm/s, but reverses direction from June until August (Robinson et al., 1953; Kow 1973), flowing in the eastward direction.

<u>Tides</u>
The tides in the South China Sea are influenced by semi-diurnal tides (mainly the principal solar component S2 and the principal lunar component M2), as well as diurnal oscillations associated with the moon's declination (K1 and O1). Their relative importance varies spatially due to local amplification and damping of the various constituents. Near Singapore, the tides are mixed, mainly semi-diurnal, with dominance of semi-diurnal tides alternating with dominance of diurnal tides. This alternation is the result of the phase difference between the O1-K1 spring-neap cycle (13.66 days) and the M2-S2 spring neap tidal cycle (14.77 days), resulting in a 182.62 days period. Since this is exactly half a year (by definition; this would also follow from an analysis of the 6 principal Doodson numbers which form the basis of the harmonic tidal constituents), the variation of semi-diurnal and diurnal dominance is constant through time (except for the 18.6 year cycle). Around March and September, spring tides are dominantly semi-diurnal (but neap tides diurnal) whereas spring tides are dominantly diurnal (and neap tides semi-diurnal) around June and December.

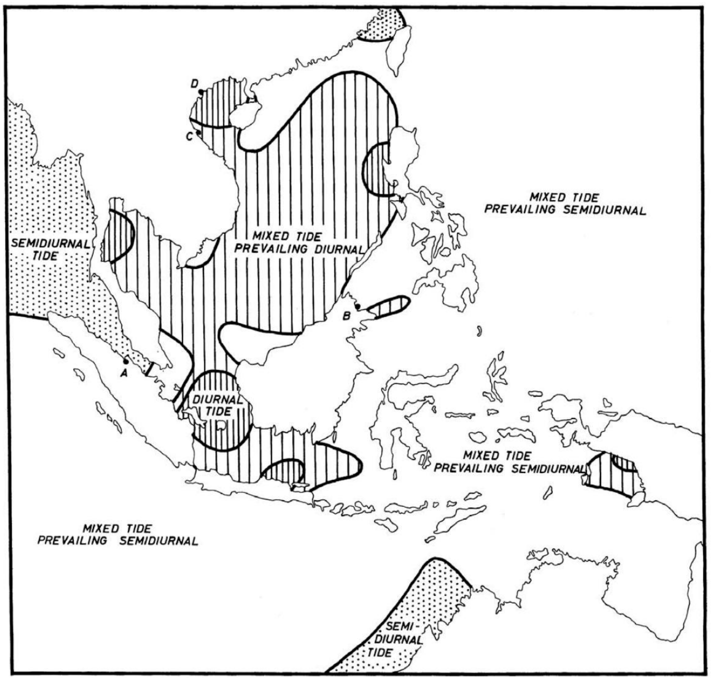

Figure 2.1 Tidal regimes in the South China Sea

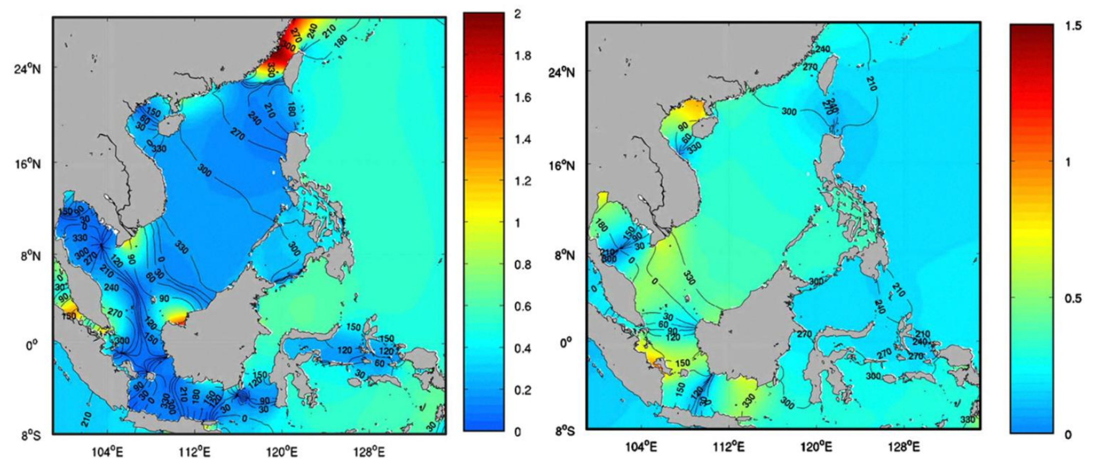

Figure 2.2 Amplitude (m) and phase (degrees) of M2 (left) and K1 (right). From Zu et al. (2008).

Singapore is located in an exceptionally sharp transition zone where dominantly diurnal tides (in-between Sumatra and Borneo) change into semi-diurnal tides (in-between Sumatra and Malaysia, just North of Singapore) within a distance of only 400 km (Figure 2.1). The transition from diurnal to semi-diurnal is the result of an increase of the M2 amplitude (especially in the Singapore Strait) and a decrease in diurnal amplitudes (Figure 2.2 Amplitude (m) and phase (degrees) of M2 (left) and K1 (right). From Zu et al. (2008).). This strong gradient has two important consequences:

1) Strong tidal currents occur where separate basins having different tidal regimes are connected by a narrow channel (i.e. Pugh, 1987). Therefore, the sharp transition in tidal regimes is expected to generate strong tidal currents in the Singapore Strait.
2) In most shelf seas, the tidal wave of each tidal constituent is a combination of a (progressive) Kelvin wave and a standing wave. Progressive tidal waves have

maximum currents at high and low water (lagging the water levels by 180°), and their magnitude increases with the wave amplitude. Hence, they do not exist near amphidromic points where water levels variations are low. Standing tidal waves, however, have maximum tidal currents at amphidromic points, with currents lagging the water levels with 90°. As a result, sharp transition in tidal regimes may generate tidal currents in the Singapore Strait which strongly deviate from the local water levels. While water levels are mixed, mainly semi-diurnal, the flow velocities are mainly diurnal.

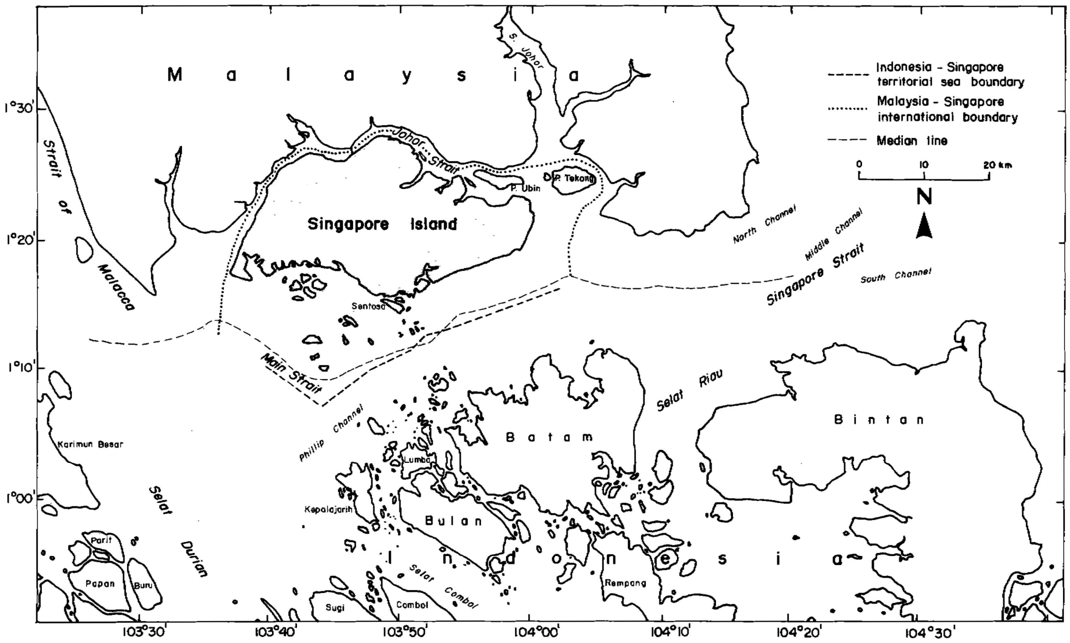

Figure 2.3 Singapore, south Malaysia and the Indonesian Riau islands.

The Singapore Strait (see Figure 2.3 for location) is relatively narrow, resulting in flow velocities up to 3 m/s (Chen et al., 2005). These strong flow velocities have scoured the main channel in the Singapore Strait to an average depth around 50 m (see Figure 2.4), although locally the depth exceeds 100 m. The current measurements show that currents are more strongly diurnal than semi-diurnal (while water levels predominantly being semi-diurnal). During some periods a strong (eastward) residual flow is observed throughout the Singapore Strait. Several model studies presenting measured and simulated flow velocities have been published (Chen et al., 2005; Chao et al., 1999, Zhang and Gin, 2000; Zhang, 2006). Additional model studies, presenting model results but lacking actual field data, include Tkalich et al. (2002) and Pang and Tkalich (2003). Although these studies were carried out with different models, all use the same model domain with a 1 by 1 km grid, measuring 110 by 70 km. Most are based on the Princeton Ocean Model (POM; Chen et al., 2005; Zhang and Gin, 2000; Zhang, 2006; Tkalich et al., 2002; and Pang and Tkalich, 2003). MIKE3 is additionally applied by Zhang (2006) while Chao et al. (1999) setup their own model. A refined MIKE21 model has grid cells down to 75 m (Doorn-Groen, 2007). All model studies, but especially Chen et al. (2005) overestimate the semi-diurnal currents and underestimate the diurnal currents. Water levels are fairly accurately reproduced. This is in line with the decoupling of water level variation with tidal currents, as discussed above: the models are forced by the predominantly semi-diurnal water level variation, underestimating the diurnal currents generated by the standing component of the O1 and K1 tidal constituents.

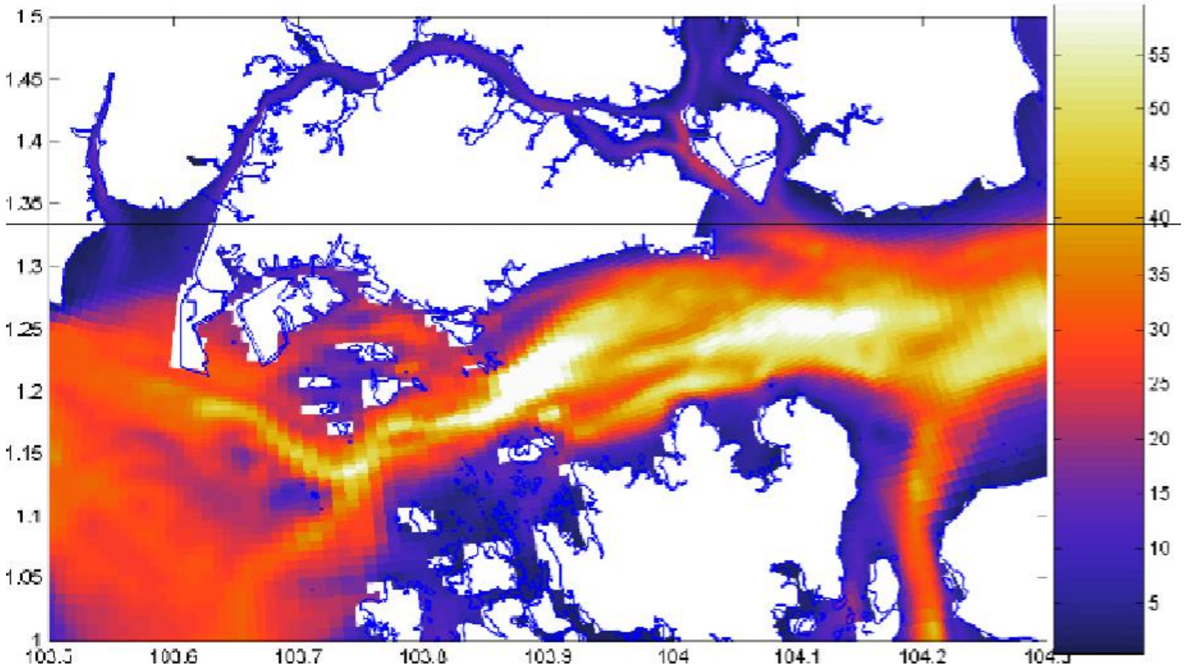

Figure 2.4 Bathymetry in the Singapore and Johor Strait (based on Admiralty Charts).

2.1.2 Rivers

Several small rivers drain into the coastal waters around Singapore. The largest of these is the Johor River, flowing into the Johor Estuary (Figure 2.3). Several smaller river systems flow into the Johor Strait from Malaysia (in the clockwise direction: the Pulai, the Pendas, the Melayu, the Skudai, the Tebrau and the Kim-Kim River). From Singapore, the Punggol, the Sungei Buloh, the Sungei Kranji, the Sungei Seletar, the Sungei Serangoon flow into the Johor Strait while the Sungei Kallang drains into the Singapore Strait. The discharges of the smaller rivers are poorly known, but the daily averaged discharge of the Johor is published by the West-Malaysian drainage and irrigation division. The long-term average discharge is 37.5 m^3/s, varying from 70 m^3/s in December to around 30 m^3/s in February to October (Figure 2.4). It can be assumed that other smaller rivers have a similar seasonal variation, but a lower discharge.

The sediment load of these rivers is poorly known. Najah et al. (2009) give an average sediment concentration for the Johor River of 79.8 mg/l (with minimum and maximum tabulated values of 35 mg/l and 164 mg/l, resp., although their graphs show apparent monthly averaged values exceeding 250 mg/l). A study on runoff from a small urban catchment in the Skudai River (Nazahiyah et al., 2007) shows maximum concentrations during high energy events up to 1 g/l. ASEAN/US CRMP (1991) give suspended sediment concentrations, based on sampling in 1987, of 24 mg/l for the Skudai (10 samples), 34 mg/l in the Tebrau (4 samples), and 29 mg/l for the Johor River (10 samples).

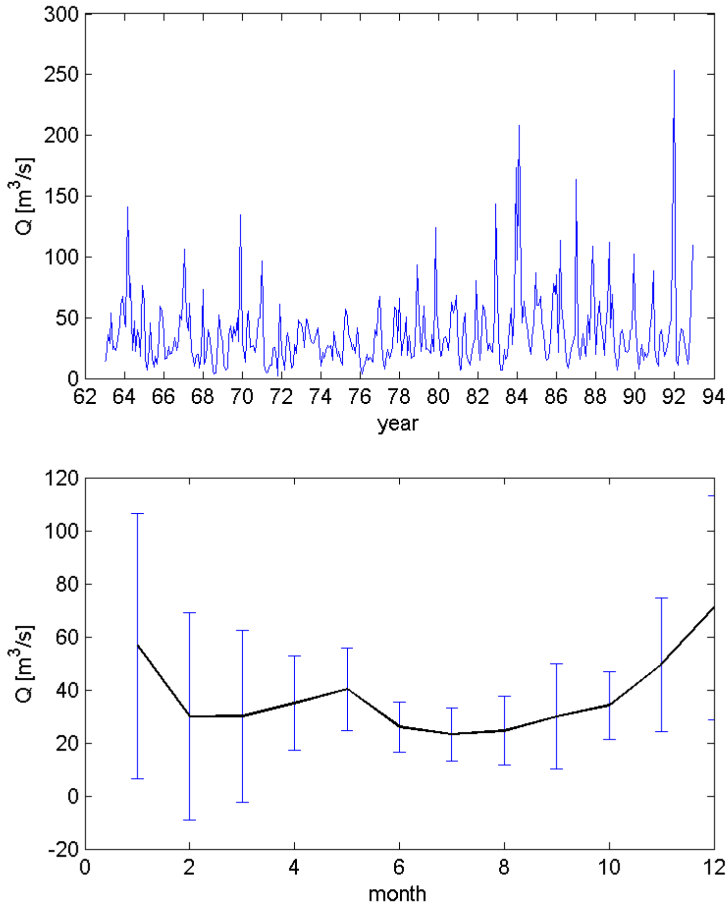

Figure 2.5 Discharge of the Johor River near Rantau Panjang (catchment area of 1130 km^2): timeseries (top) and monthly averages, with standard deviation (bottom). From West-Malaysian drainage and irrigation division.

Data published by the Drainage and Irrigation Division Malaysia (1985, details on sampling methods and location are not known) are in line with the data published by Najah et al. (2009). The average concentration from 1980 to 1985 is 123 mg/l, with two maxima during the discharge peaks of December and May (Figure 2.5). Note, however, that observations are probably limited by the maximum concentration detectable by the turbidity sensor: the maximum concentration is 238 mg/l too frequently. The observation that the detection limit is exceeded so frequently indicates that:
(1) the average concentration should be higher
(2) the maximum concentration is much more than 238 mg; probably closer to 1 g/l.

Using an average concentration of 150 mg/l and an average discharge of 37.5 m^3/s, gives a long-term sediment influx equal to 5.6 kg/s or 0.17 million ton per year. Although little is known about the combined discharge and sediment loads of all the smaller river systems, a first order estimate can be obtained by comparing the catchment of Rantau Panjang with other rivers, and extrapolating the Rantau Panjang loads. Considering Figure 2.6, only half of the Johor Catchment is sampled at Rantau Panjang. Also the additional Malysian catchment has an area close to that of Rantau Panjang, while the Singapore area is approximately half of the Johor upstream of Rantau Panjang. In total, the catchment area draining into Singapore's waters is about 3.5 times that of the catchment upstream of Rantau Panjan. Assuming, as a first estimate, a similar sediment yield, then close to 0.6 million ton of sediment is annually supplied to Singapore's coastal waters.

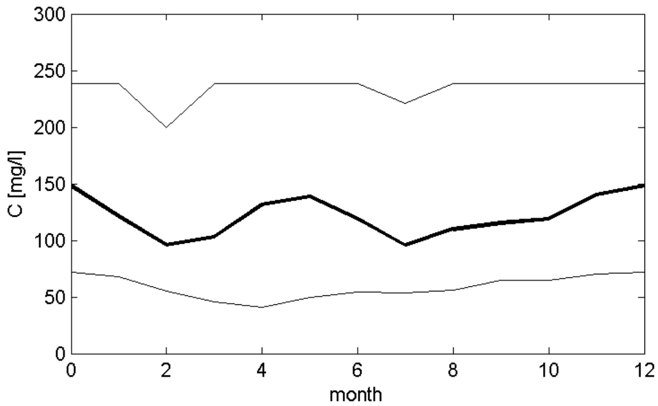

Figure 2.6 *Mean (thick line), maximum and minimum sediment concentration (thin line), of the sediment concentration on the Johor at Rantau Panjang. Data based on monthly minimum, maximum, and mean sediment load and discharge from 1981 to 1985, published by the Drainage and Irrigation Division Malaysia (1985). The average concentration is computed by dividing the mean monthly concentration by the mean monthly discharge, and similarly for the minimum and maximum concentration. The average sediment concentration is then the average of 5 years whereas the minimum and the maximum are (resp) the minimum and maximum of those 5 years.*

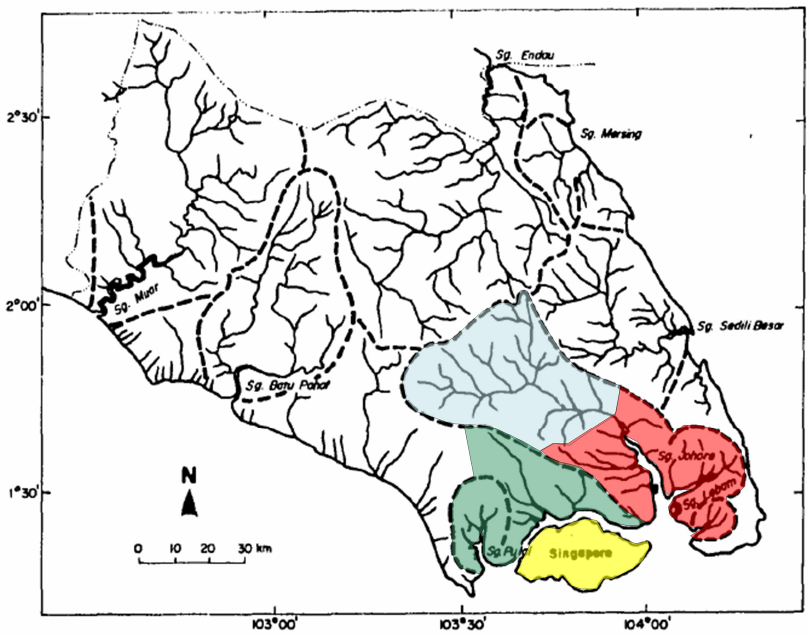

Figure 2.7 *River basins in south Johor (ASEAN/US CRMP, 1991), with the Johor basin upstream of Rantau Panjang in blue and downstream in red; other Malaysian river basins in green (including the Pulai, the Pendas, the Melayu, the Skudai, the Tebrau and the Kim-Kim River); and Singapore in yellow.*

2.1.3 Wind and Waves

Wind speeds in and around Singapore are generally low, with the exception of the North-East monsoon when wind speeds can exceed 8 m/s (Figure 2.8). There is a distinct diurnal variation with maximum wind speeds occurring in the afternoon (Chia et al., 1988).

The wave fetch length around Singapore is generally short, and the directions of maximum fetch length rarely coincide with the direction of the strongest winds. The wave energy is additionally dissipated through obstruction and refraction by the shallow waters, islands and reefs. Consequently, the average wave breaker height (due to shoaling) near Singapore is less than 20 cm (Wong, 1985 and Chia et al., 1988). Measurements at Bedok (south coast of Singapore), reported by Wong (1985) showed that the significant wave height H_s is 0.2-0.4 m for 55% of time during the northeast monsoon, but less than 0.2 m for the remaining period. The maximum recorded wave height, during the 12 month measurements, was 1.1 m. Higher waves occur east of Changi during the northeast monsoon due to refraction of swell from the South China Sea, resulting in a H_s of 1 to 1.25 m some 5 km east of Changi (frequency unknown). Squalls with wind speeds of 20-25 m occasionally occur during the southwest monsoon, generating waves about 1 m high along the southwest coast (Wong, 1985).

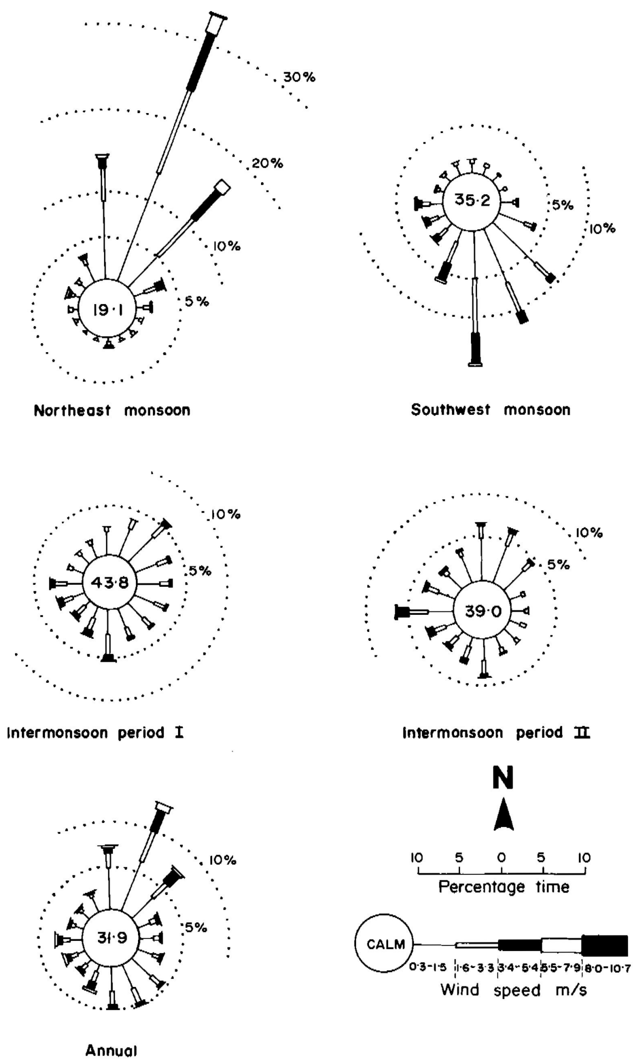

Figure 2.8 Windroses in Singapore (Chia et al., 1988).

2.2 Distribution, properties and transport of (fine) sediments

The seafloor in most of Singapore's coastal waters is covered with unconsolidated sand and mud, some deposited at the end of the Pleistocene Era (Chia et al., 1988). According to Goh and Chou (unpublished) and Chou et al. (2004), the percentage of silt and clay (mud, median grain size less than 63 μm) varies from several percent to 40%. Mud is absent in the tidal channels where large tidal current velocities occur. An exception is the large amount of mud found in the southern Strait of Malacca. Here tidal currents are strong and waves substantial, but the environment is still muddy. This mud is supplied by the numerous rivers draining Malaysia (Keller and Richards, 1967) and as long as the amount of mud supplied to the system exceeds the reworking capacity of waves and currents combined, mud dominates the seabed.

Mudflats and mangrove forests border the estuaries draining into Singapore's coastal waters from Malaysia; especially along the Johor Estuary. Mudflats stretch from the mouth of Tampok River southward to Johore Strait for a distance of 74 km. This curvilinear length of coastline consists of a series of shallow bays. The principal soil type along the mud coast is marine clay, having depths exceeding 25 m, often covered with a thin surface layer of shell and sand (ASEAN/US CRMP, 1991). The length of Singapore's mainland coastline is 131.5 km with an additional 150 km on the combined islands (Chia et al., 1988). The present coastline of Singapore is strongly dominated by man-made structures. Originally, the coastline was a combination of beaches (mainly southeast coast), cliffs and headland, spits around river mouths, and mangroves with mudflats in sheltered regions (Wong, 1985). Sediment transport is in the westward direction on Singapore's Southeast coast, confirmed by tracer experiments and spit configuration (Figure 2.9). This westward transport is due to dominant westward tidal currents and due refracted swell from the South China Sea (Wong, 1985). Transport directions on the Southwest coast are more variable along the coastline.

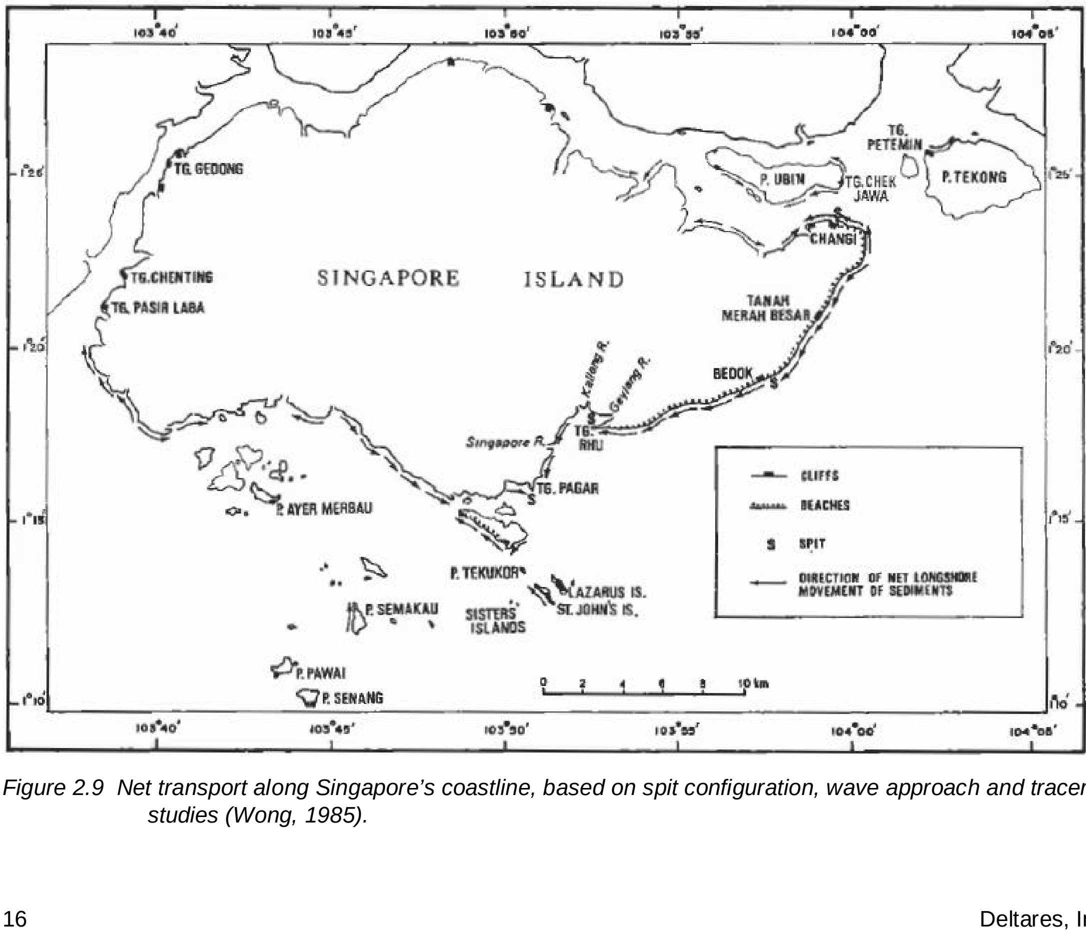

Figure 2.9 Net transport along Singapore's coastline, based on spit configuration, wave approach and tracer studies (Wong, 1985).

Measurements by Wood et al. (1997) show that sedimentation rates in the Strait of Johor and the Johor estuary vary from around 20 (Johor estuary and parts of the Straits) to several 1000's mg/cm^2/year (Johor Strait). Assuming a typical density of 500 kg/m^3, this equals a sedimentation rate between 0.5 mm/year and 10 cm/year. Sedimentation rates (predominantly sand with some silt) around P. Semakau (coral reefs) are 10 to 90 mg/cm^2/day (Chou et al., 2004), which corresponds with 7 to 65 cm/year (again using a density of 500 kg/m^3). This therefore can only be short-term deposition, rather than long-term deposition.

Turbidity was not measured until recent years, and therefore the apparent increase in turbidity is mainly based on qualitative or semi-quantitative descriptions. The most detailed description of the increase in turbidity is given by Chou and Chia (1991):

'Until as recently as the early 1960s, water visibility was still at approximately 10-m depth around the Southern Islands, in spite of increasing population and industrial activity. However, since the mid-sixties extensive land reclamation projects have resulted in very high levels of sedimentation that often reduce visibility to less than 2 m on a clear day. Sediment has settled in thick layers on the seafloor off the entire southern coast of the mainland and on the bottom of channels in between the offshore islands. Reef and shore flats have not been spared the effects of sedimentation which is turning the sandy substratum into soft mud'.

The present-day suspended sediment concentration is typically between 5 and 20 mg/l along the west coast of the southern islands of Singapore (water depth approximately 4 m), based on a survey of 6 islands for a one-year period (Dikou and van Woesik, 2006).

2.3 Anthropogenic measures and their impact on the physical system

The high population density and rapid socio-economic development of Singapore in the last decades has led to extensive land reclamation works. New beaches, industrial parks, commercial and housing development, port and airport facilities, and other important infrastructure have increased the surface area with nearly 20% in the past decades. These reclamation works strongly influence the long-term hydrodynamics and sediment dynamics around Singapore through modification of residual flows and maximum flow velocities, and the creation of low-energy sheltered areas. The construction phase, with strong dredging impact, has a more profound effect on the short-term, but is of shorter duration. Forest clearance and catchment urbanisation, finally, increase the amount of sediment transported seawards by rivers.

2.3.1 Reclamation works

The estuaries on the Singapore mainland used to be regularly flooded, and consequently fine sediment could accumulate at a rate approximately equal to the rate of compaction plus the net growth rate. Typical growth rates are the rate of sea level rise (at equilibrium conditions) or faster (implying an accreting coast, often observed in areas with substantial fluvial sediment supply). The growth rates of fine sediment deposits in Singapore are, however, unknown, and therefore the best estimate is the average rate of sea level rise in the past century (i.e. around 0.2 m/century). Most of the intertidal areas of the estuaries have been reclaimed, preventing accumulation of fine sediment. Therefore this sediment sink no longer balances terrestrial sediment supply from local rivers, and may therefore increase the turbidity in the marine waters. Additionally, fine sediment accumulates in mangrove areas. A large amount of the mangrove area has been cleared for aquaculture (the mangrove cover has decreased from 13% in 1819 to 0.5% in 1994; Ng and Low, 1994), and therefore the fine sediment trapping efficiency of the mangrove areas along the strait of Johor has probably been substantially reduced. It can be hypothesized that such a reduction of sediment trapping efficiency has led to an increase in the turbidity around Singapore. On the other hand, the closing of the estuaries also immobilized a large amount of sediment, which may therefore have reduced the turbidity – especially on the shorter term.

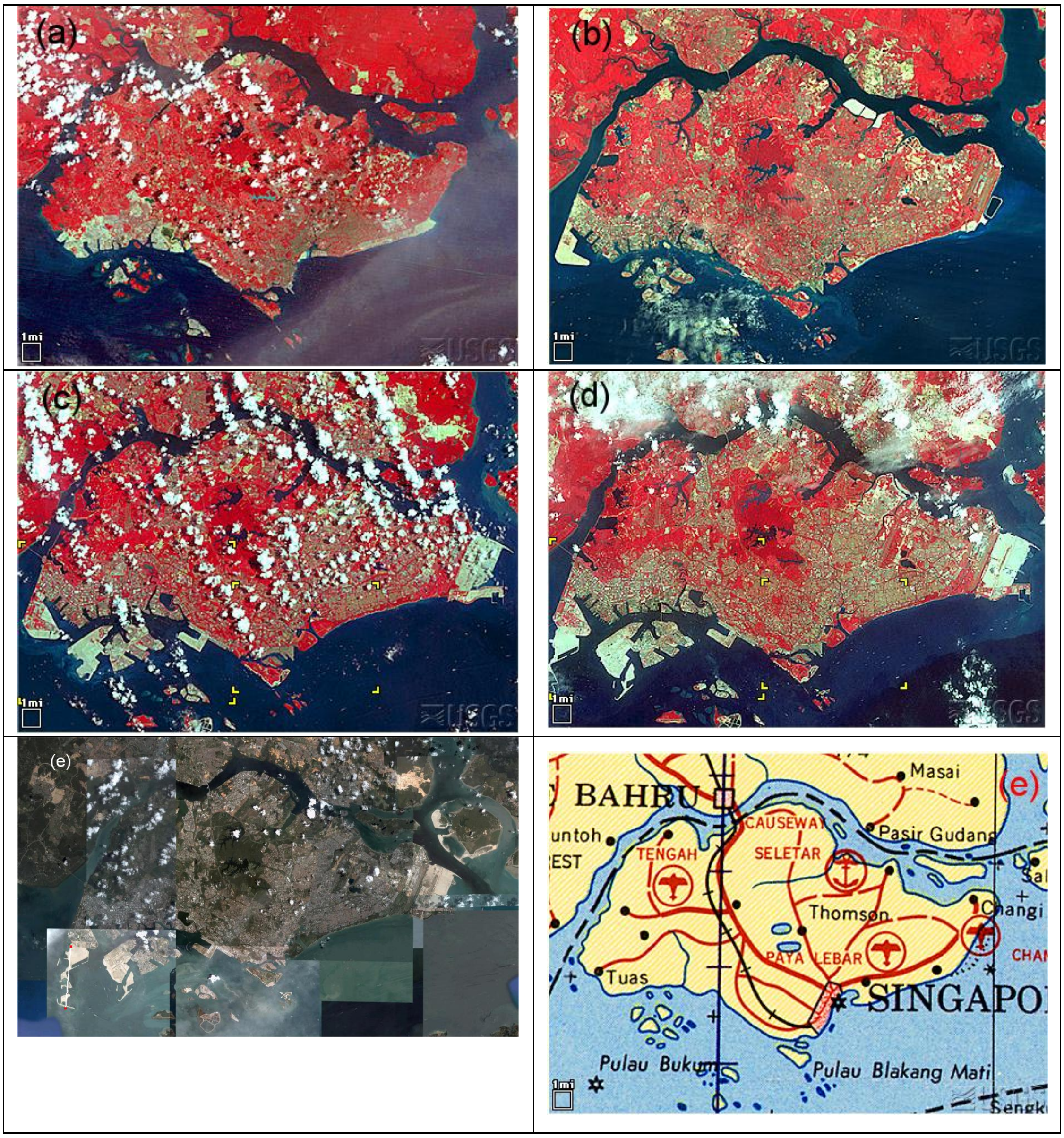

Figure 2.10 Satellite images in 1973 (a; Landsat 1, 17 oct), 1990 (b; Landsat 4, 17 apr), 2000 (c; Landsat 7, 3 sep) and 2002 (d; Landsat 7, 11 sep) a more recent Google Earth image (e) and a map from 1965. (a-d and f from http://earthshots.usgs.gov/Singapore/Singapore)

The major construction works in Singapore's coastal waters will be evaluated here briefly to assess the impact on the physical system; see chapter 4 for a more complete overview. The first major construction work was the causeway of the Johor strait in

1924, blocking through-flow in the Johor Strait. The Johor Strait used to connect the South China Sea and the Malacca Strait, resulting in currents of several knots in the Johor Strait. (Wood et al., 1997). The blocking of the channel by the causeway resulted in deposition of a very distinctive clay layer: anoxic, black, very porous with high water content, strongly smelling of $H2S$, and lacking any living organisms (Wood et al., 1997). This layer stretches about 5 km east and west of the causeway.

From the 1965 map and the satellite images available for 1973, 1990, 2000, and 2002 (Figure 2.10), the following main construction works can be observed (also refer to Chapter 4):

- Between 1965 and 1973, land was reclaimed at the Singapore river mouth and the south-east coast was extended seaward up to about 1 km.
- Between 1973 and 1990,
    - the mouth of the Singapore River (south of the East Coast Parkway) was further reclaimed.
    - The island's east coast (near Changi) was extended seaward for several kilometres.
    - A 1 km wide stretch of land in the Johor Strait, between Punggol and Serangoon, was reclaimed.
    - The port of Singapore Port was extended at Tuas (approximately 4 by 5 km)
    - P. Sedong was enlarged, as well as some of the islands later to merge with Jurong Island.
- Between 1990 and 2000,
    - Changi airport (east Singapore) was build, extending Singapore island nearly 4 km in the eastward direction.
    - In the west, Tuas and Jurong were further enlarged.
    - Large areas around P. Semakau were reclaimed.
    - The large jetty near Pasir Panjang was constructed.
- The main developments between 2000 and 2002 were the 7 km southward extension of Tuas, and the enlargement of Jurong island
- After 2002, major developments have been around P. Tekong, east of Singapore Island. The western part of the island was enlarged, while sheet piles were constructed south of the island.

The effects of the construction works on large-scale turbidity changes are unknown. However, their affect can be estimated through expert judgement, and probably mainly is:

- Mangroves generally trap fine sediments, and therefore clearing of mangrove forests reduces trapping of fine sediments. About 13% of Singapore used to be covered with mangroves, which corresponds to about 70 km^2. Assuming that mangroves keep pace with sea level rise (0.2 cm/y), and a dry bed density of 1000 kg/m^3 (i.e. compacted clay), the mangroves used to accommodate 0.14 million ton of clay annually. In reality a thicker layer of lower density will be deposited annually, which consolidates over time, but with a sediment mass equal to 0.2 cm*1000 kg/m^3). An amount of 0.14 million ton is nearly equal to the sediment sampled at Rantau Panjang (also refer to Section 7).
- The protruding reclamations such as Tuas form a relatively sheltered area with lower flow velocities and wave-induced re-suspension. Settling lag effects typically generate a transport of fine sediment from areas of high energy to low energy, leading to locally increased sedimentation rates and/or turbidity. Therefore it is likely that the sediment concentration in the sheltered areas will increase.

2.3.2 Dredging

Extent of dredging

Dredging in the coastal waters of Singapore has been extensive and still is extensive. All construction works carried out in the past decades have required huge capital dredging efforts. Simultaneously, coastline maintenance guarantees dredging efforts in locations where construction works are completed. In the first years of dredging, sand needed for reclamation was mined from Singapore's coastal waters whereas presently sand is mainly imported. However, there is no information available on the amount and type of dredged sediment, location and timing of dredging, and type of dredging. Similarly, it is not known whether maintenance dredging is needed in the port of Singapore and its approach channels.

Effect of dredging

The effect of dredging on turbidity depends on the amount of sediment dredged, the type of dredging, and mitigation measures reducing sediment losses. With increasing environmental awareness it seems likely that the impact of dredging has been reduced in the past decades by reducing loss of sediment, and the resulting increase in turbidity. Additionally, sand mining (also increasing the overall turbidity) is not done in Singapore anymore. It therefore seems likely that the effect of dredging is less than it used to be. However, very little information is available to quantify the effect of dredging in Singapore's coastal waters.

The effect of dredging on surface sediments was analyzed with measurements before, during, and after dredging, in Pungol Serangoon (Johor Strait, North of Singapore), by Nayar et al. (2007). They monitored 3 locations in the Pungol Serangoon estuary, while dredging occurred at the head of the estuary. During dredging (lasting 8 months), the sand content on the sediment bed was higher than before dredging. The sand content decreased again after dredging, but was still higher than before dredging. This can be attributed to the low-energy (and therefore muddy) environment of the estuary: during natural conditions suspended sand transport is very rare at the head of the estuary because of the low flow velocities, and only mud penetrates deep into the estuary. In more sandy environments the sediment bed will probably become muddier as a result of dredging.

Although very little data is available, the long-term effects of dredging and sand mining can be estimated. During sand mining, sand and mud is extracted from the seabed. A large part of the fine mud fraction of the sediment will be entrained in the water column by either near bed erosion spill (by either drag heads or buckets, depending on dredging type), or by overflow from the hopper or the bucket (again depending on the dredging type). Spilling of sand is comparatively lower. During dumping of sediment (near the construction works), the release of sediment is strongly determined by the type of sediment, and the dredging method (dredging type and mitigation measures). In the early years of construction works, sand was mined (partly) in Singapore, probably containing relatively large amounts of mud, while mitigation measures where probably absent or relatively ineffective. In later years, sediment was imported from Indonesia and Malaysia, probably containing less fines. Without sand mining, more mitigation measures, and less fines in the dumped sediment, the loss of sediment has probably reduced.

2.3.3 Deforestation

The watersheds of small rivers in Malaysia and Indonesia are increasingly deforested, and the rivers canalized (also in Singapore). As a result, sediment in the watersheds is more easily eroded and more efficiently transported seaward. Due to upstream development in catchment areas, river input to many of South Johore's estuaries is high in sediment load and pollution. In the Pulai and Johore estuaries, for example, waste from palm oil mills and high sediment loads from sand mining activities may have a profound effect in the downstream areas (ASEAN/US CRMP, 1991).

Therefore the input of sediment into the coastal system has probably increased in the last decades. On the other hand, damming of waterways may lead to a reduction of sediment loads. The damming of the Kranji River (in 1980), and the resulting loss of sediment loads, is possibly responsible for 50 m erosion of the coastline near Sungei Buloh-Kranji (Bird et al., 2004).

2.3.4 Shipping

A large number of ships sail south of Singapore towards its main port in the west. Additionally, smaller ports exist in the Johor Strait on both the Malaysian and the Singapore side, and in the Johor Estuary (Malaysia) which is also frequented by large ocean vessels. The effect of ships on turbidity is twofold:

- Ship-induced currents increase the bed shear stress, thereby increasing re-suspension of sediments close to the approach channels.
- Ship-induced waves propagate to shallow coastal areas, thereby re-suspending shoreline sediments. In the low-energy, sheltered coastal environments around Singapore (and especially in the Johor Strait and Estuary), these ship-induced waves substantially increase the natural background of (wave-induced) re-suspension. The mud-dominated environments (mangrove areas) may be most severely affected by shipping.

2.4 Data and knowledge gaps

This literature review reveals clear gaps in data, while details on the knowledge gaps partly depend on the available data. When more data is available, the knowledge gaps can be formulated more explicitly. An important development has been Environmental Impact Assessments are required for development projects in the coastal and marine areas since 2004 (see Chapter 5). Data collection before this period is probably limited, while data must have been collected since 2004 around large construction works.

2.4.1 Data gaps

Very little data is available in Singapore’s water. In order to understand the sediment dynamics around Singapore, more details on sediment sources, sediment properties, and sediment sinks are needed. More specifically, data needed includes

- Updated bathymetric maps
- Fluvial sediment loads from the Johor River but preferably also smaller river basins. This includes river discharge and sediment concentration (will be addressed in SI 1.1 and SI 1.2).
- Time series of sediment concentration and velocity at a number of locations around Singapore (some data available through SI 1.1 and SI1.2).
- Sediment erosion and settling properties (will be addressed in SI 1.2).

- A sediment grain size distribution map of Singapore's coastal waters.

2.4.2 Knowledge gaps

Studies on hydrodynamics and sediment dynamics (as described in literature), or available directly, presently lack the details to describe knowledge gaps in detail. Processes that may be important in Singapore's waters, but are as yet insufficiently understood, include flocculation, sand-mud erosion, mixing of turbid fresh water plumes with ambient water, ship-related re-suspension processes, and effects of vegetation. However, determining which of these processes should be further investigated requires further analyses of data (partly unavailable yet) and model results.

Within the SDWA programme, some of the knowledge gaps will be addressed. These include analyses of sediment properties in Singapore's waters, mixing processes between the Johor and marine waters, sand-mud processes, and mud trapping by mangroves.

3 Water quality aspects of the coastal waters around Singapore

3.1 Nutrients and HAB in the coastal waters around Singapore

Nutrients, usually in the form of phosphorous or nitrogen compound, are important parameters used to define the quality of a water body, as an increase in nutrients levels can increase the primary production, with impacts on the whole water column. An increase of nutrients input in a water body is a phenomenon known as eutrophication, which it is commonly referred to when the nutrients increase is caused by human activities. The impacts of eutrophication vary depending on the magnitude of the increase. E.g., a low nutrients input enhances primary production of benthic algae without affecting biomass, species composition or trophic structure. With moderate nutrients input, primary production and biomass in both phytoplankton and benthic algal population may increase. With further nutrients increase, massive algal blooms may develop (Chia, 2000).

These blooms may have different detrimental effect on the water column; in such a case they are commonly called harmful algal bloom (HAB). Harmful algal bloom can cause oxygen depletion with different mechanisms: they form a thick layer in the surface, preventing the atmospheric oxygen to diffuse to the water column. Moreover, once the blooms starts to die, oxygen depletion can occur due to high quantity of oxygen required by bacteria for the decomposition of such amounts of algae (Todd *et al.*, 2000). In some cases, massive algal blooms produce toxins that can have immediate effects on marine organisms or accumulate in the food chain.

Leaching of animal manure from farms, fertilizer run off, waste material from aquaculture, atmospheric deposition, sewage, and industrial discharges typically act as nutrient subsidy (Todd *et al.*, 2000). In the coastal waters of Singapore, the main sources of nutrients and organic pollutants are land-based inputs such as rivers, urban runoff, domestic and industrial sewage. Singapore is the only country in SE Asia with a comprehensive sewerage system and major sewage effluents are situated in the Seletar, Punggol and Serangoon areas (Cheong and Shanker, 2001). The rivers and the mangrove forest on the Malaysian side are other sources of nutrients to the Johor strait (Choo and Roosly, 2001). Table 3.1 is a summary of the main total loads of Nitrogen (Total-N), Phosphorus (Total-P) and Biological Oxygen Demand (BOD) into Singapore coastal waters.

The goal of this chapter is to examine the available scientific and “grey” literature and present a general status overview for nutrients in the coastal waters of Singapore. Data on oxygen, chlorophyll-a levels (as indicator of algal biomass) and HAB are reported as well, as they are parameters normally associated to eutrophication (as explained above).

Table 3.1 The loads of BOD, Total-N and Total-P (calculated from data) emitted into the Johor estuarine system. (Delft Hydraulics, 2005).

Source	**Compartment**	**BOD (kgO_2/year)**	**Total-N (kg/year)**	**Total-P (kg/year)**
S. Tebrau and coastal sources (M5)	W. East Johor Straits	1,723,588	412,492	96,122
Sembawang (S6)	W. East Johor Straits	108,398	91,765	10,697
S. Punggol and S. Seletar (S7, S8)	M. East Johor Straits	123,174	101,070	11,981
Seletar WWTP[1] (S7)	M. East Johor Straits	539,266	75,498	5,393
S Serangoon (S8)	M. East Johor Straits	230,791	33,881	11,131
Km Chuan WWTP[1] (S8)	East Johor Straits SH.	60,562	52,726	5,802
Loyang[3] (S9)	East Johor Straits SH.	1,776,108	244,215	22,201
Changi[3] (S9)	East Johor Straits SH.	30,458	27,690	3,060
P. Tekong West[3] (S11)	Kuala Johor	30,458	27,690	3,060
Var. rivers and coastal sources (M13)	Kuala Johor	1,427	3,717	123
S. Johor, w. coastal sources (M1,2,3,6)	Sungei Johor	42,347	82,852	5,588
Sungei Johor east coastal sources (M7)	Sungei Johor	430,629	869,778	88,119
S. Santi upstream sources (M8)	Sungei Johor	69,283	222,739	13,636
Various rivers, coastal sources (M14)	Sungei Johor	47,116	232,519	9,935
P. Tekong East[3] (S11)	Calder Harbour	74,297	276,127	11,678
Changi East WWTP[2]	Calder Harbour	1,427	3,717	123
Kallang River[2]	Singapore Straits	-	-	-
	Singapore Straits	-	-	-

3.1.1 Nutrients

Several studies on nutrients and primary productivity in coastal water around Singapore are examined in this chapter. Two main water bodies surround the main Singapore Island: Johor Strait (East and West) in the North and Singapore Strait in the South (see Figure 3.1). Since in general the straits are characterized by a different water quality, in the following sections we will distinguish between the two water bodies when reporting the results of the studies examined.

<u>Johor Strait</u>
In the study of Wolanski (2006), analyzing several samples taken from November 1997 to December 1998, it was noticed that nutrient levels are 5 to 10 times higher in East Johor Strait than in Singapore Strait. The results of a monitoring campaign conducted in August, September, November 1999 (Gin et al., 2002) showed that Tot N (total nitrogen) and Tot P (total phosphorous) respectively ranged from 1900 to 7300 µg l-1 and from 20 to 280 µg l-1. In November 1999 several water quality parameters were measured in the eastern Johor Strait during a complete spring-neap cycle and used for the validation of a water quality model (Cheong and Shanker, 2001). Then, ammonia concentrations ranged from 40 to 1490 µg N l-1, nitrate from 10 to 40 mg l-1, phosphate concentrations varied between 38 to 110 µg P l-1. Relatively high nutrient concentrations were found in the Ponggol estuary (Nayar and Goh, 2005). Here ammonia concentrations in the surface waters varied from 14 to 252 µg N l-1, nitrate from 16 to 117 µg N l-1 and Phosphate from 20 to 108 µg P l-1.

According to Wolanski (2006), in Johor Strait the DIN to DIP ratio varied from 16 to 32, due to the higher and more variable nitrogen loads from Singapore and Malaysia sewage effluents, runoff, and rivers. Measurements taken in year 2000-2004 (Delft Hydraulics, 2005) show that phosphorus could be the limiting factor in the East Johor Strait (inorganic N 200 µg l-1, average inorganic P <50 µg l-1 in the inner part of the Strait).

In the study of Cheong and Shanker (2001), considering that the highest N loads occurred in areas near the sewage outfalls at Seletar and Serangoon and that the phosphate levels of already sustained significant algal growth, it was concluded that these areas show a potential for eutrophication in case the nitrogen inputs would increase further. When combining the available nutrient studies and the high temporal and spatial variability of nutrients concentrations in this Strait, nitrogen and phosphorous may both be limiting factors in this environment.

Singapore Strait
Water samples were taken in June and December 1996 and May 1997 in six stations around the island of Paulau Semakau (Singapore Strait) during reclamation works (Chou et al., 2004). Here ammonium concentrations varied from 5 to 141 µg N l-1, nitrate and nitrite were below 1 µg N l-1. These concentrations did not differ among the stations sampled (8 stations). Gin et al. (2002) found Total N and Total P concentrations in surface water samples ranging respectively from 210 to 1100 µg l-1 and from 5 to 31 µg l-1 in the Singapore Strait. In a more recent study with water samples taken in the period October 2005 - December 2006 in Singapore Strait (Delft Hydraulics, 2007), Total N concentrations varied between 6 to 220 µg l-1 and Total P concentrations were in the range of 10 to 60 µg l-1. In all cases, DO did not drop below 4 mg l-1. According to Wolanski (2006), the waters in Singapore Strait had DIN/DIP ratios varying from 6 to 18 (average 11), implying possible limitation by nitrogen.

Figure 3.1: Map of Singapore showing the locations mentioned in the study

3.1.2 Chlorophyll-a

In permanently stratified tropical water the Chl-a concentration at the surface is generally very low (Wolanski, 2006).

Johor Strait
In the shallow and more enclosed waters of the East Johor Strait, frequent algal blooms with chlorophyll levels up to 60.0 µg l-1 were recorded. The occurrence of the blooms did not depend on the season, but more likely on variation of anthropogenic inputs and sub-tidal conditions, such as when neap tides result in higher levels of chlorophyll (Wolanski 2006). Measurements between 2000 and 2004 (Delft Hydraulics, 2005) show decreasing

chlorophyll-a concentrations going from the middle of the Strait (concentrations up to 92.0 µg l-1) towards Kuala Johor (concentrations up to 70.0 µg l-1). Similar results were found by Gin et al. (2002). Chlorophyll-a levels fluctuated widely in East Johor Strait, ranging from 0.5 to 139.4 µg l-1, with an average value of 10.4 µg l-1. The higher average values were found at the station close to a fish farm, making it more prone to eutrophication.

Singapore Strait
Using pooled data from September 1996 to December 1998, low chlorophyll concentrations (average 1.4 µg l-1) were found in Singapore Strait during the North-East monsoon, while higher chlorophyll level (average 3.3 µg l-1) coincided with the South-West monsoon (Wolanski, 2006). Relatively low values of chlorophyll-a in Singapore Strait were also encountered from June to December 1998 (average 1.7 µg l-1; Gin et al., 2002) and from October 2005 to December 2006 with the highest values of chlorophyll-a being 3.4 µg l-1 (Delft Hydraulics, 2007).

3.1.3 Harmful Algal Blooms

Algal blooms may become harmful for marine and human life. We can distinguish three main harmful effects for the ecosystem:

1. production of potent toxins that directly kill marine organisms
2. production of toxins that can accumulate at top of the marine food chain and poison mammals, birds or humans.
3. other harmful effects derive from oxygen depletion due to microbial decomposition of biomass when the bloom collapses. Fish kills due to asphyxiation can occur.

In Asia-Pacific areas, phytoplankton blooms have had negative impacts on coastal waters, particularly those areas used for sea farming. Health and economic impacts have occurred by mid-1994 (Corrales and MacLean, 1995). In the East Johor Strait, two blooms of Chattonella marina were reported in 1983 and 1985, causing significant shrimp and fish mortality. The cause of the bloom is attributed to high nutrient loads coming from the Malaysian rivers. Malaysia palm and oil industries, and pig farms produced effluents with high nitrogen and phosphorous loads that are discharged directly into the rivers or in the estuary (Choo and Rosly, 1994).

Singapore waters contain a number of dinoflagellate species that produce toxins which can be fatal to marine organisms: e.g., Cochlodimium spp. is commonly found in Johor Straits and has been linked to fish kills in this waterway. Also, blooms of three raphidophytes species (Chattonella marina, Fibrocapsa japonica, Heterosigma akashiwo) that seems associated to fish killing events occurring in Johor Strait (Wolanski, 2006). Several dinoflagellate species related to seafood poisoning were found around Singapore, though till now none of them was seen in bloom concentrations yet. These organisms are linked to three type of seafood poisoning: paralytic shellfish poisoning (PSP), diarrheic shellfish poisoning (DSP) and ciguatera. The first two types occur by eating bivalve shellfish contaminated with saxixtoxins and okadaic acid analogues, respectively, accumulated by filter feeding of planktonic dinoflagellates and are of major concern for local and regionally produced seafood. Okadaic acid was demonstrated to be produced by four species of dynopsoid dinoflagellate, with Dinophsys caudata being the most abundant, found in Singapore waters (Johor Strait) and in contaminated green mussels guts (Holmes et al., 1999).

Gymnodium catenatum is an organism responsible for the production of PSP and normally associated to temperate waters. Assumable, translocation through ballast water may explain the presence of this species in Singapore waters since 1997, although the species here revealed a unique toxin profile (Holmes and Bolch, 2002). Ciguatera is caused by bioaccumulation of ciguatoxins produced by dinoflagellates of the genus Gambierdiscus into finfish (Holmes and Teo, 2002). Only three species of this genus were sporadically found on coral reefs in southern Singapore waters.

3.1.4 Dissolved oxygen

Dissolved oxygen appears to reflect the differences in nutrients and chlorophyll concentration of the two main water bodies surrounding Singapore.

<u>Johor Strait</u>
In the sampling campaign from December to May 1997 around Kuala Johor, the minimum DO concentration measured was of 4.3 mg l-1 and the maximum 14.7 mg l-1 (Palani and Liong, 2008). Cheong and Shanker (2001) observed that DO level in the East Johor Strait can drop below 4 mg l-1, to values (2-3 mg l-1) detrimental to most marine life. However, they did not provide information on the frequency of occurrence of low DO levels. Measurements for the years 2000 to 2004 in the East Johor Strait carried out by Deltares (Delft Hydraulics, 2005) showed similar results for DO. While DO concentrations averaged between 2.0 to 11.0 mg l-1, highest concentration occurred during rainy season and lowest concentrations at the end of the long rainy season (October). In the central part of the strait, oxygen stratification was observed. DO concentrations were around 2.0 mg l-1 close to the bottom and the water column became less DO stratified towards the direction of Kuala Johor.

<u>Singapore Strait</u>
The sampling campaign in June and December 1996 and May 1997 in six stations around the island of Paulau Semakau (Singapore Strait) during reclamation works (Chou et al., 2004) found DO values varying between 4.8 to 6.0 mg l-1. A more recent study from Delft Hydraulics (2007), shows that in Singapore Strait oxygen never drops below 4 mg l-1.

Table 3.2 summary of water quality parameters around Singapore in the different literature studies examined.

			NO3+NO2 _N (µg/l)	NO3_N (µg/l)	NO2_N (µg/l)	NH4_N (µg/l)	NH3_N (µg/l)	PO4_P (µg/l)	Tot N (µg/l)	TotP (µg/l)	Chlf-a (µg/l)	DO (mg/l)	T (º C)	Salinity (ppt)
East Johor Strait	Cheong t al., 2001		-	10-40	-	40-1490	-	38-110	-	-	-	2.0-5.9	-	-
	Gin et al., 2002		-	-	-		-		1900-7300	20-280	0.5-139.4	3.7-14.4	27.6-32.2	19-33
	Palani et al., 2008		60-200	-	-	340-730	-	10-80	1970-5700	20-120	0.8-71.7	4.3-14.4	27.60-31.8	19.0-31.0
			<1	-	-	-	n.d-57	2	1300-2100	20-167	1-60	-	27.6-32.2	19-33
	Delft Hydraulics, 2005		-	-	-	-	-	-	-	-	0-92	2.0-11.0	-	19.0-32.0
West Johor Strait	Gin et al., 2002		-	-	-		-		-	26-167	0.5-139.5	4.2-8.3	29.8-32.0	16-35
Singapore Strait	Gin et al., 2002		-	-	-		-		210-1100	5-31	0.5-2.4	4.38-6.33	30.2-32	16-31
	Wolanski, 2006		1-20	-	-	-	n.d.-17	n.d.-8	200-1100	5-31	0.4-10.5	-	28.3-31.2	28.7-32.2
	Delft Hydraulics, 2007		-	-	1	3-28	-	3-24	6-220	10-60	0.9-3.4	4.0-6.2	28.0-30.0	29.0-32.0
Paulau Semakau	Chou et al., 2004		-	-	-	5-141	-	-	-	-	-	4.8-6.0	29.8 (avrg)	24.5-30.2
Ponggol Estuary	Nayar et al., 2005	surface	-	16-107	7-15	-	14-225	21-60	-	-	-	6.3-8.9	29.0-31.7	22.9-26.5
		1 m	-	16-117	7-15	-	22-153	30-66	-	-	-	6.6-10.5	29.3-31.6	24.9-26.9
		2 m	-	26-92	8-16	-	57-132	36-87	-	-	-	4.9-8.5	29.5-31.3	26.6-27.4
		3 m	-	24-79	8-19	-	35-252	42-108	-	-	-	3.5-6.3	29.5-31.2	26.7-27.6
Baseline model	Tkalich et al., 2003		-	20	-	-	-	3	-	-	-	5.4	-	-

3.2 Chemicals in the coastal waters around Singapore

Marine pollution in Singapore has been attributed to exhaust emissions from boats, increased shipping activities and related activities, release of antifouling paints from boats, industrial sources, and dredging (Nayar et al., 2004b). The input of pollutants can be divided into different types such as anti-fouling; heavy metals; POPs (e.g. PAHs, PCBs, including petroleum/oil. These groups are described in the following sub-paragraphs with respect to their presence in Singapore coastal waters. In Table 3.3 is an overview of concentrations of three contaminant groups (metals, alkylphenols, and PAHs in Singapore marine waters (in µg/l) are given.

It should be noted in advance that this chapter focuses on an overview on the presence of chemical-groups in coastal waters around Singapore. However, depending on the chemical and its characteristics, its presence in sediments could be more relevant to address. Chemicals in sediments around Singapore are therefore taken into account as well and mentioned in the text Chemicals in biota and their corresponding effect concentrations are not described in this chapter. For information on the latter subject, and for more detailed information on the upcoming sections we refer to the report of project SI 1.3.

3.2.1 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 not only inhibit the settlement of marine organisms on the ships hull, but also have negative effects on the environment through the release of biocides. Paints are composed of e.g. toxic copper, organotin compounds or other special chemicals. The most common and effective chemical used to date in antifouling paints has been tributyltin (TBT). However, TBT causes many environmental problems.

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 tributyltin (TBT), triphenyltin (TPhT) and Irgarol-1051 were determined from seawater obtained from 26 locations along the whole coastline and off the coast of Singapore in 2000 (Basheer et al., 2002). TBT concentrations in seawater had a mean value of 1.40 ± 0.60 µg/l. There is as yet (Basheer et al., 2002) no legislation, regulating the use of antifouling paints in Singapore, and thus their presence in Singapore waters. However, in 2001, the International Maritime Organisation (IMO) adopted a new International Convention on the Control of Harmful Antifouling Systems on Ships, which will prohibit the use of harmful organo-toxins 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. Ecotoxicological risks should be addressed. 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. Irgarol-1051 was found to be present at concentrations with a mean value of 2.00 ± 1.20 µg/l.

Table 3.3 . Overview of concentrations in Singapore marine waters (µg/L).

Metals

Area	Location	As	Cd	Cr	Cu	Ni	Pb	Zn	Reference
Mangrove water, S. Buloh		0.47	0.159	0.094	0.284	0.272	0.193	1.577	Cuong et al. 2005
Mangrove water, S Khatib Bongsu		1.083	0.051	0.208	0.656	0.447	0.104	1.378	Cuong et al. 2005
Coastal water near Seletar		1.08	0.254	0.213	0.64	0.508	0.98	3.731	Cuong et al. 2005
Coastal water near Kranjii		0.312	0.015	0.067	0.17	0.234	0.006	2.366	Cuong et al. 2005

Alkylphenols

Area	Location	4-n-butyl-phenol	4-t-butyl-phenol	4-n-pentyl-phenol	4-t-pentyl-phenol	4-n-octyl-phenol	4-t-octyl-phenol	4-n-heptyl-phenol	4-nonyl-phenol	Reference
Eastern straits of Johor and Singapore	1	1.57	2.3	0.05	0.1	0.36	0.14	2.14	1.08	Basheer et al. 2004
Eastern straits of Johor and Singapore	2	0.06	0.01	0.02	0.13	0.06	0.04	0.28	0.64	Basheer et al. 2004
Eastern straits of Johor and Singapore	3	0.01	0.06	nd	0.05	0.01	0.02	0.02	0.34	Basheer et al. 2004
Eastern straits of Johor and Singapore	4	0.89	0.27	0.32	0.19	0.53	0.46	2.92	2.08	Basheer et al. 2004
Eastern straits of Johor and Singapore	5	nd	0.01	0.01	nd	0.07	0.02	0.02	1	Basheer et al. 2004
Eastern straits of Johor and Singapore	6	0.01	0.01	nd	0.03	0.02	0.01	0.01	1.26	Basheer et al. 2004
Eastern straits of Johor and Singapore	7	0	0.07	nd	0.01	nd	0.01	nd	0.43	Basheer et al. 2004
Eastern and central Singapore straits	8	0.01	0.01			0.05	0.03	0.05	1	Basheer et al. 2004
Eastern and central Singapore straits	9		0.07		0.02		0.01	0.01	0.93	Basheer et al. 2004
Eastern and central Singapore straits	10		0.1	0		0.11	0.15	0.09	0.33	Basheer et al. 2004
Eastern and central Singapore straits	11		0.12		0.02	0.01	0.02		0.67	Basheer et al. 2004
Eastern and central Singapore straits	12	0.59	0.95	0.06	1.86	0.13	0.32	0.07	2.76	Basheer et al. 2004
Eastern and central Singapore straits	13	0.44	1.06	0.2	0.55	0.19	0.54	1.59	2.4	Basheer et al. 2004
Eastern and central Singapore straits	14	0.01	0.01		0.03			0.89	0.02	Basheer et al. 2004
Southern Islands	15	0.01	0.03		0.01	0.05	0.04	0.03	1.03	Basheer et al. 2004
Southern Islands	16	0.02	0.03			0.1	0.01	0.01	0.32	Basheer et al. 2004
Southern Islands	17	0.11	0.01	0.01	0.03	0.02	0.04	0.01	1.63	Basheer et al. 2004
Southern Islands	18		0.31		0.03		0.01		0.61	Basheer et al. 2004
Southern Islands	19		0.01	0.01	0.01	0.03	0.02	0.03	0.44	Basheer et al. 2004
Western Singapore Straits	20		0.11		0.01	0.01	0.01	0.01	0.77	Basheer et al. 2004
Western Singapore Straits	21	0.02	0.4	0.03	0.18	0.14	0.13	0.06	1.36	Basheer et al. 2004
Western Singapore Straits	22		0.01	0.04	0	0.11	0.06	0.02	0.28	Basheer et al. 2004
Western Singapore Straits	23	0.05	0.03		0.04	0.02	0.02	0.01	0.37	Basheer et al. 2004
NW Johor, W Singapore Straits	24	0.68	2.25	0.07	1.03	0.65	0.8	0.07	1.26	Basheer et al. 2004
NW Johor, W Singapore Straits	25	0.01	0.01		0.03	0.01	0.01		0.2	Basheer et al. 2004
NW Johor, W Singapore Straits	26		0.05		0.01		0.01	0.01	0.93	Basheer et al. 2004
NW Johor, W Singapore Straits	27	0.02	0.05		0.02	0.02	0.02	0.01	1.51	Basheer et al. 2004
NW Johor, W Singapore Straits	28	0.02	0.05	0.01	0.01	0.01	0.04	0.01	1.01	Basheer et al. 2004

PAHs

Area	Location	Naphthalene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Chrysene	Benzo[a]pyrene	Reference
Northeastern coastal region	Surface NE-01	0.68	2.73	16.68	1.18	5.96	2.41	6.01	Obbard et al. 2007
Northeastern coastal region	Surface NE-02	2.62	5.87	48.64	204	3.27	13.79	2.12	Obbard et al. 2007
Northeastern coastal region	Surface NE-03	2.2	10.82	73.66	3.37	16.96	3.17	7.64	Obbard et al. 2007
Northeastern coastal region	Surface NE-04	2.49	6.5	45.56	2.3	14.85	7.55	1.74	Obbard et al. 2007
Northeastern coastal region	Surface NE-05	2.07	4.5	23.42	5.18	5.26	2.08	5.44	Obbard et al. 2007
Northeastern coastal region	Surface NE-06	2.85	2.87	24.32	0.86	4.33	10.29	4.47	Obbard et al. 2007
Southwestern coastal region	Surface SW-01	0.86	3.19	14.89	2.09	10.52	7	1.29	Obbard et al. 2007
Southwestern coastal region	Surface SW-02	0.62	4.43	15.72	3.74	11.11	4.16	3.03	Obbard et al. 2007
Southwestern coastal region	Surface SW-03	2.66	6.37	31.96	4.62	23.27	9.08	4.76	Obbard et al. 2007
Southwestern coastal region	Surface SW-04	0.31	2.04	7.76	3.39	12.63	2.41	6.06	Obbard et al. 2007
Southwestern coastal region	Surface SW-05	2.68	3.77	23.29	4.76	23.97	18.28	3.77	Obbard et al. 2007
Southwestern coastal region	Surface SW-06	0.69	1.65		1.62	8.19	2.95	2.13	Obbard et al. 2007
Southwestern coastal region	Surface SW-07	2.49	6.28	37.28	4.02	20.23	5.03	8.99	Obbard et al. 2007
Southwestern coastal region	Surface SW-08	0.46	1.79	16.3	2.97	4.91	12.48	1.17	Obbard et al. 2007
Southwestern coastal region	Surface SW-09	0.76	3.05	24.38	1.44	7.25	11.82	0.86	Obbard et al. 2007

TBT

Area	Location	TBT total (TBT + irgarol)	Reference
			Basheer et al. 2002
Northeastern coastal region	Sembawang Park	4.06	Basheer et al. 2002
Northeastern coastal region	Punggol	5.12	Basheer et al. 2002
Northeastern coastal region	Pasir Ris	4.22	Basheer et al. 2002
Northeastern coastal region	Changi	4.99	Basheer et al. 2002
Northeastern coastal region	Off Pulau Tekong	1.66	Basheer et al. 2002
Southeastern coastal region	East Coast Park	5.23	Basheer et al. 2002
Southeastern coastal region	Off East Coast Park	1.9	Basheer et al. 2002
Southeastern coastal region	Marina East	1.95	Basheer et al. 2002
Southeastern coastal region	Off Marina East	0.52	Basheer et al. 2002
Southeastern coastal region	St. John's Island	0.88	Basheer et al. 2002
Southeastern coastal region	Sister's Island	0.88	Basheer et al. 2002
Southeastern coastal region	World Trade Centre	2.98	Basheer et al. 2002
Southwestern coastal region	Labrador Park	2.85	Basheer et al. 2002
Southwestern coastal region	Pulau Jong	0.69	Basheer et al. 2002
Southwestern coastal region	Pulau Satumu	1.42	Basheer et al. 2002
Southwestern coastal region	Pulau Hantu	0.89	Basheer et al. 2002
Southwestern coastal region	Cyrene Reef	3.02	Basheer et al. 2002
Southwestern coastal region	West Coast Park	2.41	Basheer et al. 2002
Southwestern coastal region	Jurong Island	1.93	Basheer et al. 2002
Southwestern coastal region	Jurong Pier	2.71	Basheer et al. 2002
Southwestern coastal region	Sultan Shoal	1.1	Basheer et al. 2002
Southwestern coastal region	Tuas jetty	3.78	Basheer et al. 2002
Southwestern coastal region	Raffles Marina	4.52	Basheer et al. 2002
Northwestern coastal region	Sarimbun	1.37	Basheer et al. 2002
Northwestern coastal region	Lim Chu Kang	1.38	Basheer et al. 2002
Northwestern coastal region	Kranji	2.57	Basheer et al. 2002

3.2.2 Heavy metals

Studies on heavy metals in the coastal waters around Singapore, relate more to presence of heavy metals in the underlying sediments than to fractions in seawater as heavy metals cumulate in sediments. Observations near the Ponggol estuary by (Nayar et al., 2003) reveal high concentrations of metals in suspended particulates and sediments, compared to the concentrations in water.

Concentrations of Arsenic, Cadmium, Chromium , Copper, Nickel, lead and Zinc in the subsurface water samples, SML (Surface micro layer)[1] and in sediments were determined at two mangrove sites (Sungei Buloh and Sungei Khatib Bongsu) and two coastal sites (Cuong et al., 2005).

Heavy metal levels in the SML for both mangrove sites were higher than coastal SML samples. No substantial enrichment of metals is evident in the coastal SML compared to subsurface water (Cuong et al., 2005). Concentrations of heavy metals in mangrove sediments of Singapore are on average lower then reported elsewhere in the world (Cuong et al., 2005), especially for lead and Zinc.

Metal concentrations were furthermore 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, tin, lead, nickel, cadmium, and copper. Tin, lead, nickel, cadmium, and copper in particulate and dissolved fractions and sediments ranged from ND (undetectable)[2]–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). Intensive dredging activity during the monitoring period may have led to the re-suspension and bioavailability of particulate metals (Nayar et al., 2004a). For all metals higher concentrations were observed in the suspended particulates than in the sediments.

Metals dissolved in water were always low and in certain instances below detection limits. Several factors collectively explain higher concentrations of heavy metals in particulates and sediments of the Ponggol estuary (Nayar et al., 2004a), as mangrove mud binds metals via:

- fine sediments; have a larger surface area, which allows heavy metals and other contaminants to be adsorbed easily;
- 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.

Heavy metals are known to accumulate in mangroves (Cuong et al., 2005) and toxicity effects of heavy metals in Singapore have been observed (Nayar et al., 2004a). This section however only reflects on the chemical quantities and not the impact. In project SI 1.3 the impacts of water quality are addressed in more detail. Heavy metals are included in the report of SI 1.3.

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[1] The sea-surface microlayer (SML) represents the interface between the ocean and the atmosphere, where the transfer of material is controlled by complex physicochemical processes. This interface can serves as both a sink and a source of anthropogenic compounds, including chlorinated hydrocarbons, organotin compounds, petroleum hydrocarbons and heavy metals due to its unique chemical composition—in particular, its high content of lipids, fatty acids and protein. The SML plays an important role in the fate of persistent organic pollutants (POPs) in aqueous ecosystems (Wurl & Obbard, 2004)

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

3.2.3 POPs

POPs are Persistent Organic Pollutants, and include ‘conventional’ POPs as organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), but also the polybrominated diphenyl ethers (PBDEs), which have emerged in the last decade as potential ‘new’ POPs of concern. This does not only hold for Singapore, but is a mondial trend. POPs are chemical substances that persist in the environment, bioaccumulate through the food web, and pose a risk of causing adverse effects to human health and the environment. With the evidence of long-range transport of these substances to regions where they have never been used or produced and the consequent threats, they pose a risk to the environment of the whole globe (UNEP, http://www.chem.unep.ch/pops/)

POPs are present in all compartments of Singapore’s marine environment, including marine sediments, seawater and biota (Bayen et al., 2005).

Because of the oil related industry (e.g. oil trading and refining) in Singapore the pressure of the introduction of petroleum/oil into the marine environment of Singapore is highly relevant. 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. For specific information on oil related compounds we refer to the PAH information in below section.

Polycyclic aromatic hydrocarbons (PAHs) are a class of persistent organic compounds. 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[3].

Obbard et al. (2007) preformed a thorough review study on POPs in the marine environment of Singapore. They concluded that locally high levels of POPs are present, and that these can be attributed to activities as shipping, industrial discharge and land reclamation. Atmospheric deposition is another source of POPs, and this includes the input of e.g. pesticides from neighboring countries.

Notably, POP concentrations and contamination patterns in biota and sediments differed on one side of the land-link causeway between Singapore and Malaysia in the Straits of Johor compared to the other, see Table 3.4 (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 3.2), to determine any differences of POP exposure in mangrove biota, are available. Overall, the levels of POPs in mangrove sediments can be regarded as low (generally below or in the ng g_1 dw range). A simple interpretation of pollutant data for a large number of organisms is however not readily feasible when comparing the two mangrove sites studied, due to the many factors influencing uptake of contaminants. The ubiquity of these pollutants in the Singapore marine environment supports the need for a greater awareness of POP

[3] 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.

bioaccumulation processes, particularly for organisms cultured locally and destined for human consumption (Bayen et al., 2005).

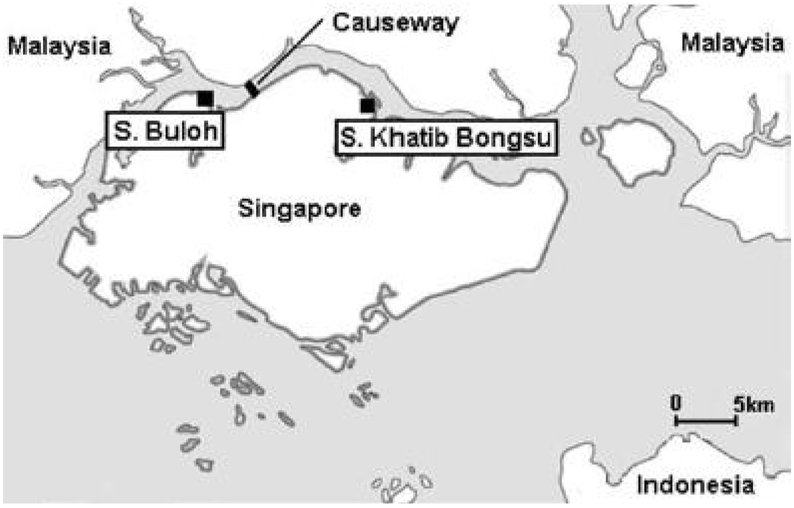

Figure 3.2 Location of Sungei Buloh and Sungei Khatib Bongsu mangroves in Singapore (Bayen et al., 2005).

Concentrations of PAHs in Singapore 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). Higher molecular PAHs were more prevalent in Singapore coastal waters that lower molecular PAHs. Overall, data on PAHs indicate extensive PAH contamination of Singapore coastal waters (Obbard et al., 2007).

The prevalence and concentration of PAHs in marine sediments from Singapore's coastal environment were studied by Basheer et al. (2003a). The total PAH concentration in the northeastern and the southwestern regions were similar, ranging between approximately 13 and 85 µg/g. The highest concentration of total PAH i.e. 84.92 µg/g 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. Overall, widespread PAH contamination in the coastal sediments of Singapore is apparent (Obbard et al., 2007), and with reference to other regions, they can be classified as moderately contaminated (Obbard et al., 2007).

PAHs are as well observed in the sea-surface microlayer (SML) of Singapore (Lim et al., 2007) and concentrations presents a potential threat to both marine biodiversity and commercial fisheries. Implications are addressed in project SI 3.3.

OCPs are, to a variable extent, insoluble in seawater, but are readily soluble in fat and absorb strongly onto suspended matter in the water column. However, OCPs were detected in samples taken at various depths at both northeastern and southwestern regions in Singapore (Obbard et al., 2007). Total OCP concentrations ranged from 3 to 22 ng/l in both northeastern and southwestern regions of Singapore. Total concentrations comprised individual contributions of e.g Lindane, diledrin, Endrin en DDT compounds. The sites were higher amounts of OCPs were detected are close to industries and shipping anchoring places. Due to atmospheric deposition OCPs can originate from Malaysia and Indonesia as well.

Wurl and Obbard (2005c) report on PCB's, OCP's and PBDE's in sediments around the coastal zone of Singapore. High concentrations are found in samples close to highly industrialized areas dominated by petrochemical plants, and lower concentrations were found in the north-eastern part. A decline in concentrations of PCB could be observed seawards. This observation confirms the dispersion of PCBs moving seawards (Obbard et al., 2007).

Pesticides (OCPs) 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 and Obbard, 2005c).

Octylphenols, nonylphenols and pentachlorophenols are some of the more commonly encountered groups of surfactants collectively known as alkylphenol ethoxylates (Basheer et al., 2004). Figure 3.3 shows the mean alkylphenol and bisphenol-A concentrations in Singapore coastal waters, grouped into five geographical sectors.

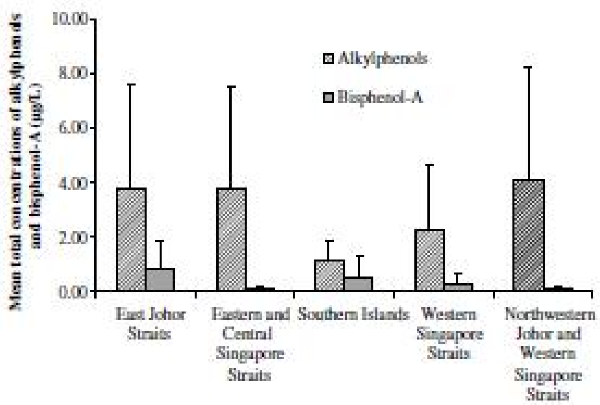

Figure 3.3 Mean concentration±standard error of total alkylphenols and bisphenol-A in seawater from Singapore waters. A total of 28 sampling locations were grouped into five geographical sectors.

Another class of POPs are polychlorinated biphenyls (PCBs). PCBs were widely used but are nowadays 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 and Obbard, 2005b).

Total PCB concentrations in seawater around Singapore were generally higher in north-eastern (0.04 to 61.7 ng/l) then in south-western regions (0.22 to 20.1 ng/l) (Obbard et al., 2007). Sources in the proximity of the locations with the highest concentrations were found to be the Bedok and Slater waste water treatment plant in the northeast and docking industries in the southwest. The (more remote) waters in Singapore could be contaminated by PCBs due to atmospheric deposition.

The north-western region of Singapore is more polluted with PCBs than the south-western region, most likely resulting from historic and periodic inputs from industries. However, hydrodynamics (causeway) and possible discharge from Malaysia could be contributing as well (Obbard et al., 2007). The concentrations of PAHs in Singapore are higher than concentrations reported elsewhere, but the concentrations of OCP and PCBs are lower then in other Asian countries (Obbard et al., 2007).

Levels of POPs in seawater and sediments in both mangrove sites are summarized in Table 3.4. All POPs, except PBDEs, were detected in subsurface seawater, sea-surface microlayer and sediments. PCBs were the dominant POPs in subsurface seawater and the sea surface microlayer.

Table 3.4 Levels of POPs (range, average between brackets) in sediments, subsurface seawater and sea-surface microlayer collected from Sungei Buloh and Sungei Khatib Bongsu 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.

Water samples within one kilometer of the coastline of Singapore were analysed to determine prevalent concentrations of a range of POPs (Basheer et al., 2003b). Total PAH concentrations were slightly higher at the surface compared to mid-depth water. The same pattern was observed for total OCP concentrations and total PCB concentrations. The POP concentrations are in line with the levels found at the mangrove sites (Bayen et al., 2005). In general, the distribution profile of POPs showed surface concentrations to be higher than at mid-depth. The implications of this conclusion are addressed in project SI 3.3.

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). Singapore sediments can be classified as moderately contaminated with PCBs, PAHs, and OCP, with probable toxicological impact to the marine ecosystem (Obbard et al., 2007).

In the coastal waters of Singapore, both ocean currents and activities as land reclamation determine the fate of POPs: Resuspension of sediments due to reclamation works increase concentrations of POPs in the water column (Obbard, 2007). The same conclusion holds for heavy metals.

3.3 Environmental impacts and management in Singapore

Since its independence in 1965, Singapore has been undergoing rapid urbanization, industrialization, infrastructural development and economic growth. With its relatively large human population of 4.6 million (still annually growing with an average 3%, see www.singstat.gov.sg) and limited land area (657 km^2), these developments have had (and still have) significant impacts on the environment, both on land and in adjacent coastal waters. Economic activities in Singapore that may be considered as the drivers behind these impacts and threats (esp. with regard to the marine environment) include: agriculture, aquaculture, coastal reconstruction, dam construction, docking, dredging, sludge disposal, fisheries, land reclamation, land-based inputs (rivers, runoff), landfill, offshore oil & gas and other petrochemical industry, pharmaceutical industry, ports, shipping, tourism, and discharges from wastewater treatment plants (Slijkerman et al., 2009).

These drivers are resulting in a range of pressures on the marine environment through water quality changes in the form of lower concentrations of dissolved oxygen, changes in pH, changes in salinity, increased turbidity, conversion/destruction of critical habitats, input of pollutants (antifouling, heavy metals, PAHs, PCB's, petroleum/oil), sediment re-suspension, introduction of microbial pathogens, noise pollution, introduction of non-native species and translocations, introduction of litter, non-selective extraction of species, nutrient enrichment, changes in sedimentation rates, smothering and hydrodynamic changes (Slijkerman et al., 2009).

To date, the direct loss of habitat and the (indirect) effects of increased turbidity and sedimentation as a result of reclamation schemes and dredging operations, possibly in combination with poor watershed management of the Johor basin (see Najah et al., (2009)) and chronic sediment disturbances from shipping, together have constituted the primary cause for the widespread loss and degradation of Singapore's critical marine ecosystems (coral reefs, seagrass beds and mangroves). Recent programmes to alter coastal lagoons into freshwater reservoirs add a further threat to the biodiversity and health of Singapore's coastal and marine ecosystems.

Other issues, such as nutrients and harmful algal blooms (see sections 3.1.1 and 3.1.3, respectively), and marine pollution appear to develop localised problems in some areas near the Singapore mainland. Increased nutrient levels, algal blooms and low dissolved oxygen concentrations, all of which are typically associated with eutrophication, periodically occur only in a few places around Singapore, primarily in the East Johor Strait. A commonality for all of these water quality issues (increased nutrients, algal blooms and chemical pollutants), is that they rapidly decrease (in extent and frequency) with increasing distance from the main island of Singapore.

Major sources of marine pollution in Singapore include discharges of shipboard origin arising from inadvertent or deliberate oil spills from ships moving in Singapore waters or along the Straits of Singapore, spillage of oil during transfers, and shore-based sources. These latter sources encompass oil refineries, petrochemical plants, power-generation plants, industries, motor and engineering workshops, agricultural activities and commercial activities, especially food centres and restaurants (Sanderson, 2001). Pollution in Singapore waters is not however considered to be serious, due largely to the flushing effect of tidal currents through the Southern Islands.

Several measures are in place to combat oil spills and Singapore is a signor of the Prevention of Oil Pollution Convention and the Convention on Civil Liability for Oil Pollution. Additionally, it has enforced the Prevention of Pollution of the Sea Act (Ch. 23) and the Merchant Shipping (Oil Pollution) Act to prevent and combat oil pollution in its waters (Business Times, 27 April 1995). There is, however, an ongoing threat from accidental oil spillage and ship collision due to human error.

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 mopping-up measures for marine pollution 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).

3.4 Data and knowledge gaps

Data of monitoring programs of agencies are not taken into account as they were not (yet) available during the processing of this report. Only data available via scientific forums could thus be obtained and used.

From the review by Obbard et al. (2007), and by studying other references on chemicals in coastal waters and sediments in Singapore, it becomes clear that most data is derived from stand alone studies rather then long-term monitoring. Furthermore, most studies are performed within the last decade.

This indicates that trend analysis on the presence of contaminants 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. However, the increase in intensity of human activities in and around Singapore will most probably result in an increased influx of chemicals. Persistent compounds as POPs and heavy metals may then continue to accumulate in the ecosystem, perhaps at an increased rate. Emerging compounds (health care products as medicines and cosmetics) are not yet taken into account in the available studies for Singapore, but are impacting ecosystems worldwide.

The prevalence of POPs and its relatively high concentrations in Singapore's coastal waters and sediments indicate a need for further research to fully evaluate their fate, transport and biological impact on the marine environment (Obbard et al., 2007). Furthermore, effect concentrations of the chemicals described in this chapter have not been incorporated yet in this summary. Some studies have mentioned that the concentrations are at critical levels to biota. BwN project SI 1.3 relates the impact of the chemical observations to actual risk for the marine environment of Singapore.

Coverage and number of sampling stations around Singapore depends upon the individual studies. A total coverage of each compound for each sampling station in Singapore does not exist according to the available data. Sampling stations near seagrass, corals and mangroves have to be analyzed together with the information obtained in the coral, seagrass and mangrove chapters. Information on critical concentrations and impacts is covered in project SI 1.3. With the data available, first tier risk assessment analysis can be performed.

Summary of gaps:

- Historic trend in chemical status unknown
- Emerging compounds[4]

[4] *Traditionally emerging compounds are e.g.*

** Brominated Dioxins and Furans*

** Polybrominated Biphenyls (PBBs)*

** Hexabromocyclododecane (HBCDD)*

** Tetrabromobisphenol A (TBBPA)*

** Perfluorinated Carboxylates and Sulfonates (including PFOS and PFOA)*

** Perfluorinated Sulfonamides and Telomer Alcohols*

- Effect concentrations for tropical species in general
- Synchronization of chemical sampling stations and information on concentrations within seagrass, coral and mangrove hot spots of Singapore. Has to be combined with corresponding chapters of this report, and with information in project SI 1.3. This is not covered in this report.

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* *Pharmaceuticals and Personal Care Products (PPCP)*
* *Triclosan*
* *Bisphenol A and Metabolites*
* *Mono Phthalate Esters and Metabolites*
* *Nonyl Phenols and Nonyl Phenol Ethoxylates*
* *Sterols and Hormones*
* *Parabens*

4 Human activities in the coastal waters of Singapore

4.1 Development of marine Infrastructure – past, present and future

Over the past 100 year, Singapore has been significantly developed. The population increased from roughly 200,000 in 19th century to almost 5 million people in the present day (Figure 4.1). With limited hinterland and access to natural resources, the Island's primary economic resource relies on is its sheltered deep water coastline and its strategic location between Europe and East Asia (Krausse, 1983). The current high population density and fast economical and industrial development have resulted in the need for extensive land reclamation and dredging works along Singapore's shore. This section provides an overview of the marine infrastructural developments along the coasts of the Singapore Islands and will focus particularly on land reclamation, dredging activities and sand mining.

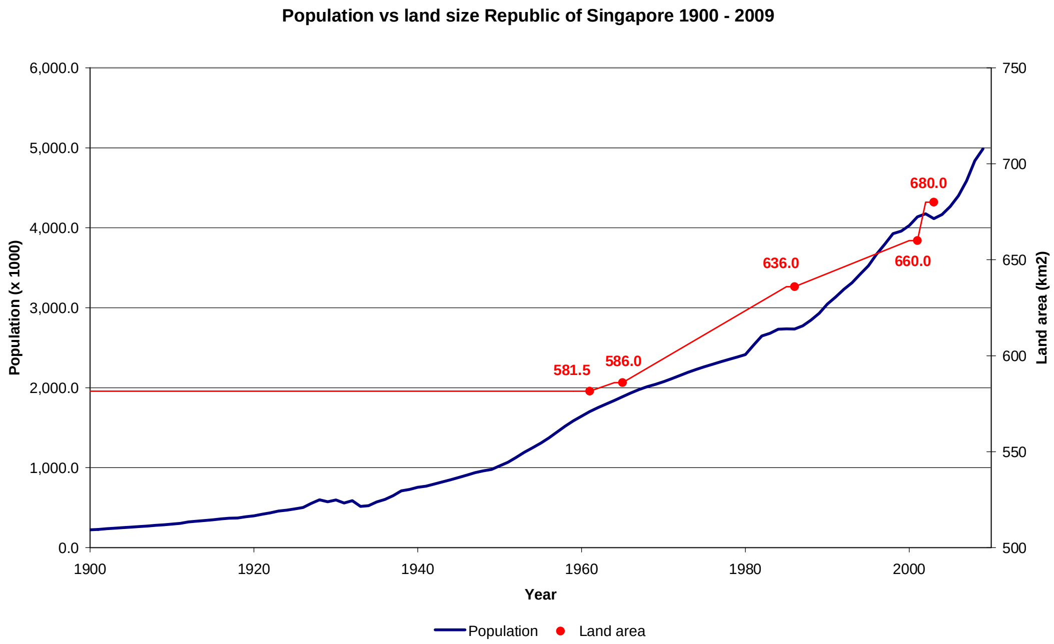


Figure 4.1 Development of the population and land size of Singapore between 1900 and 2009 (Sun, 2005; Statistics Singapore Website, 2009)

4.1.1 Earlier development

Prior to the reformation of Singapore's coastline, extensive tidal flats, shallow lagoons and mangroves formed the barriers between land and sea. In the early 20th century, the first marine infrastructure developments were carried out in the area of Telok Ayer Bay and at Singapore River. Material used for the foreshore reclamation works were obtained from onshore sources such as levelling hills and creation of inland borrow areas (Bogaars, 1956). The total amount of land area reclaimed before 1959 is approximately 3 km^2 (Pui, 1986).

4.1.2 Developments since 1959

After gaining official self-rule in 1959 various marine infrastructural works were initiated in order to cope with the rapid development in public housing, industry, commerce, recreation, airport and seaport developments (Pui, 1986). The Jurong Town Council (JTC), the Urban Redevelopment Authority (URA) and the Housing and Development Board (HDB) (Krausse, 1983) have dominated land acquisition and physical development in coastal areas in Singapore. In 1986, these agencies together accounted for a total reclaimed land area of $48km^2$, representing 90% of the total land area reclaimed over the preceding 100 years (Rashakrishnan et al., 1983).

From 1983 onward, JTC started major marine infrastructural (mainly port) developments on the southwest side of the Singapore Islands, around the peninsula of Tuas and the group of 7 islands (Pulau Merlimau, Pulau Ayer Chawan, Pulau Ayer Merbau, Pulau Seraya, Pulau Pesek and Pulau Pesek Lecil). The pensulina of Tuas was extended by 1,903 hectares over the course of several projects such as Tuas View Reclamation (1983-1988) and Tuas View Extension of which the last phase 4 was finished between 2000 and 2005. The seven islands east of Tuas were combined to form one single island, Jurong Island. The reclaimed land is used in the development of a major oil and chemical platform. In Table 4.1, a summary of phases of reclamation of Jurong Island and Tuas View Extension is presented. Figure 4.2 shows the situation in 2003. Most of Jurong Island and Tuas View were under construction except for Jurong Island Phase 4; This section was finished in 2009 (Kelly, 2009). Phase 4 included an additional extension of the Jurong Island with another 540ha of land reclamation.

Table 4.1 Summary of phases of reclamation of Jurong Island and Tuas View (from: Sun, 2005)

Phase	Period	Area (ha)	Contractor	Remarks
1	1991-199	218	Penta Ocean Koon Construction Dredging International	Height 5m Side slopes 1:3 - 1:4 Includes causeway linking the Jurong Island to Singapore
2		372	Penta Ocean Koon Construction Dredging International	
3	1998-2002	1000	Penta Ocean Koon Construction Dredging International	21Mm3 including construction of sandkey
4	2000-2005	1464	Penta Ocean Koon Construction Dredging International Boskalis HAM	Extension of both Jurong and Tuas. Largest job in history of dredging.

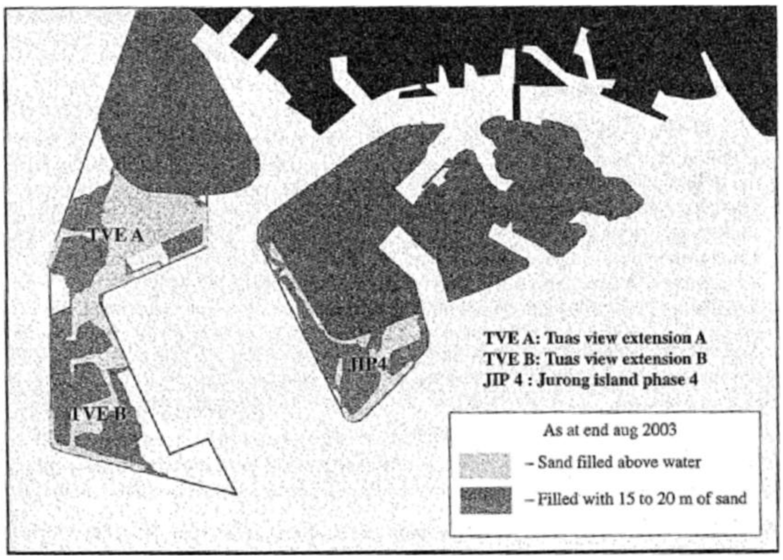


Figure 4.2 Construction status of Tuas View and Jurong Island in 2003 (taken from: Sun, 2005).

Presently, the situation of the Tuas View Extensions A and B is similar as presented in Figure 4.2. HDB has developed marine infrastructural projects mainly for housing, commercial and recreation purposes. Table 4.2 provides an overview of the coastal developments in which HDB was involved.

Table 4.2 Summary of marine infrastructural project by HDB.

Period	Location	Area (ha)	Remarks	Reference
1965-1971	Southeastern coastline	1525	Developed in 7 phases. Fill material was sources on shore by means of levelling hills at Bedok and Tampines	Pui, 1986
2000	Pulau Ubin and Pulau Tekong	1218	Sand sources offshore in neighbouring countries. Construction of offshore disposal site of 24 Mm^3 soft clay	HDB, 2004
1983-88	Punggol	276		HDB, 2004
1993	Punggol	960		HDB, 2004
1985-90	Punggol	472		HDB, 2004
1996	Coney Island	15		HDB, 2004
1997-2001	Punggol and Coney Island	155		HDB, 2004
1990-92	Woodland Checkpoint	9.7		HDB, 2004
1993-95	Tuas Checkpoint	20		HDB, 2004
1992-95	Marina Bay and Tonjong Rhu	43.6		HDB, 2004
2000-03	Southern Islands	35	Foreshore reclamation of Renget Island, Lazarus Island and Renget Shoal	HDB, 2004

Two major seaport developments, conducted by the Marine and Port Authority (MPA, formerly Port of Singapore PSA), are the construction of the Changi airport and the Pasir Panjang Container Terminal Extension (Sun, 2005). The Changi Development, located along the east coast of Singapore, started in the early 1970’s and took about 30 years to complete. A total area of 2,200ha of land was reclaimed (Sun, 2005). Six major seaports have been developed over the course of the country’s independency in the mid-1960s. Pasir Panjang is considered to be the largest (Figure 4.3). In 1990, the extension of Pasir Panjang started and is set to become the largest port in the world. The development, executed in four phases, comprises the construction of a total of 26 berths and a handling capacity by 18 million TEU per year. The construction was set to be completed in 2009, but is still ongoing.

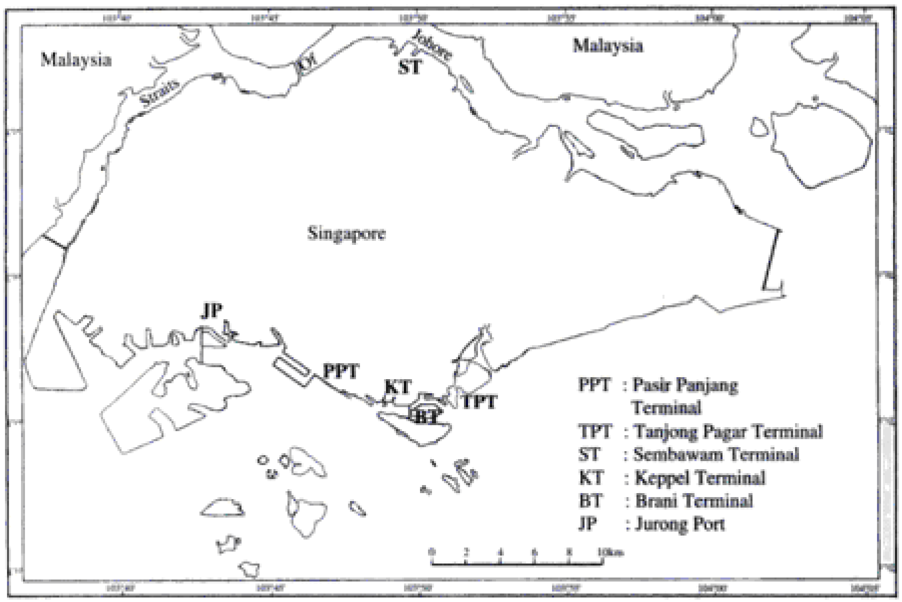


Figure 4.3 Location of 6 seaports in Singapore (Sun, 2005)

4.1.3 Sand mining

Up to 1974, most fill material used for the creation of additional land for industrial areas and public housing developments was sourced onshore; by means of leveling hills and creating large borrow areas. The latter were mostly converted into fresh water reservoirs (Wei and Chiew, 1983).

With the increasing land development projects, in number as well in size, suitable onshore borrow areas rapidly diminished and consequently sand mining had to be sourced offshore (Sun, 2005). At first in the territorial water of Singapore, but later, when shortage of suitable fill material for reclamation purposes became evident in this region, in neighboring areas, such as Malaysia, Indonesia and the South China Sea. This has caused tension between Singapore and its neighbors in such a way that currently the exploitation of new offshore sand extraction areas has been halted.

4.1.4 Impact on the environment

Early charts of the southern coastal region of Singapore, prior to the start of the extensive marine infrastructural development projects, show large areas of coral reefs along the south coast as well as around more than 60 offshore islands (Burke et al., 2002). In the aforementioned development projects, land reclamation has resulted in a decline of reef areas (Sun, 2005).

The continuous presence of dredging activities and coastal construction works over more than 30 years has likely resulted in an increase of suspended sediments and therefore reducing the visibility in the coastal waters in the Singapore area (NSS, 2003).

Although various studies have reported observation of physical changes (e.g. Chua and Chou, 1992; Chou, 2001), there is hardly any direct physical evidence defining the relationship between dredging works and the decrease in quality of the surrounding environment because very little environmental monitoring has been carried out prior to and during the major construction project. Most of the natural coast line has been replaced by hard coastal defense structures, quay walls, berths and artificial sand keys.

4.2 Other human activities

Despite the absence of natural resources or an agricultural base, Singapore has a steady economic base which depends on the manufacturing sector, and its achievements in shipping, air transport, and oil refining. In this chapter, the focus is on those human activities in Singapore which influence water quality. These activities are presented in Table 4.3. Activities are categorized as land based and sea based activities.

Table 4.3 Activities in Singapore related to water quality, divided to origin: sea based or land based

Sea based	***Land based***
Dredging	*Agriculture (Singapore and Malaysia)*
Landfill	*Land-based input (rivers, runoff)*
Coastal construction works	*Cooling water discharge and intake*
Surface mining off shore	*Petrochemical industry*
Port activities	*Pharmaceutical industry*
Maritime transportation	*Wastewater treatment plant discharge*
Docking	
Aquaculture	
Fisheries	
Tourism	

The previous chapter on water quality indicated the industries which are most significant in impairing the water quality are those related to maritime transportation (including ports and docks), agriculture (including aquaculture) and (petro-) chemical industries (via discharge). These activities are described in brief in the following sections.

4.2.1 Landfills

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, commissioned in 1999, covers a sea area of 350 ha. A 7 km rock bund encloses the landfill. The Semakau Landfill provides a capacity of 63 million m^3, 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 leaching 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).

4.2.2 Coastal construction works

Coastal reconstruction

Nearly Singapore's entire coastline is reconstructed. Very few natural beaches remain and they are located mostly along the north-western sector of the main island and some of the offshore islands (Chou, 2006). A rich intertidal flat that resembles pristine conditions may be found at Chek Jawa, located at the eastern tip of Pulau Ubin in the Johor Straits. In spite of coastal reclamation along the southern coastline, the sediment carried down the Johor River, and the wash from passing vessels, the marine flats support seagrass, coral and a rich diversity of marine life. About the only pristine beach along the southern coastline is found at a short stretch of rocky shore at Labrador with seagrass patches and a coral 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 mostly replaced the original shore profile along the southwestern coastline and many of the offshore islands (Chou, 2006). Numerous concrete jetty piles have been constructed on the southern islands. At Raffles Marina, on the northwest coast of Raffles Island, a variety of structures were used in the reconstruction works, including floating pontoons, sea walls and pilings.

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).

Construction of dams

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).

There are two man-made connections between Singapoe and Malaysia: 1) the Johor-Singapore Causeway in the north and 2) the Tuas Second Link in the west.

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).

4.2.3 Offshore oil and gas and petrochemical industry

Singapore has no national oil or gas reserves thus there are no offshore oil and gas activities in the territorial waters of Singapore. Despite its lack of domestic oil resources, Singapore is a major oil refining and trading hub. Although Singapore does not produce oil domestically, local companies have become active in overseas exploration and production (EIA, 2007). The petroleum industry is mainly concentrated on Jurong Island and secondly, Bukom Island (Pulau Bukom). The petrochemical industry is related to the pressure 'pollution' on the marine environment of Singapore, with in specific the introduction of petroleum/oil and heavy metals.

4.2.4 Port activities and maritime transportation

Singapore is situated at the crossroads of the main shipping routes, and therefore serves as a major shipping hub in Asia. The Port of Singapore is the biggest port of Singapore and lies in south west of Singapore. Jurong Port is the second largest port operator in Singapore.

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 a wide variety of vessels.

The main shipping lane is the Strait of Singapore, which is 105-kilometer long, 16-kilometer wide, and connects 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 (BIntan, Batam, and Karmum) 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. The Straits of Johor in the north (between Singapore and Malaysia) is currently impassable due to the Johor-Singapore Causeway linking Singapore and Malaysia.

Besides Maritime shipping lanes, regional ferry lines are important and busy navigational routes. Ferry lanes exist between Singaporean islands, and between Singapore and neighboring countries. Shipyards are concentrated along the West Coast of Singapore. Singapore has of total of 29 docks, of which 15 are graving docks and 14 floating docks. Trend of maritime transportation over the last decade shows a steady increase of both numbers and tonnage (report SI1.3).

Port activities and maritime transportation are related to the following pressures on the marine environment of Singapore: pollution (in specific introduction of antifouling, heavy metals, PAHs and petroleum/oil), introduction of litter, introduction of microbial pathogens, introduction of noise, introduction of non-native species and translocations.

4.2.5 Tourism

In the scope of this report, 'tourism' is regarded as the travel over sea for recreational or leisure purposes. Besides developing its terminals for handling cargo, Singapore has been working to develop its passenger terminals to cater to the growing cruise industry. There are three public landing places in the Singapore port:

- West Coast Pier (WCP) in the western sector, which serves the public going to and from ships anchored at the western anchorages.
- Marina South Pier caters to those going to and from the eastern anchorages, and the outlying islands.

- Changi Point Ferry Terminal (CPFT) in the northern sector, which serves the public going to and from the outlying islands at the northern sector such as Pulau Ubin and Pulau Tekong.

Increase of number of tourists, and cruises is an ambition and set goal (UN, 2002). Tourism is related to the following pressures on the marine environment of Singapore: introduction of antifouling; iintroduction of litter, and abrasion.

4.2.6 Agriculture, aquaculture and fisheries

Agriculture, including aquaculture and fisheries, is of very limited significance to the Singapore economy. Total coverage of agricultural land has decreased significantly over the last decades. With limited land and sea resources for agriculture, Singapore's agricultural developments take place mainly in allocated areas, called Agrotechnology Parks on land and Marine Aquaculture Parks at sea. About 1500 ha of land is reserved for our Agrotechnology Park Development while 500 ha is reserved for Marine Aquaculture Park development. Singapore's agricultural products include, in order of value, rubber, copra, fruit, orchids, vegetables, poultry, eggs, and ornamental fish.

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 human-consumption fish and shrimps 28 ha (AVA 2009a). The fish farming is mainly from coastal fish farms. No specific information on individual fisheries in the waters of Singapore was found. Landings in Singapore are reported, but source information is unknown. Total fish production is divided into fishing by capture (36 percent) and aquaculture (64 percent).

There are several pressures linked to aquaculture in Singapore: 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), pollution in general, sedimentation and water/tidal flow changes. The pressure on the marine environment of Singapore related to agriculture is pollution. Chlorinated pesticides and polychlorinated biphenyls (PCBs) have been found in the marine environment of Singapore (Wurl & Obbard 2005c, a). Fisheries are related to the following pressures on the marine environment of Singapore: introduction of litter and non-selective extraction of species (bycatch).

4.2.7 Land-based input (including waste water treatment plants)

Wastewater in Singapore is treated at Water Reclamation Plants before being discharged into water courses, which will end in the coastal zone of Singapore. Land-based input trough runoff is very diffuse as rainfall can wash into the sea along the coastline of Singapore. The spatial scale of river 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 it is now part of the Marina Reservoir.

Land-based input is related to the following pressures on the marine environment of Singapore: pollution (in specific introduction of heavy metals and PAHs), introduction of litter, and nutrient enrichment. The discharge of waste water treatment plants is related to the following pressures on the marine environment of Singapore: change in oxygen and pollution in general.

4.3 Environmental impacts and management in Singapore

4.3.1 Environmental Impacts

Human activities place stress on the marine environment with their pressures, such as emissions. All pressures from all activities together cumulate into (potential) impact on the marine ecosystems of Singapore. In order to be able to prioritize mitigation measures, information is needed on the actual and potential impact of all pressures and activities. In Figure 4.4 the causal linkages between activities, pressures and ecosystem components are presented in a conceptual framework.

In chapter 3 on water quality, it was concluded that information on a single pressure and impact can be (very) limited. Identifying cause-effect relationships on the ecosystem level is then a complicated task. Even more challenging is to take into account the conceptual framework of Figure 4.4, and accumulate all pressures and identify the relative contribution of each pressure and activity to an ecosystem component, such as coral reefs or seagrass.

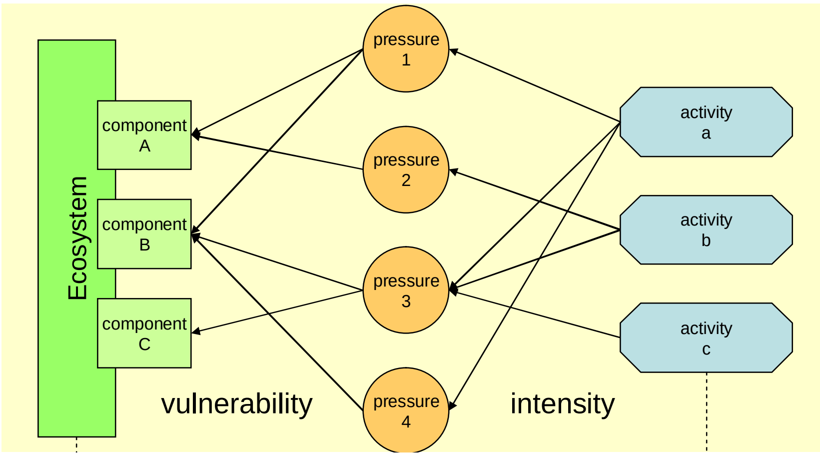


Figure 4.4 Relation between activities, pressures and ecosystem components (Karman, 2008).

In the coastal waters around Singapore multiple activities place multiple pressures on the ecosystem. In Table 4.4 all possible linkages between coastal activities in Singapore and their pressures are summarized. A cross indicates a linkage between an activity and a pressure. A question mark indicates an uncertain linkage.

Main pressures which relate to the activities were already briefly described in previous sections. Water quality issues are described in more detail in the previous chapter.

This table does not give information on intensity, nor on significance to the marine environment. However, in the conceptual framework as presented in Figure 4.4, it is relevant to address all possible linkages. In project SI1.3, the relative contribution of water quality aspects compared to sedimentation is addressed.

Table 4.4 Summary table on activities (column) and related pressures (rows) in the coastal waters of Singapore

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													

4.3.2 Management

Different ministries of Singapore deal with sector activities and the marine environment. These are the Ministry of National Development (MND) and the Ministry of the Environment. The Urban Redevelopment Authority (URA), under the Ministry of National Development (MND) is the national planning authority. It handles every aspect of planning from strategic long-term planning to day-to-day development control. URA draws up and regularly reviews the Concept Plan, the Master Plan and Development Control guidelines to guide developments island-wide. The Concept Plan is the strategic land use plan which balances land needs and constraints. It includes provisions for long-term land-intensive uses such as housing and infrastructure, as well as development strategies (UN, 2002).

The Ministry of the Environment was set up in 1972 with the task of protecting and improving the environment. The ministry has the capacity to ensure compliance with its laws and standards. The administrative and enforcement capacity of the ministry has been strengthened over the years by integration of functions, reorganization, redeployment of resources and adopting state-of-the art monitoring techniques. Bodies responsible for natural and environmental disasters are: the ministries of Home Affairs, Defense, Communication, and the Environment, Maritime and Port Authority, Port of Singapore Authority, Civil Authority of Singapore, and various other agencies. Depending on the issues at hand, the relevant groups are invited to participate in the formulation of policies or to provide feedback on proposed policies.

Regulations and guidelines to help prevent, reduce and cope with natural and environmental disasters are encompassed in various planning, maritime and environmental laws. Codes of practice are established by the government in consultation with industry and academia. Commitments under international conventions and protocols were beginning to have an impact on Singapore's businesses and industries. It was clear that a new approach was needed to keep to the path of sustainable development. The Singapore Green Plan (SGP), released in 1992, resulted from a major review of policy in previous decades. The SGP is the national environmental master plan that sets out the strategic directions Singapore would need to further improve the living environment and raise public health standards. It covers the core areas of environmental management, infrastructure development and public health.

The Ministry of the Environment (ENV) works closely with industry, trade associations and business groups to carry out waste minimization and recycling programmes, set up recycling plants, and divert waste for recycling. ENV is also responsible for the control of the import, transport, storage and use of hazardous substances, which include toxic chemicals. ENV also assesses and evaluates the hazard and pollution impact of new industries, which use hazardous substances to ensure that they do not pose unmanageable health and safety hazards or pollution problems. A new industry can only be set up if it is sited in an appropriate industrial estate and can comply with pollution control requirements. ENV encourages the setting-up of environmental committees by trade associations and the private sector to spearhead and coordinate waste minimization and other environmental efforts (UN, 2002).

The Maritime and Port Authority of Singapore (MPA) is responsible for marine environment protection from shipping activities. MPA adopts a comprehensive approach towards the protection of Singapore's marine environment, based on prevention and preparedness. The key ministries and bodies involved in the issues related to climate change and sea-level rise are the Ministry of the Environment, the Ministry of Trade & Industry and Attorney-General's Chambers. When considering whether or not to accede to a particular convention, the MPA holds consultations with relevant agencies and organizations, which could include non-governmental organizations, unions, business and industry, and other government agencies. The regulations set by the MPA on maritime safety and prevention of marine pollution are in accordance with the provisions of international maritime conventions to which Singapore is party, including e.g. the Prevention of Pollution of the Sea Act and the Merchant Shipping (Civil Liability and Compensation for Oil Pollution) Act. The MPA has established the Marine Emergency Action Procedure (MEAP) to deal with marine emergencies, including oil spills. The MEAP sets out the roles of various other agencies involved in such emergencies.

Although several management regulations are set to minimize and monitor the impact of activities to the marine environment, scientific studies (see chapter 3) show significant influence of human activities. Monitoring data from agencies are not available to this project in order to evaluate the stand alone studies in chapter 3.

4.4 Data and knowledge gaps

Due to the large number of activities and the corresponding high intensity, accumulating pressures on the marine environment is evident in Singapore’s coastal waters. To quantify each pressure and prioritize the relative importance / significance of pressures, information of spatial and temporal aspects of both activities in the coastal zone of Singapore, and their related pressures is key in the identification of spatial and temporal risk to the marine environment / ecosystem.

Information on spatial scales of ecosystems and their sensitive attributes should be coupled to the information of the pressures. The geographic distribution of the activities, pressures and ecosystem components could be implemented in GIS (Geographical Information System) in order to identify specific regional risks. An extensive set of up-to-date GIS maps should be made of each “factor” (activity, pressure, ecosystem component). Finally, the map of cumulated pressures should be combined with the map with the ecosystem components.

Needed:
- GIS maps on activities
- GIS maps on pressures
- GIS maps on ecosystem components (Corals, mangrove, seagrass)

5 Marine Ecosystems – Coral reefs

5.1 Ecosystem characteristics and ecosystem services

Coral reefs are impressive three-dimensional structures built up over many centuries by small, coral polyps that live in symbiosis (mutual beneficiary relationship) with microscopic algae (called zooxanthellae). The coral polyps protect the algae against predators; the algae provide the coral with excessive sugars. Together they can extract calcium carbonate from seawater to build their limestone skeleton as the coral polyps bud and grow. Over time massive coral reefs structures are formed by these reef builders that creates habitat for many other species. Corals supply food and shelter to an enormous variety of organisms, including sponges, cnidarians (which includes some types of corals and jellyfish), worms, crustaceans (including shrimp, spiny lobsters and crabs), molluscs (including snails, clams, squids and octopus), echinoderms (including starfish, sea urchins and sea cucumbers), sea squirts, sea turtles, sea snakes and fish. A few of these species feed directly on corals, most however graze on algae on the reef or participate in the complex food webs.

Most Scleractinian corals spawn in synchrony once a year, for many species at predictable times (Harrison and Wallace, 1990). In many coral assemblages, spawning is synchronized not only among colonies within a population, but also among numerous species within an assemblage. Recent evidence shows that mass-coral spawning on the reefs of Singapore peak in March-April (Guest et al., 2002).

Traditionally, sea surface temperature has been considered the major seasonal cue partly because of the important influence that temperature exerts on physiological processes and partly because many examples of spawning occur as waters are warming or close to the annual maxima in many locations (Harrison and Wallace 1990).

The period of mass spawning of corals is a sensitive stage to high sediment loads in the water since the last reduces the probability of fertilization of gametes. Another sensitive stage to sedimentation is the settlement of coral larvae. Settlement of larvae can be reduced by sedimentation both by reducing the opportunity for larvae to locate surface to settle and by smothering settled larvae. Larvae have relative low energy reserves such that their potential to clean the sediments from their surface is low.

Coral reefs deliver many ecosystem services (see Box 5.1) including provisioning (e.g., subsistence and commercial fisheries attained from healthy reefs), regulating (protection of beaches and coastlines from storm surges and waves, sediment stabilization, fixation of nitrogen in nutrient-poor environments), cultural (tourism and recreation) and supporting (nursery habitats).

Box 5.1 Goods and Services delivered by coral reefs after Moberg & Folke (1999).

------- Goods -------		------------------------ Ecological services ----------------------------					
Renewable resources	Mining of reefs	Physical structure services	Biotic services (within ecosystem)	Biotic services (between ecosystems)	Bio-geo-chemical services	Information services	Social and cultural services
Sea food products	Coral blocks, rubble / sand for building	Shoreline protection	Maintenance of habitats				
Raw materials and medicines	Raw materials for lime and cement production	Build up of land	Maintenance of biodiversity and a genetic library	Biological support through 'mobile links'	Nitrogen fixation	Monitoring and pollution record	Support recreation
Other raw materials (e.g. seaweed)	Mineral oil and gas	Promoting growth of mangroves and seagrass beds	Regulation of ecosystem processes and functions	Export organic production etc. to pelagic food webs	CO_2 / Ca budget control	Climate control	Aesthetic values and artistic inspiration
Curio and jewellery		Generation of coral sand	Biological maintenance of resilience		Waste assimilation		Sustaining the livelihood of communities
Live fish and coral collected for aquarium trade							Support of cultural, religious and spiritual values

Given climate change, global warming and rising sea levels, conservation of coral reefs is needed to ensure the continued provision of goods and services such as shoreline protection. This is especially important for Singapore given its high population density and dependence on reefs for its coastal protection. The economic benefit reefs provide should not be underestimated as exemplified by a recent study by Cooper et al., (2008) who showed that the estimated economic benefit of coral reefs and mangroves in providing coastline protection in Belize, a small island nation similar to Singapore, was between US$231 to US$347 million, which is between 1/5 and 1/4 of its GDP for the assessment year 2007 (Hamid et al., 2009).

Despite major losses in the last half century the reefs of Singapore still have high species richness; more than 250 species of hard or "stony" corals from 55 genera are found which provide habitat for more 120 reef fish species from 30 families (Hamid et al., 2009). Stony corals, the actual reef builders, include brain corals (Family Mussidae), bubble-corals (Family Caryophyllidae), pore corals (Family Poritidae), mushroom corals (Family Fungidae), cauliflower coral (Pocillopora sp.), cave corals and disc coral (Family Dendrophyllidae), and the table and staghorn corals (Acropora sp.). Among the reef fishes damselfishes (Family Pomacentridae) and wrasses (Family Labridae) are the most diverse and abundant. Other common reef fishes are the copperband butterflyfish (Chelomon rostratus) and vermiculated angelfish (Chaetodontoplus mesoleucus). Some of the reef fishes are economically important for fisheries such as groupers (Family Serranidae), snappers (Family Lutjanidae), scads and trevallies (Family Carangidae). Next to coral species Singapore reefs sustain good diversity of other marine organisms, such as gorgonians (Goh et al., 1997), and purple-coloured sea anemones. The last with their symbiotic clownfish are a common sight in Singapore waters. Many sponges, sea squirts (tunicates), feather-duster worms and stinging hydroids are attached on the reef substrata.

Singapore reefs are very attractive to the general public since they can be viewed from the shoreline without entering the waters and are located near to the city. As a result of the turbid waters appealing stony coral species, generally only found in deeper waters, can be seen during a shore walk at low tide (Figure 5.1). There are many volunteer groups that organize guided walks along Singapore's shores. Over 3,500 Singaporeans volunteer in conservation and in public education as nature guides to shore and reef areas. Over 100,000 people attend these guided walks and conservation/education events annually. In addition, thousands of SCUBA divers visit Singapore's reefs (Hamid et al., 2009).

Figure 5.1 Guided shore walk (Hamid et al, 2009).

5.2 Distribution in (and around) Singapore

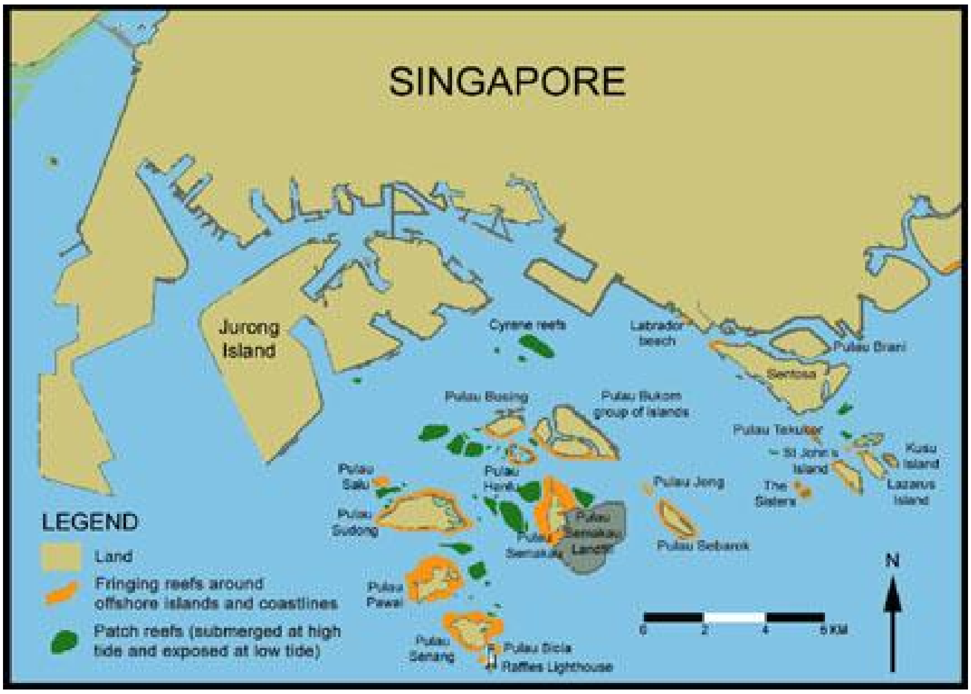


Figure 5.2 Location of fringing and patch reefs in Singapore. (http://coralreef.nus.edu.sg/)

In earlier days many island shores of Singapore were fringed by healthy coral reefs, and these reefs had some of the highest biodiversity in the world (Bellwood et al., 2004). Over the last few decades, however, Singapore has lost close to half of its coral reefs due to land reclamation. Nowadays, the remaining reefs are located on the southern Islands only (Figure 5.2). Coral reefs in Singapore form a continuum with reefs in Southeast Asia (Figure 5.3). Reef quality in Singapore is low compared to other reefs from Southeast Asia (Table 5.1).

Table 5.1 Status of Southeast Asian coral reefs (Chou, 2000).

Table 1: Status of ASEAN coral reefs based on data from the ASEAN-Australia Living Coastal Resources project (Chou et al. 1994a). Live coral cover determined on transects placed usually at depths of 3 and 10m on reef slope. Condition values refer to percentage of transects with cover >75% (excellent); <75% and >50% (good); <50% and >25% (fair); <25% and 0% (poor)

Country	No. of transects	Excellent %	Good %	Fair %	Poor %
Indonesia	190	2.6	24.2	31.6	41.6
Malaysia	193	11.4	52.8	27.5	8.3
Philippines	238	1.3	7.5	49.2	42.0
Singapore	142	2.8	9.2	20.4	67.6
Thailand	178	16.9	42.1	34.8	6.2

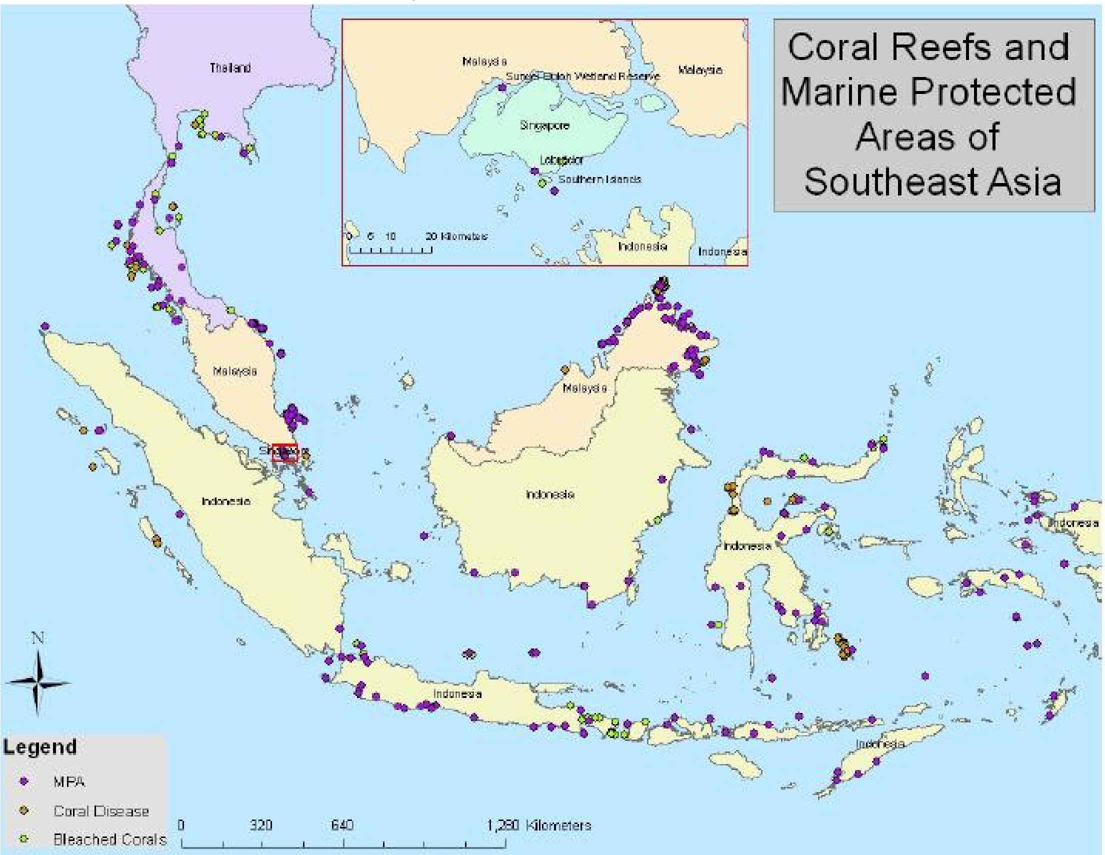


Figure 5.3 Map showing the distribution of coral reefs in Southeast Asia (Knoell, 2008).

Of the over 60 offshore islands and patch reefs that once existed south of mainland Singapore, many have disappeared since the mid 1970s when major land reclamation was undertaken on the mainland as well as the offshore southern islands. Most of the southern islands were reclaimed, adding 1695 ha to Singapore's total land area. Some islands were merged as a result. The reef flats of many islands e.g. Pulau Sudong, Pulau Hantu and Kusu Island were reclaimed right up to the reef slope. As a consequence many of the coral reef organisms were smothered by sediment or affected by the resulting water turbidity (Hamid et al., 2009). Since 1986, most coral reefs in Singapore have lost up to 60-65% of their live coral cover (Chou, 2006; 2008). High turbidity restricts light penetration and nowadays most coral life in Singapore waters ends at a depth of approximately 8m below the water surface (Hamid et al., 2009). Resulting from these low light levels in the water the reef is very compact (since at low light levels coral growth is reduced (Rogers, 1983; Telesnicki and Goldberg, 1995)), as opposed to reefs in clear waters, which can be found up to depths of 20m and more.

Ongoing reef monitoring at 11 sites in Singapore illustrates the influence of high turbidity and sedimentation. Only few sites have deeper reefs and the percentage of dead coral in general is high (Table 5.2).

Table 5.2 Percentage of dead stony coral found on 11 reef monitoring sites (http://coralreef.nus.edu.sg/), reported year underlined, dd: data deficient.

site	**monitoring year**	**% dead coral**	
		Sub crest <2.5m	**Deep reef>2.5m**
Kusu Island	2003-<u>2004</u>	38	28
Pulau Hantu	1992-<u>2003</u>	17	23
Labrador Beach	2000	26	dd
Terumbu Bayan	2000	38	dd
Pulau Semakau	1998-<u>2005</u>	27	19
Pulau Bukom	2000	46	dd
The Sisters	2004	28	dd
Raffles Lighthouse	1998-<u>2003</u>	17	50
Lazarus Island	2000-<u>2003</u>	14	17
Terumbu Bukom	2000	46	dd
Cyrene Reefs	1989-<u>1999</u>	29	25

Resulting form the high turbidity and sediment load the highest reef species diversity is found at the reef crest. At the reef slope at a depth of around 8 m stony corals are scattered and densities are low, at the sea floor over 10 m stony corals are very scarce. Reef diversity and density decrease with proximity to land reclamation, dredging and dumping sites (Chou, 2001) resulting in generally healthier reefs farther from Singapore city.

5.3 Environmental impacts and management in Singapore

Worldwide, coral reefs are in decline due to overfishing (Jackson, 1997), pollution (Dubinsky and Stambler, 1996), disease (Aronson and Precht, 2001) and climate change (Hughes et al., 2003; Hoegh-Guldberg et al., 2007). Other causes often mentioned are siltation, eutrophication, recreational damage, anchorage damage, sediment deposition and water turbidity.

Singapore has lost close to half of the coral reef cover due to land reclamation projects to expand the city (Dikou and Woesik, 2006). According to Glaser et al. (1991), “Over 10% of the total land surfaces of Singapore comprise land reclaimed from the sea and this proportion will continue to rise”. Currently the most significant cause of reef degradation in Singapore is sedimentation (see also Chapters 1 and 4). Land reclamation, dredging of shipping channels and dumping of earth spoils, together with soil erosion due to major developments in the upland watershed of Johor River in neighbouring Malaysia, have increased the sediment load of Singapore coastal waters. Live coral cover of reefs close to or in the path of sediment plumes dropped drastically (Chou, 2001). Like other coral reefs around the world, Singapore reefs suffered a mass bleaching event in June 1998. Over 50% of all reef organisms in Singapore were affected by this bleaching event, particularly the stony corals, soft corals and anemones (http://coralreef.nus.edu.sg/). Increased sedimentation and suspended sediments smothers live corals and thereby increases their energy expenditure to remove overlying sediments. Moreover, reduced light penetration due to increased turbidity reduces photosynthesis and coral growth at all depths and results in very low coral density beneath 8m. This consequently reduced the amount of hard surface available for coral larvae to settle on. Overall high sedimentation load and turbidity reduces the structural integrity and therefore the strength the coral reef framework.

High sedimentation loads, resulting in increased energy requirements to remove sediment cover and lower energy input from photosynthesis, make the coral reefs in Singapore more vulnerable to other stress factors such as coral bleaching, oil spills and pollution. Coral bleaching events, such as June 1998 have strongly impacted reefs in Singapore and recovery proved slow (Hamid et al., 2009). Bleaching events result from higher water temperatures and given climate change an increase in such events can be anticipated. Coral reefs in Singapore are located near to the surface on the reef crest, as a consequence of high sedimentation loads which reduce penetration of light. Water temperature during bleaching events is especially increased near the water surface, making reefs in Singapore more sensitive to climate change. The highest biodiversity of reefs at the reef crest also makes Singapore's reefs more vulnerable to oil spills. Hydrophobic oil particles will smother especially the reef crest when oils films get into contact with the crest at low tide or resulting from wave action. In contrast, the reef slope will be less vulnerable to direct effects of oil spills. Also the impact of tramping by tourists is in particular acting on the reef crest.

Only a single stony coral species is red listed according to the international IUCN criteria (Table 5.3). The other marine species appearing on the list have low numbers resulting from habitat degradation or collection by humans such as the Clear Sundial Architectonica perspective whose beautiful shell is collected for shell trade. Many stony corals, however, are threatened in Singapore and therefore should be protected.

Table 5.3 Singapore Marine species in the Red data book (2008), where EN=Endangered, CR=Critical and VU=Vulnerable. (next four pages)

Species	Status	Habitat	Distribution	Threats	Conservation	Scientific interest and potential value
Clear Sundial *Architectonica perspective* Phylum/Family Mollusca / Architectonicidae	EN	Sandy bottoms, just beneath the surface of the sand.	Indo-Pacific.	Habitat destruction; collection for the marine curio trade	Original shore habitats where the species could be found previously have been lost through reclamation. Legislation to protect marine life from over-collecting needs to be instituted	Shell trade
Tiger Cowrie *Cypraea tigris* Phylum/Family Mollusca / Cypraeidae	EN	Coral reefs. It is usually found on live coral colonies, particularly table forming *Acropora*.	Indo-Pacific	Habitat degradation; collection for marine ornamentals trade.	Although considered one of the commonest cowries of the Indo-Pacific, and present on Singapore reefs in the past, it is now exceedingly rare. A large specimen was seen on one reef of the southern islands in 1988. Some sites need to be designated as nature areas or marine protected areas, and legislation to protect marine life from over-collecting needs to be instituted	Shell trade; less common colour varieties are more costly.
Sea Fan *Mopsella spongiosa* Phylum/Family Cnidaria / Melithaeidae	EN	Coral reefs on rocky or hard substrata. Grows to large size in shallow reef areas, but also found in deeper water.	Western Pacific, extending north to Japan, east to Fiji, south to Bass Strait and west to Singapore	Habitat degradation; collection for marine ornamentals trade.	Now uncommon, especially larger colonies from more accessible reefs. Some sites should be designated as nature areas.	Traded as a marine curio
Hood Coral *Stylophora pistillata* Phylum/Family Cnidaria / Pocilloporidae	CR	Coral reefs, preferring shallow areas with strong wave action. Polyps are extended only at night.	Widespread throughout the Indo-Pacific.	Habitat degradation; elsewhere, the marine ornamental trade.	Has not been seen since it was last reported in the 1960s, except for a single colony observed in 2007.	Very active larvae that attach readily to floating materials, where they develop into colonies and produce further larvae. They are thus transported across the seas and are widespread in distribution.
Mosaic reef crab *Lophozozymus pictor* Order/Family Decapoda / Xanthidae	EN	Found in littoral and sublittoral rocky and coral rubble areas, and coral reefs.	Recorded from the Indian Ocean, Singapore, Philippines, Thailand, Vietnam, China, Japan, Ambon (Indonesia) and	Loss of rocky shore and coral reef habitats due as a result of dumping, land reclamation	No info	This is one of the most poisonous crabs in the world. The neurotoxin it possesses is not denatured by heat during cooking, and can easily kill a man. In fact, the poison in an average crab has been estimated to be able to kill

			Western Australia	and coastal development.		tens of thousands of mice—what it means in human terms is that this will kill a large number of people! The source of its toxin is from its food, and may include poisonous sea cucumber species which it is known to feed on.
Crinoid snapping shrimp *Synalpheus stimpsoni* Order/Family Decapoda / Alpheidae	CR	The species is an obligate commensal on feather stars (Crinoidea) and frequently occurs in pairs. The shrimp feeds on the mucus produced by the feather stars and probably in return, helps the feather star defend itself against possible predators and settlement of encrusting organisms. The distinctive colour pattern of the shrimp allows it to camouflage itself remarkably well on the feather star.	Occurs in warm western Pacific waters. In Singapore, it is found in reefs in the southern islands	Coral reef destruction and siltation are serious problems	The survival of this species is inextricably linked to that of its feather star hosts, which in turn occur only on good coral reefs. Conservation of such areas is thus essential. Over the last few years, feather star numbers have fluctuated and/or decreased, but the exact cause is uncertain. There is no doubt, however, that the loss of the host feather stars will also condemn this peculiar shrimp to extinction	The details of the unusual relationship between the shrimp and its feather star host are well known; studies have shown it to be very tight, with both species benefiting from the relationship. Presence of complex symbiotic relationships, especially commensalism and mutualism, are very useful in determining if reefs are healthy or excessively stressed—their absence is usually an indication that something is amiss.
Chaetodiadema granulatum Phylum/Family Echinodermata / Diadematidae	EN	Occurs on soft sediments of the continental shelf.	Tropical Indo-west Pacific. In Singapore, found near the north end of Pulau Semakau, Southern Islands	Land reclamation, particularly if this extends to deeper waters	Encountered just once in waters of the Southern Islands, the conservation of this rare species probably requires designation of a Marine Protected Area in this region	Throughout its range this sea urchin is generally found at depths greater than 45m but in Singapore it has been found at 15m.
Key-hole Sand Dollar *Echinodiscus truncatus* Phylum/Family Echinodermata / Astriclypeidae	VU	Using its velvet-like covering of small, short spines it burrows just beneath the surface of intertidal sands.	Indo-west Pacific from East Africa to New Caledonia	This uncommon species, restricted to very few sites, mainly in the	The only location where these sand dollars are known to occur in significant numbers is the sandy foreshore at Chek Jawa on Pulau Ubin. Effective conservation of this sand dollar (and the rich assemblage	Various explanations for the adaptive value of the lunules have been put forward. One theory if that the lunule spins assist in burrowing while another ideas is that the holes have a

				Pulau Ubin/Tekong area, is under threat from coastal development in land scarce Singapore.	of many other invertebrates species) hinges on designation of this site as an MPA (Marine Protected Area).	hydrodynamic function in reducing lift in strong currents and thus preventing dislodgment.
Peppermint sea star *Fromis monilis* Phylum/Family Echinodermata / Ophidiasteridae	VU	Found on reef slope rocky strata	Indo-West Pacific. In Singapore waters known only at Sultan Shoal.	Collection by SCUBA divers might easily lead to local extinction	The discovery of this species here in 1992 was a new record for Singapore, and brought the local species count for asteroids to more than 20. The restricted access to Sultan Shoal is perhaps indicative of better water quality at this offshore islet	This species is typical of oceanic reef systems in the Indo-West Pacific and its presence at Sultan Shoal is perhaps indicative of better water quality at this offshore islet.
Giant Knobbly Seastar *Protoreaster nodosus* Phylum/Family Echinodermata / Oreasteridae	EN	On reef flats amongst sea-grass. Uncommon in Singapore waters except at isolated locations on a reef flats in the Southern Islands and one other site at Pulau Ubin in the Johor Straits. An extra-oral feeder, but little is known of its biology.	Rarely seen in Singapore waters in recent years. In 1991 a small population (about 5 per 100m2) was found on a reef flat fringing Pulau Semakau, part of which has now been overtaken by development. By 2004 another population had been found intertidally in the eastern Johor Straits, and another population in the north-east. Distribution is thus very restricted.	Vulnerable to potential mutilation or disturbance by reef walkers or to habitat loss during reclamation.	Persistence in Singapore is unlikely unless its refuge habitats are conserved (e.g. as marine protected areas) and remain free from degradation or inappropriate development.	Little is known of its biology but large size indicates that it may be an important part of the reef ecosystem. A useful bioindicator species for monitoring reef health.
Clownfishes, Anemonefishes	VN	Inhabit coral reefs where they live among	Indo-west Pacific. In Singapore, found on	Habitat destruction	Habitat protection and strict policing against illegal collecting are required.	Popular aquarium fish that can be bred in captivity. However,

Amphiprion spp. Order/Family Perciformes / Pomacentridae. Five species are recorded from Singapore: Clown Anemonefish (*Amphiprion ocellaris* Cuvier, 1830), Tomato Anemonefish (*Amphiprion frenatus* Brevoort, 1856), Clark's Anemonefish (*Amphiprion clarkii* [Bennett, 1830]), Saddleback Anemonefish (*Amphiprion polymnus* [Linnaeus, 1758]) and the Pink Skunk Anemonefish (*Amphiprion perideraion* Bleeker, 1855).		the venomous tentacles of large sea anemones. Clownfishes are usually found in groups comprising an adult pair and many juveniles	reefs in the Singapore Straits.	from land reclamation and water pollution, Uncontrolled collection of fish and host anemones for aquarium trade.	Promote the sale of captive-bred fish in the aquarium trade.	captive-bred fish are considerably more expensive than wild-caught stocks. Although anemonefishes are totally reliant on their host sea anemones in the wild they can thrive and even breed without them in captivity.

In Singapore protection of terrestrial habitats is well established and managed by specific agencies supported by appropriate legislative framework, the same does not apply to marine living resources. This strongly reduces conservation of reefs, since without a national policy on marine resources, a distinct reef management structure, and institutional mechanisms for coordinated protection of coral reefs and marine life; it remains difficult to exert effective management of reefs.

Specific issues on marine biodiversity are however managed reasonably well such as restrictions in illegal trade of marine organisms. In Singapore's highly urbanized society, fishing and collecting from reefs and other coastal areas, either for the aquarium trade or for subsistence, declined steadily since the 1980s. Illegal collection of corals and other reef invertebrates stopped with stronger enforcement by the Police Coast Guard and a more informed public. Furthermore general policies are developed to raise awareness of the public on the value of marine biodiversity. In 1991 the Urban Redevelopment Authority (URA) developed the national concept plan 'Living the Next Lap' aimed at developing Singapore into a tropical city of excellence. A subsequent Green Plan was published by the Ministry of Environment in 1992, detailing the Government's long term plan for developing Singapore into a model green city, and the policy directions on environmental management (including nature conservation), education, participation in international environmental program and technology development. Four marine areas covering a total of 37sq km with 7sq km of coral reefs were identified as possible nature areas recommended for conservation. Following the Green Plan, an action program was published in 1993, which called for the protection of coral reefs against commercial harvesting within the four identified conservation areas and tighter enforcement of laws for the protection of the corals by the Coast Guard. The action program also advocated monitoring of water quality and land reclamation projects to minimize pollution and excessive siltation in the sea.

In 1996, the URA announced that five southern islands have been designated as a Marine Nature Area (The Straits Times, 28 May 1996, Singapore). This indicates that all development proposals for the islands will be assessed and are subjected to detailed controls by the National Parks Board (NParks), the body which manages national parks and nature reserves. However, no administrative structure presently exists to support the management of the Marine Nature Area.

Since 2004, Environmental Impact Assessments (EIA) are required for development projects in the coastal and marine areas. Each plan has to be delivered with an EIA to the Urban Redevelopment Authority (URA). The EIA must be consulted with NParks before the Central Authority gives approval. In Singapore an EIA is not enforced through an act but it is an administrative issue. Projects that cause damage to the natural environment are required to include mitigation, repair and compensation for damages and the Environmental Monitoring and Management Programme currently provides a framework for managing ongoing development activities to ensure that impacts do not exceed pre-determined threshold limits and this provides a mechanism for management agencies to take immediate action when threshold limits are violated (Hamid et al., 2009).

Box 5.2

Example: **The Semakau Landfill** – mitigation measures employed during construction to protect adjacent coral reefs and conserve part of the island’s intertidal habitats included mangrove restoration and silt curtains to minimize sediment damage of sea grass, reefs and sandy shores. Mangrove restoration and management is another example of proactive conservation undertaken by the government. The Semakau Landfill is known internationally as a showcase for “building with nature” and is used for recreation by the public in a collaborative partnership between government and civil society (Bland, 2007; Chou and Tun, 2007) (Hamid et al., 2009).

Like many other nations Singapore has developed Marine Protected Areas (MPAs) to attempt conservation and protection of its marine resources and habitats. The three MPAs in Singapore are Sungei Buloh Wetland Reserve (http://www.sbwr.org.sg/), Labrador Nature Reserve (http://www.nparks.gov.sg/nature_labrador.asp), and Southern Islands Nature Reserve. Of these Sungei Buloh is the only reserve that is strictly dedicated to the preservation and conservation of the natural habitat. The Labrador Nature Reserve is used as extra storage space for the nearby ports and the Southern Islands Nature Reserve houses the offices and laboratories of the Tropical Marine Science Institute (TMSI) and Agri-Food and Veterinary Authority (AVA) of Singapore’s Marine Aquaculture Centre. Given intense human activity in the area preserving or conserving of the marine environment in this nature reserve is not optimal (Knoell, 2008).

The Blue Plan (Hamid et al., 2009) recently developed by members of the International Year of the Reef and universities advocates the principle of: “conserving 10% of the original, natural and unmodified coastline. In this plan the following recommendations are made:

a) Form a central coordinating agency, including representatives from government agencies, NGOs, academia and public interest group to: i. Review Environmental Impact Assessments and Environmental Monitoring and Management Plans for coastal development projects ii. Engage in active public consultation, and to incorporate multi-sector feedback into any development projects
b) Review existing laws and regulations that relate to the coastal and marine environment, including: 1) Fisheries laws and regulations, especially relating to recreational fishing using unsustainable and damaging fishing devices such as drift nets, and 2) Laws and regulations related to anchorage of sea-going vessels near sensitive marine receptors to prevent physical grazing or scraping of shallow-water coastal and habitats
c) Establish an ecosystem-based approach to conservation in Singapore where multiple internal and external influences are considered including the need to balance diverse biological, social and economic objectives
d) Raise awareness and respect for Singapore’s marine biodiversity

The civil society in Singapore is very active in reef protection and undertakes actions to manage and conserve marine biodiversity by awareness raising of the general public and training of volunteers. Active conservation groups include: Blue water volunteers, The Singapore Reef Survey and Conservation Committee (SRSCC), Nature Society (Singapore) and the Singapore Underwater Federation (SUF). Actions by the civil society have had good results; however, they cannot influence sedimentation, the biggest threat to reefs, since sedimentation is caused by actors that can only be regulated by governmental institutions.

5.4 Data and knowledge gaps

Although sedimentation and increased turbidity clearly are the most important threats to reefs in Singapore, the added effect of other factors remain largely unknown.

Threats, such as an increase in nutrient level, sedimentation, oils spills, tourist and anchorage damage, pollution, climate change and overfishing negatively affect the health of the reefs but may also have more drastic impacts such as changes from coral dominance to another alternative stable state (ASS) such as macroalgae dominated, soft coral and sponge dominated (Nyström et al., 2009). Such shifts are of particular importance for shoreline protection of the densely populated city of Singapore. In contrast to stony coral dominated reefs, where reef builders maintain the reef structure and thus the shoreline protection, macroalgae cannot build reefs resulting in degradation of reef structure, and thus its protective role for the shoreline, over time. Knowledge of what causes such a phase shift from stony coral dominated towards macroalgae dominated reefs is therefore of primary importance for Singapore.

As suggested by theoretical and modelling work loss of resilience, which makes coral reefs more sensitive to changes in stables states following pulse disturbances (Nyström et al., 2000), is caused by threats such as overfishing of herbivorous fishes, which precedes phase shifts from coral to macroalgal states (Mumby 2006). Nutrient overloads are generally assumed to be less important than the loss of key herbivores, although the first can contribute to reef degradation, they are unlikely to lead to phase shifts unless herbivory is unusually or artificially low (McCook, 1999; Szmant, 2002). Hughes et al., (2007) showed experimentally that a reduction of large herbivorous fish leaded to an explosion in macroalgae. In disrupted systems (after a large coral mortality event) these macroalgae strongly reduce settlement of coral larvae, reducing coral recovery.

Such clear suggestions cannot be made for phase shifts from corals dominated to corallimorpharian, soft coral or sponge dominance. Like in case of other ASS these shifts are usually triggered by pulse disturbances (e.g. mass bleaching), however it is difficult to determine whether a loss of resilience preceded this proximal trigger. High corallimorpharian abundances are correlated with both high sedimentation and nutrient levels (Muhando et al., 2002; Kuguru et al., 2004) and high irradiance and increased temperature (Kuguru et al., 2007). A positive correlation between eutrophication and high boring sponge abundances on live massive corals and branching rubble at nine Indonesian reefs was found by Holmes et al., (2000). Moreover, patterns of coral decline and clionid sponge increase in the Florida reef tract are correlated to high levels of sewage stress (Rose and Risk, 1985; Ward-Paige et al., 2005). These findings, together with other often anecdotal evidence, suggest that phase shifts to sponge, corallimorpharian and soft coral dominance are driven by bottom-up forcing linked to declining water quality (Nyström et al., 2009). In contrast, macroalgae dominated reefs seem to be primarily driven by a loss of top-down control. The increase in macroalgal abundance leads to the physical preemption of coral settlement space and a higher frequency of coral–macroalgal interactions. This can further affect coral recruitment (Kuffner et al., 2006), reduce coral growth rates (Tanner, 1995) and result in additional coral mortality (Smith et al., 2006; Box and Mumby, 2007), which further reinforce the macroalgal state. It is plausible that similar feedback mechanisms, generated by quick monopolization of open space and subsequent inhibition of coral recruitment and coral growth, reinforce soft coral, corallimorpharian and sponge dominance**.**

A major data gap in Singapore is the <u>need for monitoring data on the impacts of other stress factors than sedimentation and turbidity on coral reefs.</u>

Knowledge gap considering phase shifts are:

1 lack in understanding of the potential range of phase shifts to other alternative stable states for Singapore waters,

2 what causes them,
3 which mechanisms lead to their establishment as ASS, and
4 are there early warning indicators e.g. does a change in composition indicate possible shift in ASS?

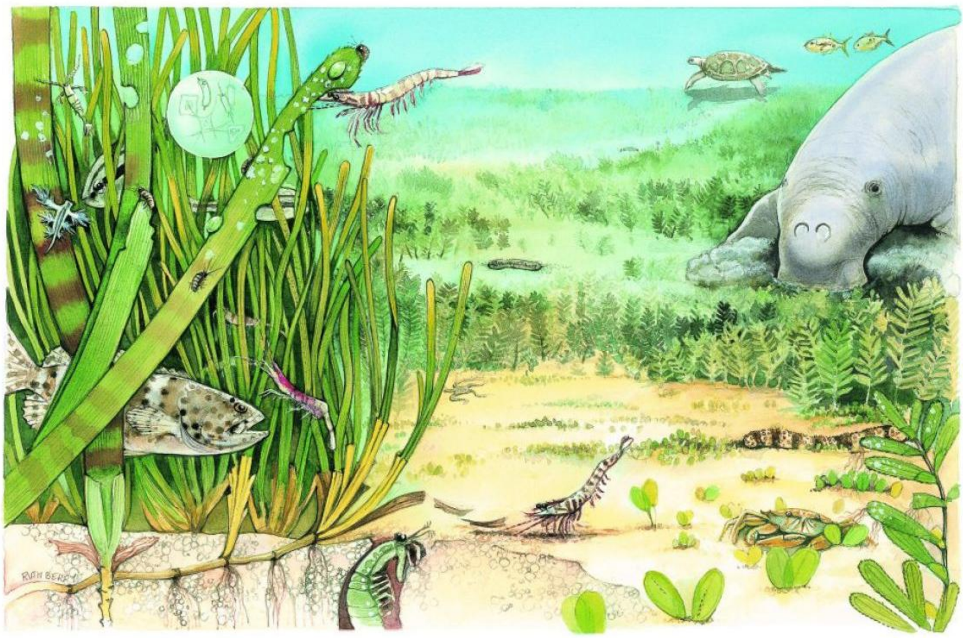
<u>Apart from these knowledge gaps directed at changes in phase shifts, according to ongoing research in Singapore (pers. Comm. P. Erftemeijer) also more info is needed on issues influencing the health status of reefs:</u>

- coral larval dispersal dynamics
- coral recruitment
- natural recovery potential
- factors determining coral reef resilience

6 Marine Ecosystems – Sea grass meadows

6.1 Ecosystem characteristics and ecosystem services of seagrass beds

Seagrasses comprise a functional group of about 60 to 70 species of underwater marine flowering plants worldwide. They grow primarily on soft substrates from the intertidal down to maximum depths of around 70 m. In shallow (coastal) waters, they can form dense meadows that constitute valuable and often overlooked habitats that provide important ecological and economic functions and services. Such seagrass beds provide nursery grounds and adult habitats for fish and shellfish (including many species of economic importance), and perform important physical functions of filtering coastal waters, dissipating wave energy and stabilizing sediments. Seagrasses often occur in proximity to coral reefs, mangroves, salt marshes, bivalve reefs and other marine habitats, with which there can be significant ecological interactions. Seagrasses are an important food source for mega-herbivores such as green sea turtles, dugongs, and manatees, and provide critical habitat for many associated organisms, including several charismatic and/or endangered animal species of importance to conservation.



Like elsewhere, seagrass meadows in Singapore play a vital role in supporting coastal and marine communities and in maintaining a diverse flora and fauna. They are an important component of coastal fisheries productivity and play an important role in maintaining coastal water quality and clarity. The seagrasses of Singapore are also important food for marine green turtles and dugongs.

A total of 12 different seagrass species have been recorded in Singapore to date (Yaakub, 2008; McKenzie et al., 2009). They include *Enhalus acoroides*, *Halodule uninervis*, *Halodule pinifolia*, *Thalassia hemprichii*, *Cymodocea serrulata*, *Cymodocea rotundata*, *Halophila ovalis*, *Halophila minor*, *Halophila spinulosa*, *Halophila beccarii*, *Halophila decipiens* and *Syringodium isoetifolium*. These are the 'foundation' species of the seagrass beds, i.e. the species without which the habitat would not exist. This is particularly so because they bind the sediment with their root systems, oxigenate the root zone, have a high primary productivity and offer opportunities for attachment and shelter within their leaf canopy. In addition to the seagrasses themselves, seagrass meadows harbour diverse communities of associated flora and fauna, which includes macroalgae, fishes (incl. many juveniles), epibenthic animals (starfishes, sea urchins, sea cucumbers, sponges, nudibranches, sea anemones, corals, etc.), benthic fauna (bivalves, polychaete worms, crustaceans etc.), and larger grazers such as dugongs (*Dugong dugon*) and Green Turtles (*Chelonia mydas*), both of which feed almost exclusively on seagrasses. These latter species, along with sea horses and a number of colourful gastropods, constitute some of the 'flagship' species of the seagrass ecosystem that draw the attention of the general public and have played a role in raising support for the need to conserve Singapore's seagrass beds.

The seagrass meadows in Singapore have not been subject to any detailed study until recently (Loo et al., 1996; Yaakub, 2008). Earlier work on seagrass communities in Singapore was limited to passing references and qualitative observations on the presence of seagrass species at various localities in Singapore. There are a few studies on fauna associated with seagrasses in Singapore (Itoggi, 1971; Low, 1973; Loo et al., 1990; Loo et al., 1996).

6.2 Distribution of seagrasses in (and around) Singapore

6.2.1 Historical distribution

Historical records of seagrasses in Singapore are few and primarily consist of herbarium specimen (some of which have been reviewed in Den Hartog, 1970) (see overview below in text box). Seagrasses were reported to be common between the late 1950's and early 1970's on reef flats and intertidal zones at Kranji and West Johor Strait (Chuang 1961; Johnson 1973). Loo et al. (1996) reported seagrasses at Changi beach and Beting Bemban Besar (patch reef). Other studies reported the presence of seagrasses from locations south of the main island of Singapore which included Pulau Hantu, Pulau Semakau, Terumbu Raya (patch reef) and Hantu West (patch reef) and in the north, Pulau Tekong (Hsu and Chou, 1989a,b). An example of the widespread loss of seagrass habitats in coastal Singapore due to land reclamation schemes is shown in Figure 6.1.

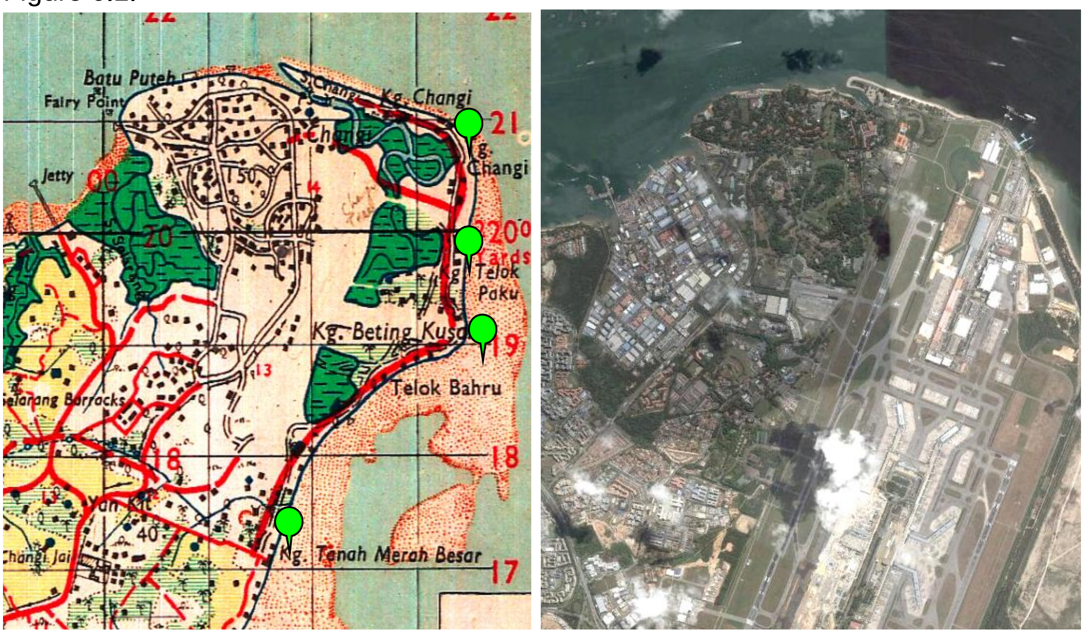


Figure 6.1 Coastal area at Changi (Singapore) before (left) and after (right) major land reclamation for Changi airport, with some historical seagrass sites (marked in green) lost due to the reclamation.

Historical records of seagrasses in Singaporean waters
(source: Den Hartog 1970)

Cymodocea rotundata
Tanah Merah Besar, 14-3-1953, J. Sinclair 39508 (K, SING); **Telok Paku**, seashore on sandy flats, near low-water mark, 17-2-1955, J. Sinclair 40527 (K, L, SING); on mid-littoral mud, 3-3-1956, Burkill 392 (A, BO, L, SING); **Changi**, on muddy sand near low-water mark, 17-12-1967, C. den Hartog 1202 (L).

Cymodocea serrulata
Pulau Samulun, north end of the kampong, 31-7-1949, J. Sinclair 38581 (SING, K); **Tanah Merah Besar**, in pools near low-water mark, 14-3-1953, J. Sinclair 39508 (SING, K, L); 6-3-1955, J. Sinclair 40536 (SING); **Changi**, muddy sand near low-water mark, 17-12-1967, C. den Hartog 1204 (L).

Enhalus acoroides
Rocks in the port of Singapore, 19-4-1860, O. Debeaux (P); several collections of H. N. Ridley (BM)l **Pulau Samulun**, 28-11-1948, J. Sinclair (L); **Teluk Paku**, abundant on mud and sand, 20-2-1956, H. M. Burkill 382 (L, K); **Pulau Senang**, sandy beach, 6-8-1956, H. M. Burkill 674 (L, K): **Changi**, near low-water mark, fl., fr., 17-12-1967, C. den Hartog 1201 (L).

Halodule pinifolia
Changi, sandy flat, at low-water mark, in shallow depressions together with Halophila spinulosa and H. ovalis, 17-12-1967, C. den Hartog 1208 (L).

Halodule uninervis
Changi, sandy flat, at low-water mark, in vegetation dominated by Thalassia hemprichii, 17-12-1967, C. den Hartog 1207 (L).

Halophila beccarii
Kranji Nature Reserve, sandbank in centre of shallow broad waterway of mangrove, exposed at low-water springs, 13-8-1961, H. M. Burkill 2713 (L, SING); idem, common above railway bridge, but also seen below creeping in sand and mud in brackish water in mangrove, 25-8-1961, J. Sinclair 10631 (L, BM, K, SING); along creeks in mangrove swamp, exposed at low tide, 16-12-1967 C. den Hartog 1199 (L). **Woodlands**, north of Kranji Nature Reserve, locally abundant on mud in shaded stream bed, 19-11-1964, H. M. Burkill 3616 (L, SING). **Tanah Merah** beach, abundant in jetsam, 8-1-1964, H. M. Burkill 3413 (L, SING). **Sungei China**, Lim Chu Kang, in deep shade in mangrove, creeping in sand in bed of fresh-water stream, 11-4-1965, J. Sinclair 10779 (L, SING).

Halophila minor/ovata
Blakang Mati, 1892, Ridley 3780 (C, BM, SING). **Ponssol**, on sandy mud, exposed at low tide, 5-2-1914, Holttum (SING). **Labrador**, 21-3-1928, Holttum (SING). **Tandjong Behala Kuda, Pulau Pawai**, sandy bottom, at half-tide level, growing with Halodule uninervis, 14-3-1950, J. Sinclair 38894 (SING, L). **Pasir Laba**, in a pure stand in a bed of Halophila ovalis, in the low eulittoral on mud, 27-12-1965, H. M. Burkill 3897 (L).

Halophila ovalis
Woodlands, 1903, Ridley (SING). **West Johore Straits, K. Berih**, in 3-5 m wide mangrove channel, in mud forming a lush mat, leaves erect, 16-1-1966, H. M. Burkill 3923 (L, SING). **Bering Kusa**, muddy sand-flat, 9-1-1966, H. M. Burkill 3917 (SING). **East Lagoon**, R.S.Y.C. Anchorage, in muddy, turbid, polluted water, at 3-5 m depth, 24-7-1955, H. M. Burkill (SING). **Changi**, sandy flat, common in the undergrowth of other sea-grass vegetations, here and there pure patches on open ground, male fl., fr., 17-12-1967, C. den Hartog 1206 (L). **Pulau Senang**, in sandy pools on coral reef, 1-4-1956, H. M. Burkill 550 (SING, L). **Pulau Samulun**, north end of Kampong, in mud at extreme low water, fl., 31-7-1949, J. Sinclair 38580 (SING).

Halophila spinulosa
Pulau Tekong, on muddy bottom at 5 fathoms depth, 16-6-1929, Henderson and Comer (SING). **Tanah Merah Besar**, sandy to muddy seashore near low-water mark, 6-3-1955, J. Sinclair 40535 (L, SING, K, BM). **Beting Kusa**, sandy-muddy beach, below the low-water springs level, abundant, in large diffuse patches, 29-2-1964, H. M. Burkill 3429 (L); the same place at the low-water spring-tide level and in the shallow sublittoral, abundant towards the lower side of the *Enhalus* meadow, male and female fl., 24-10-1964, H. M. Burkill 3601 (L). **Changi**, sandy flat, at low-water mark, in shallow depressions forming an open vegetation with a few accompanying species, female fl., 17-12-1967 C. den Hartog 1203 (L).

Syringodium isoetifolium
Tanah Merah Besar, in pools near low-water mark, 14-3-1953, J. Sinclair 39509 (L, K, SING); sandy muddy substratum near low-water mark, 6-3-1955, J. Sinclair 40537 (L, K, SING); **Pulau Senang**, mid-littoral in sandy pools of coral reef, together with Halodule uninervis and Halophila ovalis, 1-4-1956, H. Burkill 547, (L, SING); **Teluk Paku**, abundant in sublittoral jetsam, 7-1-1957, H. Burkill 1119 (Sing, K, L).

Thalassia hemprichii
Telok Paku, 17-2-1955, J. Sinclair (SING); Telok Paku, on muddy shore, very abundant, fr., 6-1-1957, H. M. Burkill 1118 (K, L); Telok Paku, mud, female fl., 3-3-1956, H. M. Burkill (K, L). **Pulau Senang**, in sandy pools on coral reef, 1-5-1956, H. M. Burkill 546 (K, L). **Changi**, sandy flat at low-water mark, forming a dense vegetation, 17-12-1967, C. den Hartog 1205 (L).

Historical seagrass records at Singapore Botanic Gardens Herbarium (source: Yaakub, 2008)

Tanjong Changi:
1889: *Enhalus acoroides* (H.N. Ridley)
1892: *Halodule pinifolia* (H.N. Ridley)

Telok Paku:
1955: *Cymodocea rotundata* (Anonymous)
1956: *E. acoroides* (H.M. Burkhill)
1956: *C. rotundata* (H.M. Burkhill)
1956: *Thalassia hemprichii* (H.M. Burkhill)
1957: *Syringodium isoetifolium* (H.M. Burkhill)

Beting Kusah:
1964: *Halophila spinulosa* (H.M. Burkhill)
1966: *H. major* (H. ovalis) (H.M. Burkhill)
1966: *H. minor* (H.M. Burkhill)

Tanah Merah Besar:
1919: *E. acoroides* (I.H. Burkhill)
1953: *C. serrulata* (J. Sinclair)
1953: *S. isoetifolium* (J. Sinclair)
1955: *H. spinulosa* (J. Sinclair)
1964: *H. beccarii* (H.M. Burkhill)

6.2.2 Present day seagrass distribution

There are at least 25 sites in Singapore that are known to have seagrasses at present, 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'. Some sites harbour dense meadows, most notably the extensive reef flats of Cyrene reef, west of Pulau Semakau and off Pulau Ubin. Six seagrass sites have been monitored quarterly since 2007 under the Seagrass-Watch programme (Figure 6.2).

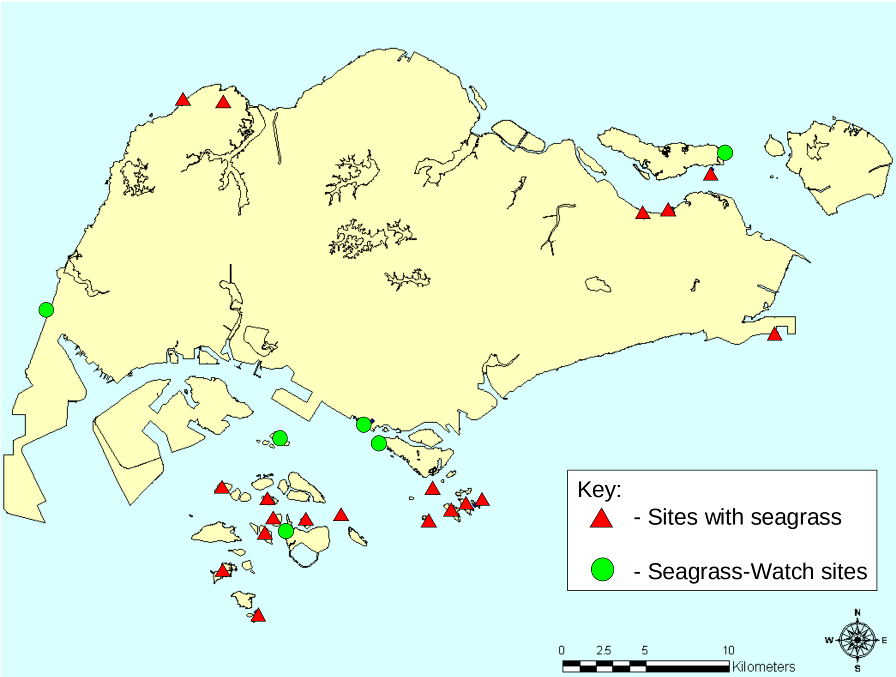


Figure 6.2 Distribution of seagrasses in Singapore: known sites with significant growth of seagrass and sites currently monitored under the Seagrass-Watch programme (Yaakub, 2008).

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 appears 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, 2005).

Distribution of seagrasses in neighboring Johor Straits is shown in Figure 3. For further details regarding seagrass distribution in neighboring Malaysia and Indonesia, please refer to the corresponding chapters in the World Seagrass Atlas by Green & Short (2003) and Japar Sidik et al. (2006).

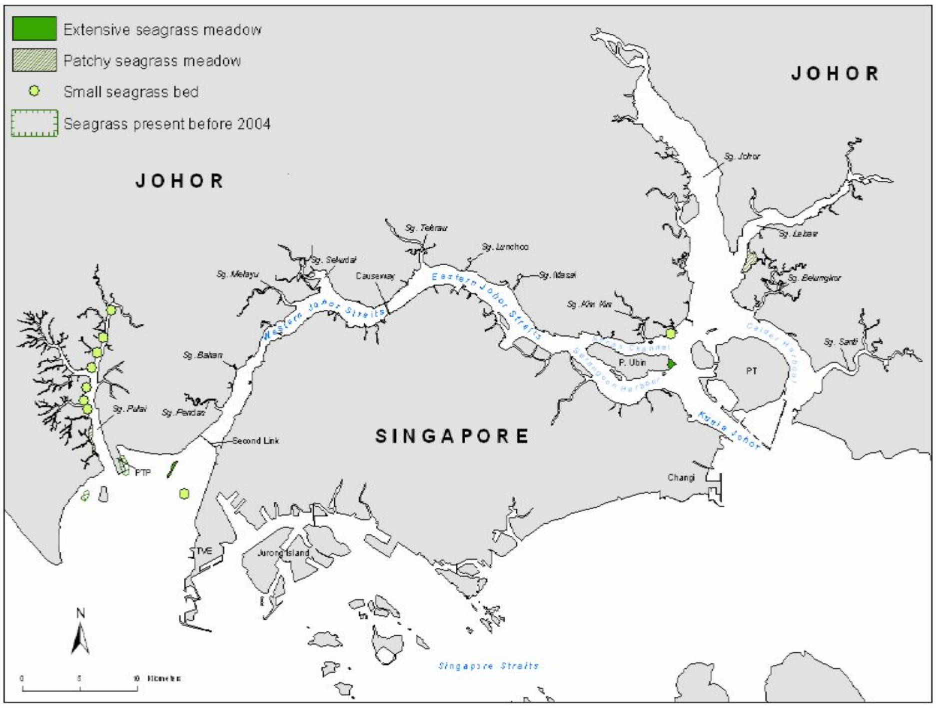


Figure 6.3 Seagrass distribution in the Johor straits (Joint Study, 2004)

6.2.3 Singapore's main seagrass sites

The following 6 sites constitute some of the most important and extensive (dense) seagrass sites in Singapore today (for location of these sites see Figure 6.4).

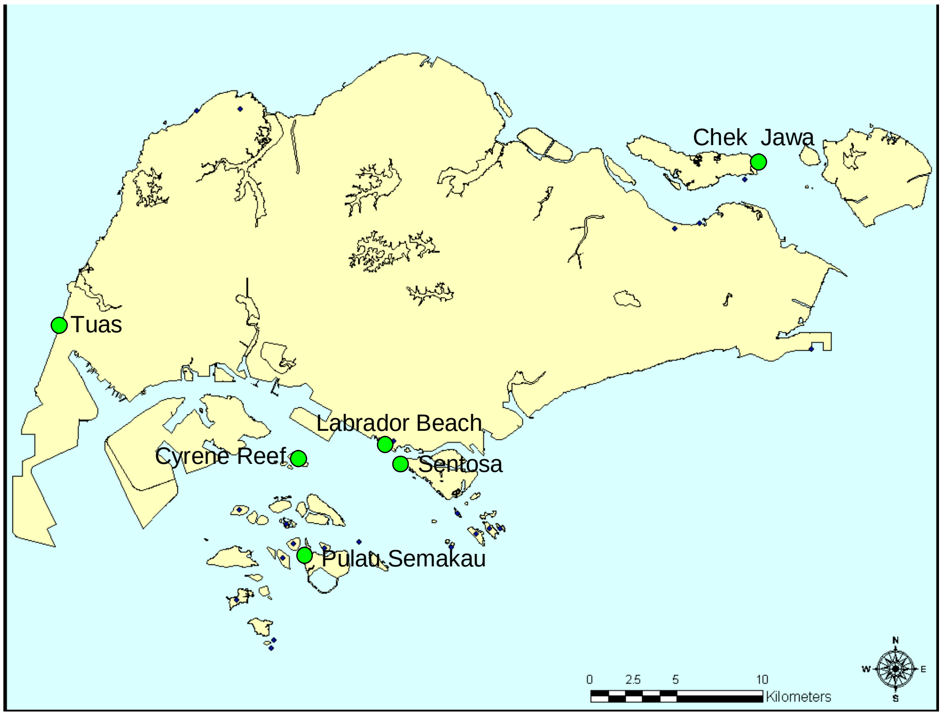


Figure 6.4 Location of Singapore's 6 main seagrass sites

Chek Jawa (Pulau Ubin)

Tanjong Chek Jawa is a cape and the name of its surrounding areas located on the south-eastern tip of Pulau Ubin. Pulau Ubin is a small island (10.19 km2) situated in the north east of mainland Singapore, to the west of Pulau Tekong. Granite quarrying supported a few thousand settlers on Pulau Ubin in the 1960s, but only about a hundred villagers live there today. It is presently one of the very few off-shore islands in Singapore that is still inhabited. The 1020 ha island was once a cluster of five smaller ones separated by tidal rivers, but the building of bunds for prawn farming has since united these into a single island. Two other islets, Pulau Ketam (Crab Island) and Pulau Sekudu (Frog Island), lie to its south. Slated for land reclamation in 1992, the wonderful secrets of Chek Jawa were unveiled only in December 2000. As public attention was drawn to this site, thousands of Singaporeans flocked to visit this wetland treasure. At the same time, appeals from nature lovers and the general public led to a review of its reclamations plans. After carefully considering all public submissions and extensive consultations with scientific experts and relevant government agencies, it was announced in 2001 that reclamation works would be deferred.

Eight seagrass species are found at Chek Jawa: *Halophila beccarii, Halophila spinulosa, Cymodocea rotundata, Halophila ovalis, Halophila minor, Halodule uninervis, Thalassia hemprichii* and isolated clumps of *Enhalus acoroides*. The meadows are dominated by *C. rotundata* and *H. ovalis*. The meadows are predominately within a shallow protected lagoon behind a large sand bank (Figure 6.5). Meadows are mainly intertidal, however the seaward edges of the sand bank are fringed by large *Halophila spinulosa* meadows. Macro-algal abundance averages 25-30% and fluctuates greatly. There is insufficient data to identify any trends. The site has been monitored quarterly since January 2007.

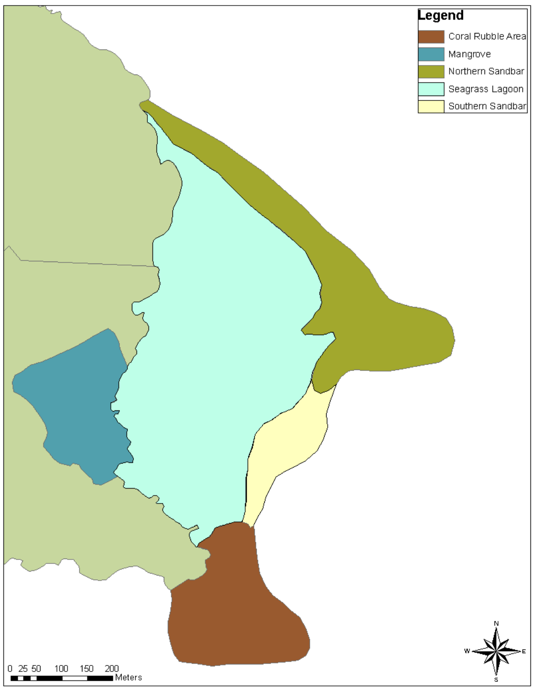


Figure 6.5 Habitat map of Check Jawa (Pulau Ubin) (seagrass areas in light blue).

Cyrene Reef

Cyrene is comprised of 3 patch reefs- Terumbu Pandan, Pandan Beacon and South Cyrene Beacon, and is one of the largest patch reef systems in Singapore. Cyrene Reef is a key maritime crossroad where east-west traffic routes cross north-south routes. Approximately five hundred ships transit the waters around the reef every day. The reef is also next to massive industrial sites like Jurong Island and Pulau Bukom, and opposite Singapore's container terminals. With abundant seagrass meadows and other marine life, Cyrene is a natural wonder. The reef top meadow is a mixture of *Enhalus acoroides, Cymodocea serrulata, Cymodocea rotundata, Halodule uninervis, Halophila ovalis, Thalassia hemprichii* and *Syringodium isoetifolium (*Figure 6.6*)*.

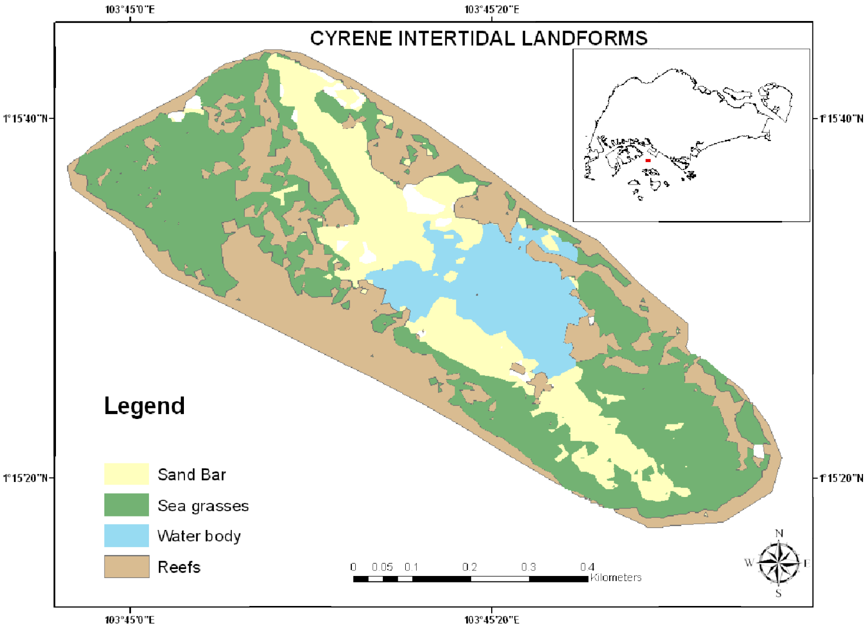


Figure 6.6 Habitat map of Cyrene Reef (seagrass areas in green).

Labrador

Labrador Nature Reserve, also known as Labrador Park, contains the only rocky sea-cliff on the mainland that is accessible to the public for recreation, education and scientific research. Since 2002, 10 hectares of coastal secondary vegetation and its rocky shore have been appointed as a Nature Reserve. The rocky shore contains a multitude of corals and crabs, seagrasses (*Halophila ovalis, Thalassia hemprichii*, and *Enhalus acoroides*), sandworms and horseshoe crabs.

Pulau Semakau

Pulau Semakau is Singapore's first offshore landfill, filled mainly with inert ash produced by Singapore's four incineration plants which incinerate the country's waste. The ash is shipped there in a covered barge (to prevent the ash from get blown into the air) every night. Semakau Landfill was formed by the amalgamation of Pulau Sakeng with the eastern half of Pulau Semakau. The western half of Pulau Semakau was left natural, unaffected by the landfill construction, and this is where the seagrass monitoring sites are located. Vast tracts of *Enhalus acoroides* fringe the island, stretching for kilometres. Pulau Semakau is one of the few places in Singapore where *Syringodium isoetifolium* occurs in abundance. The site has been monitored quarterly since March 2007. Seagrass abundance at Semakau has been relatively stable (average cover 26-50%) over the monitoring period and no seasonal trend is apparent.

Sentosa

Sentosa, which means peace and tranquility in Malay, is a popular island resort in Singapore, visited by some five million people a year. Attractions include a two-kilometre long sheltered beach, Fort Siloso, two golf courses and two five-star hotels. Seagrass species at Sentosa include *Halophila ovalis* and *Enhalus acoroides.* Issues and threats include marine debris/litter, coastal development, land reclamation and land runoff.

Tuas

Tuas is largely an industrial zone located in the western part of Singapore. The Tuas Planning Area is located within the West Region, and is bounded by Tengah Reservoir to the north, Strait of Johor to the west, Straits of Singapore to the south, and the Pan Island Expressway to the east. Seagrass species recorded at Tuas include: *Halophila ovalis* and *Enhalus acoroides*. Issues of concern include marine debris/litter, coastal development, land reclamation and land runoff.

6.3 Environmental impacts and management in Singapore

All over the world, seagrass habitats are subject to significant threats from anthropogenic activities, primarily related to rapid environmental changes as a result of coastal human population pressures, leading to large-scale losses reported worldwide (Waycott et al., 2009). Multiple stressors, including sediment and nutrient runoff, physical disturbance, invasive species, disease, commercial fishing practices, aquaculture, overgrazing, algal blooms, and global warming, cause seagrass declines at scales of square meters to hundreds of square kilometres. Reported seagrass losses have led to increased awareness of the need for seagrass protection, monitoring, management, and restoration.

The coastal and marine ecosystems of Singapore are however, limited and modified by development and the port industry (which is one of the biggest income-earning businesses in the country). Port limits extend to almost all the entire territorial waters, and reclamation has transformed almost the entire southern and north-eastern coasts of the main island considerably (Chou and Goh 1998). The steep beach front along the south-eastern coast was once composed of sandy beaches and mudflats and original rocky shores are found mainly on the southern offshore islands and small parts of the northern coast. Singapore has reclaimed land with earth & sediment obtained from its own hills and seabed and imported from neighbouring countries. As a result, Singapore's land area grew from 581.5 square kilometres (224.5 sq mi) in the 1960s to 697.2 square kilometres (269.1 sq mi) today, and may grow by another 100 square kilometres (38.6 sq mi) by 2030.

There are currently no specific laws for the protection of the existing seagrass meadows (ICRI 1997). At present, there are no true marine protected areas (MPAs) in Singapore, although three areas are protected to some extent: [1] Sungei Buloh Wetland Reserve (a 87 ha area of coastal mangrove habitat); [2] Labrador Nature Reserve (a 16 ha area of natural rocky shore and coastal hill forest, officially designated a Natural Reserve in 2002); and [3] Sisters' Islands (a Marine Nature Area).

All species of seagrass in Singapore are listed in the Singapore Red Data Book as threatened (Davison et al., 2008), though none are protected species under Singaporean law. There have been no attempts to restore seagrasses in Singapore to date.

Six of the main seagrass sites in Singapore are being monitoring under the global Seagrass-Watch programme since early 2007. The monitoring is carried out by groups of volunteers in collaboration with NParks, and coordinated by TeamSeagrass (see http://teamseagrass.blogspot.com) under the general guidance of the global Seagrass-Watch programme team (see also http://www.seagrasswatch.org/Singapore.html), which conducted training workshops in Singapore in 2007 and 2009 (McKenzie et al., 2007, 2009).

6.4 Data and knowledge gaps

Since there have been almost no previous studies on Singapore's seagrass beds other than the few earlier reports on studies of seagrass-associated fauna mentioned above, there are major gaps in the knowledge of Singaporean seagrass ecosystems. Some of the most urgent research needs include:

- Mapping of the extent and composition of all of Singapore's seagrass beds
- Monitoring of the dynamics and trends in Singapore's seagrass beds (ongoing)
- Studies on the function of these meadows as nursery grounds for fishes and crustaceans
- Studies on the diversity of flora and fauna associated with these meadows
- Greater understanding of the factors contributing to the resilience of Singapore's seagrass beds
- Experimental research on the tolerance thresholds for turbidity, sedimentation, temperature and salinity (especially the relationship between the intensity & duration of stress factors and the subsequent seagrass response)
- Studies on the effects of sediment disturbance & light reduction on Singapore's seagrasses and the morphological and physiological stress responses and adaptation mechanisms of the seagrasses to cope with sediment & light stress.
- Studies on (post-stress) recovery potential of Singapore's seagrass beds

A more detailed review of the research needs (esp. with regards to the effects of turbidity and sedimentation) can be found in the SDWA proposal "Dredging and Infrastructure Development near Critical Ecosystems (Corals & Seagrasses)".

7 Marine Ecosystems – Mangroves

7.1 Ecosystem characteristics and ecosystem services of Mangroves

Mangroves are forest growing in tropical and sub-tropical tidal areas. The forest consists of tree species that can tolerate regular flooding by saline seawater. This tolerance is due to one of the most distinct characteristics of the mangrove trees: aerial roots which are part of the day exposed to air, and thereby enable them to survive in anoxic sediments (Figure 7.1). Four types of aerial roots can be distinguished: i) pneumatophores, ii) prop and stilt roots, iii) kneed roots and iv) plank roots.

Ad i) Pneumatophores are erect side branches of the horizontal roots growing just below the soil surface. They provide a direct connection of the underground root system towards oxygen in the air. They can be found in *Avicennia* and *Sonneratia* species

Ad ii) Prop roots are roots that develop from the stem of a tree or a branch. Later on these roots are called stilt roots when the tree is older, and depends for it support on these roots. Prop and stilt roots are found in *Rhizophora* species.

Ad iii) Kneed roots are horizontally growing roots that periodically grow vertically upward, where after they bend down ward again, thereby resembling the shape of a bent knee. The regular intervals of the knees allow aeration. Kneed roots are found in *Bruguiera* and *Ceriops* species.

Ad iv) Plank roots consists of horizontal roots that have grown vertically upward, thereby creating a plank-like structure. Plank roots are found in *Xylocarpus granatum*.

Figure 7.1 A: pneumatophores of Avicennia spp., B stilt roots, C: kneed roots

Mangroves provide a wide range of well documented **ecosystem services**, such as coastal protection from wave attacks and tsunamis, a nursery function for many juvenile marine animals including commercially important (fish) species, carbon sequestration, providing wood and charcoal, etc. The relative importance of these services varies between locations. The **foundation tree species** (i.e., most abundant species building the system) in the mangroves around Singapore typically follow a clear zonation along the elevation gradient, going from the sea-side towards the higher and less inundated areas (Figure 7.2):

- ⇨ pioneer zone
  - o *Avicennia alba*
  - o *Sonneratia alba*
- ⇨ middle zone
  - o *Rhizophora apiculata*
- ⇨ back zone

- o *Bruguiera cylindrica*
- o *Bruguiera gymnorrhiza*
- o *Ceripos*
- o *Xylocarpus*
- o *Heritera*

To give an impression of the potential tree diversity, we here listed the 32 mangrove tree species checklist according the FAO world mangrove 1980-2005 report Asia: *Acanthus ebracteatus*, *Acanthus ilicifolius, Acrostichum aureum, Acrostichum speciosum, Aegiceras corniculatum, Avicennia alba, Avicennia marina, Avicennia officinalis, Avicennia rumphiana, Bruguiera cylindrica*, *Bruguiera gymnorrhiza, Bruguiera parviflora*, *Bruguiera sexangula, Ceriops tagal, Cynometra ramiflora, Excoecaria agallocha, Excoecaria indica, Heritiera littoralis, Kandelia candel, Lumnitzera littorea, Lumnitzera racemosa, Nypa fruticans, Pemphis acidula, Rhizophora apiculata, Rhizophora mucronata, Rhizophora stylosa, Scyphiphora hydrophyllacea, Sonneratia alba, Sonneratia caseolaris, Sonneratia ovata, Xylocarpus granatum, Xylocarpus mekongensis*

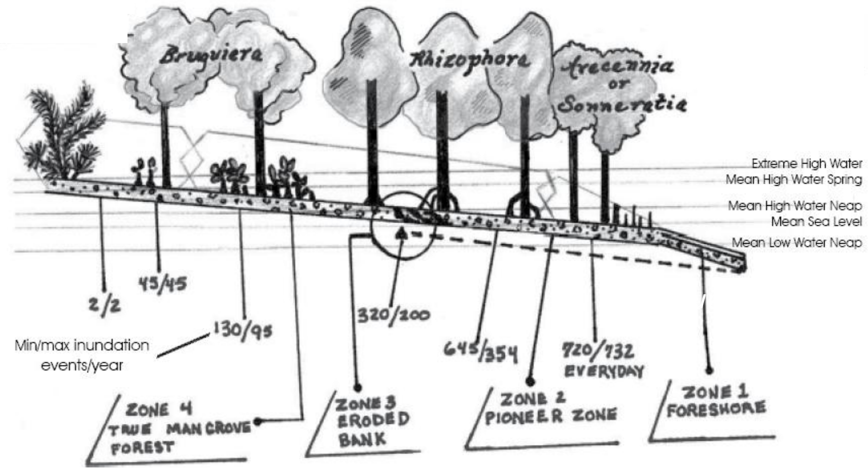


Figure 7.2 Schematic representation of the distribution of mangrove species along the elevation inundation gradient.

Mangroves around Singapore contain several **flagship species** (i.e., species appealing to large audience and/or of particular interest to conservation) (Figure 7.3). The most appealing is probably the long-tailed macaque monkeys (*Macaca fascicularis*) that live by digging up mud crabs. Another of the most characteristic species is the Mudskipper, which is an early evolutionary species reflecting the transition from sea to land. Mudlobsters (*Thallasia anomala*) are remarkable because of the large mounds they can create. Male Fiddler crabs *(Uca spp)* can not be missed on the mudflats, waving their one large claw to court females. The spitting Archerfish (*Toxotes jaculatrix*) is remarkable in that it “hunts” insect by shooting them using a jet of water. Bats living in the mangroves (e.g. approx 9 cm long Lesser dog-faced fruit bat, *Cynopterus brachyotis* & the approx 7 cm long Long-tongued nectar bat *Macroglossus minimus*) are highly important for pollination of some of the mangrove tree species like *Sonneratia*. A more complete list of the species inhabiting the mangroves around Singapore can be found in Ng & Sivasothi (1999).

Figure 7.3 Pictures of some of the flagship species that can be seen in the Mangroves around Singapore: A) macaque monkeys, B) mudskipper, C) Fiddler crab. Pictures take by Thorsten Balke, who is one of the PhD students working on the SDWA Mangrove project.

7.2 Distribution of mangroves in and around Singapore

A hundred years back, most of Singapore was covered by primary rain forests (82%) with mangroves along its fringes (13%). The mangroves were mainly used as fuel wood and charcoal production. With the growth of the human population (presently > 5000 person km^{-2}), the majority of the rain forest and mangroves has now been replaced by urbanised areas (Figure 7.4 and Figure 7.5). Mangrove loss can be particularly ascribed to land reclamation and housing (started as early as 1822 along the Singapore river), shrimp farming (started around 1900) and creation of freshwater reservoirs. As a consequence, only around 500 hectare of mangrove forest remains today in Singapore, representing a few percent of the original cover as present from before Singapore became a large city (Figure 7.6 & Table 7.1). The few remaining mangroves areas that have been preserved are now well protected. Except for Mandai, the mangroves have become national parks, be it with varying levels of protection.

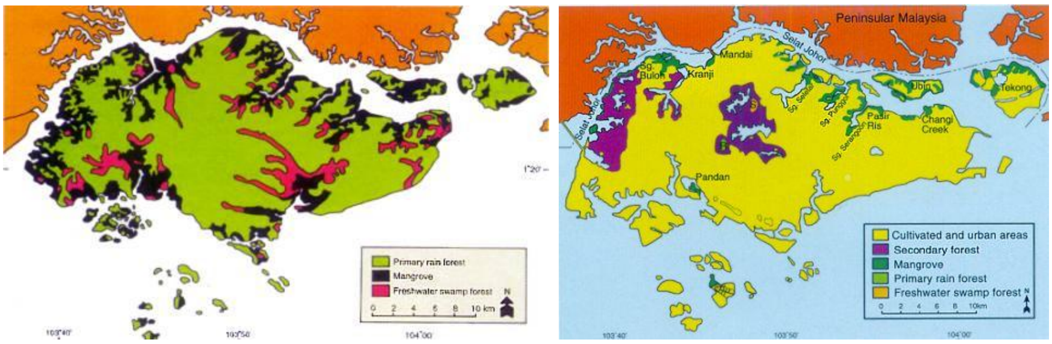


Figure 7.4 Past (1819; left) and current (1990; right) mangrove distribution in Singapore (Ng & Sivasothi 1999).

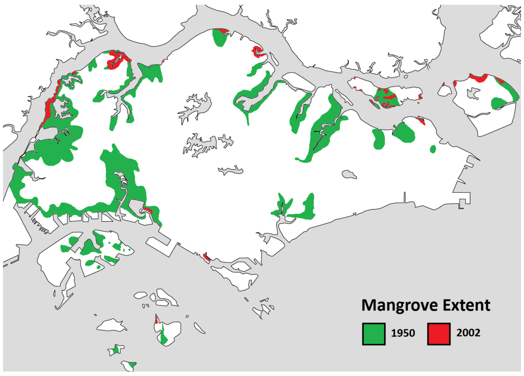


Figure 7.5 Qualitative impression of the change in mangrove area over the last 50 years, based on preliminary literature research by Dr. Dan. Friess, who is working on the SDWA Mangrove project. The 50's cover was obtained from, which was than compared by a hand tracing of the present cover. So although the absolute accuracy is limited, the qualitative trend is clear.

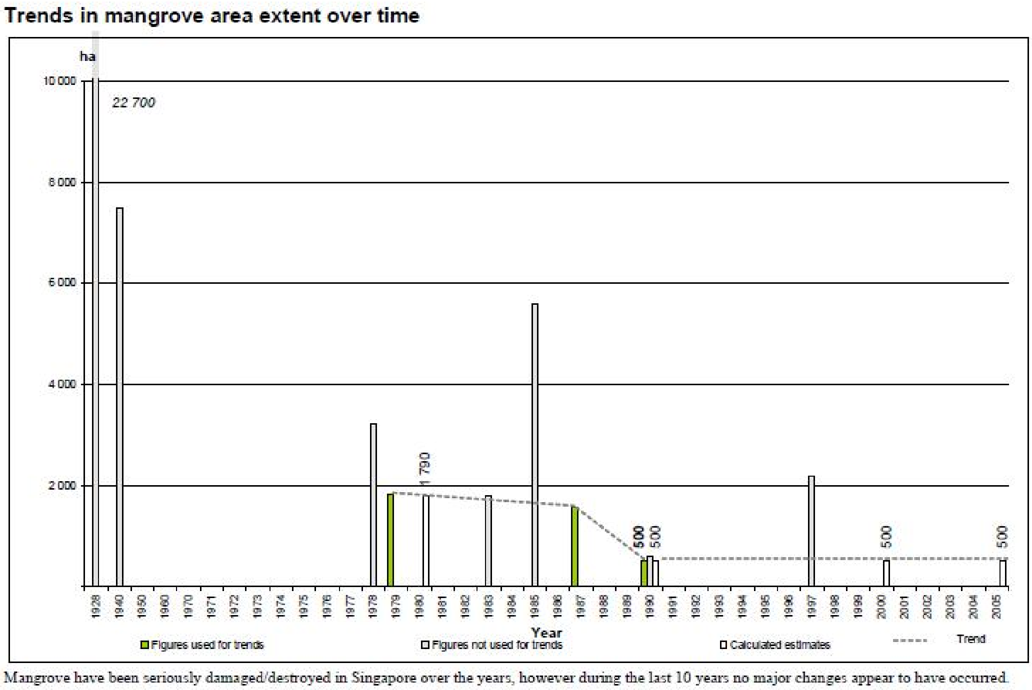


Figure 7.6 The decline in mangrove area according to the FAO world mangrove 1980-2005 report Asia. The figure is based on Table 7.1, which has been obtained from the same source.

Table 7.1 The decline in mangrove area according to the FAO world mangrove 1980-2005 report Asia. The data in this table form the basis of Figure 7.6, which has been obtained from the same source.

National level mangrove estimates

Year	Area (ha)	Source	Trend	Methodology/Comments
1928	22 700	**Watson, J.G.** 1928. *Mangrove forest of the Malay Peninsula.* Malay Forest Records No. 6 Singapore, frases & Neave. 275 pp.		Cited in: **FAO.** 1982. *Management and utilization of mangroves in Asia and the Pacific.* FAO environment paper 3. 160 pp.
1940	7 500	**Spalding, M.D., Blasco, F. and Field, C.D.,** *eds.* 1997. *World Mangrove Atlas.* The International Society for Mangrove Ecosystems, Okinawa, Japan. 178 pp.		The "Year" is dummy date; the authors are referring to it as the original extent.
1978	3 210	**Ministry of Culture.** 1978. *Singapore - Singapore facts and figures, 1978.*		Cited in: **FAO, UNEP, Zoology Department University of Singapore.** 1980. *The present state of Mangrove Ecosystems in Southeast Asia and the Impact of Pollution.* Singapore. 103 pp. The extent may include waterways and channels.
1979	1 820	**Ministry of Culture.** 1978. *Singapore - Singapore facts and figures, 1978.*	X	Estimated total mangrove area extent. Cited in: **FAO, UNEP, Zoology Department University of Singapore.** 1980. *The present state of Mangrove Ecosystems in Southeast Asia and the Impact of Pollution.* Singapore. 103 pp.
1983	1 800	**Saenger, P., Hegerl E.J. and J.D.S., Davie.** 1983. *Global status of mangrove ecosystems.* Commission on ecology Papers No.3. IUCN. Gland, Switzerland. 88 pp.		Secondary reference, no primary source provided. The "Year" is the publication year.
1985	5 600	**Corlett, R.T.** 1986. *Report on the Third Introductory Training Course on Mangrove Ecosystems,* UNDP/UNESCO, Singapore, 20 October - 16 November 1985. UNESCO, New Delhi. 46 pp.		Cited in: **WCMC.** 2000. *Coral reefs and mangroves of the world.* http://www.wcmc.org.uk/marine/data/coral_mangrove/
1987	1 570	**Thang, H. C.** 1991. *Asean Forest Resource Database Country Report Singapore*	X	Ground survey
1990	500	**Chan, L. and Richard, T. 1997.** Biodiversity in the nature reserves of Singapore, Proceedings of the Nature Reserves Survey Seminar, Singapore December 1997. Singapore Gardens Bulletin 49 (II). National Parks Board, Singapore Botanic Gardens, Cluny Road.	X	Ground survey
1990	600	**Chou, L.M.** 1990. Assessing the coastal living resources of Singapore: a study in the ASEAN-Australia Coastal Living Resources Project. *Wallaceana* Vol.59-60. pp: 7-9.		Cited by: **Spalding, M.D., Blasco, F. and Field, C.D.,** *eds.* 1997. *World Mangrove Atlas.* The International Society for Mangrove Ecosystems, Okinawa, Japan. 178 pp.
1997	2 200	**McKinnon, J.** 1997. *Protected Areas Systems Review of the Indo-Malayan Realm.*		The "Year" is the publication year.

In the area around Singapore, as well as the rest of the world, a similar development has taken place. Due to population growth, mangrove areas have decreased to enable other land use that supports economic development. However, significantly larger areas of mangroves currently remain on the islands of Indonesia and mainland Malaysia.

In the SDWA-Mangrove project, which studies how short-term bio-physical interactions between flow and vegetation govern the long-term bio-geomorphologic development of mangrove ecosystems and vice versa (for details see text on data and knowledge gaps), we focus on a limited number of study areas in Singapore (Sungei Buloh, Mandai & Pasir Ris) and Malaysia (Tanjong Piai, Pulau Kukup and Benut OR Matang; Figure 7.7). The sites are selected for a combination of contrasting developmental stages (expanding sites are Benut & Matang & perhaps some northern areas of Tanjong Piai; eroding sites are south tip of Tanjong Piai, Pulau Kukup and Sungei Buloh) in combination with logistical requirements (nearness to Singapore, accessibility of the field site, good contacts of NUS-PI with local partners, permits and possibility to safely deploy equipment).

For Thailand, there are detailed maps indicating where corals, seagrass meadows and mangroves occur together vs. separated. The availability of these maps in combination with the excellent infrastructure for diving and renting vessels plus the good contact of the NUS-PI with local authorities makes Thailand most suitable for the field research within the JBE project, which is focussed on the importance of connectivity between corals, seagrass meadows and mangroves with respect to the attenuation of hydrodynamic energy and the exchange of (organic) materials. Exact sites in Thailand still need to be decided on.

The sites in Thailand that will be used for SDWA project (Figure 7.8) are selected for a combination of contrasting environments (exposed sites are A2, B1; sheltered sites are A1, A3) in combination with logistical requirements (accessibility of the field site, good contacts of NUS-PI with local partners, permits and possibility to safely deploy equipment, etc).

Regarding the objectives of the JBE project, there will be a broader range of study sites needed, in order to get differences in connectivity between corals, seagrass and mangroves. The exact sites that will be used in the JBE project still need to be decided on. Where possible, the JBE project will try to get overlapping sites with SDWA.

Figure 7.7 Indication of the mangrove field sites in Singapore that will be used in the SDWA Mangrove project. We identified a range of contrasting field sites in Thailand, but unfortunately, these could eventually not be used.

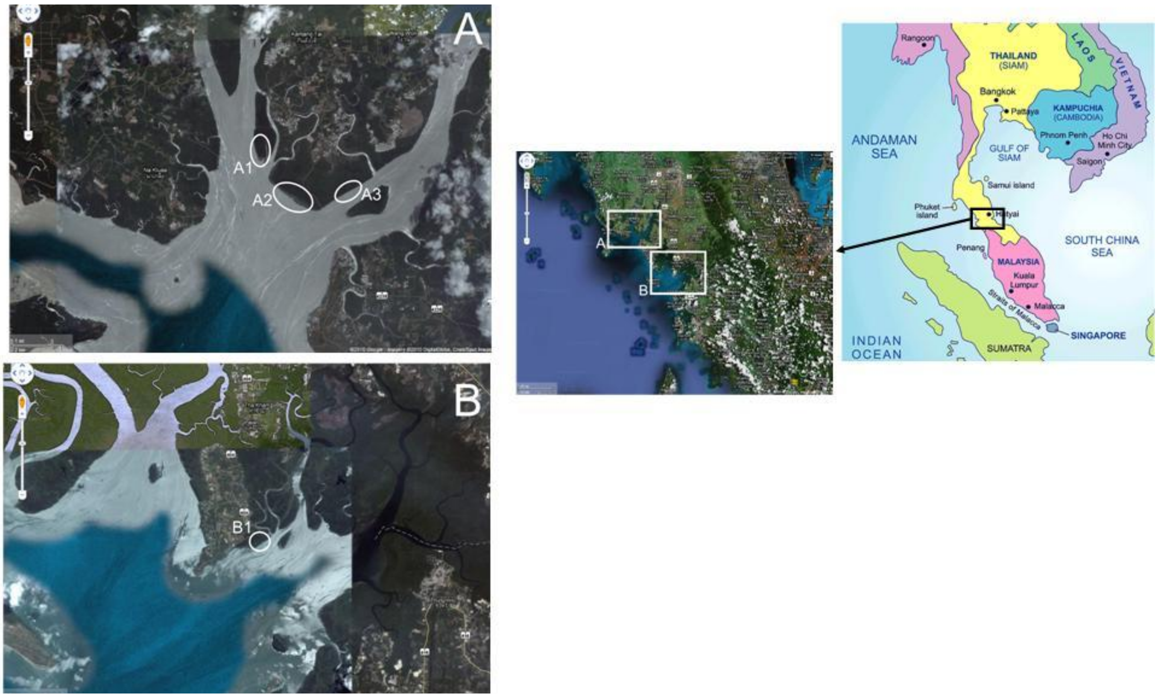


Figure 7.8 Indication of the SDWA-Mangrove field sites Kantang Tai (A1 to A3) and Palian (B1) along the West coast of Thailand. For some aspects of seedling establishment we will also do limited observations in a sheltered bay on the east-coast (Pak Phanang; not indicated in this map).

7.3 Environmental impacts and management in Singapore

Most, but still not all of the few remaining mangroves in Singapore are nowadays well protected areas. For Malaysia, where all mangroves are under the jurisdiction of the State Forest Department, we lack an exact overview of all mangrove areas and the extent to which they are protected. According to the FAO world mangrove 1980-2005 report Asia *"Only a very small percentage of Malaysian mangroves fall within legally gazetted protected areas: 0.3 percent in Peninsular Malaysia; 0.2 percent in Sarawak; and 1.3 percent in Sabah. Fortunately mangrove plantations are now being implemented also in other areas outside the managed Matang forest, especially after the tremendous 26th December 2004 Indian Ocean Tsunami, when several governments and NGOs called for the plantation/rehabilitation of mangroves. Recognizing the crucial role that mangrove forests played in mitigating loss of life and damage to property by the December 2004 tsunami, Malaysia embarked on a treeplanting programme along its coastline."* For Thailand, where most mangroves are under the jurisdiction of the Royal Forestry Department we lack an exact overview of all mangrove areas and the extent to which they are protected. According to the FAO world mangrove 1980-2005 report Asia the mangrove extend was 240000 ha in 2005 whereas most of it is controlled by the state. However, often local communities manage these forests (Sudtongkong and Webb 2008).

The most important threats to the remaining mangroves appear to be:

- (ongoing) lateral erosion of protected mangrove areas
- anthropogenic removal for land reclamation, harbour extensions, shrimp farming, etc. for unprotected mangrove areas
- risk of oil and other chemical spoils from ships passing by
- on the long-term, sea-level rise

For the protected mangroves sites within Singapore, local managers achieve high quality community involvement, as seen from well designed visitor centres with high numbers of visitor, board walks to facility public access into the mangroves and regular volunteer clean-up actions. There is not yet a structural ongoing monitoring program for the mangroves in Singapore, comparable to the seagrass monitoring program. Some of the scientists at the National University of Singapore have however a history in mapping local mangrove areas and there is interest from local parties in setting up a mangrove monitoring program. Whereas space limitations make large-scale mangrove restoration efforts in Singapore virtually impossible (except for some land reclamation areas), there is seedling planting ongoing to counter balance erosion of the remaining mangroves.

For the 2 of the 3 Malaysian mangrove sites that have been declared in 2003 wetlands of international importance and which we visited (Pulau Kukup & Tanjung Piai), local managers achieve a similar awareness and positive attitude towards mangroves preservation. Within Malaysia, Matang is quite an unique site in that it is the world's largest managed mangrove forest (ca. 40 000 ha) that is sustainable managed by rotational logging of *Rhizophora apiculata* trees for over 100 years, which are used for charcoal production. At these specific sites, local managers are highly interested in scientific knowledge that may help them in managing and preserving the mangroves. For example, it has been tried to reduce the strong erosion on the south tip of Tanjong Piai by placing geotextile bags in front of the cliff (Figure 7.9). Until now, this has however not been successful in that the erosion is still ongoing. Knowledge and measures to stop the erosion are highly interesting to the local site managers, as Tanjong Piai is a landmark (i.e., the most southern tip of mainland Malaysia) that attracts many visitors. We have however no knowledge about management of other mangrove areas outside these specific sites, but expect this to be completely different regarding the remarks the made in the FAO world mangrove 1980-2005 report Asia.

For the mangrove areas at the west coast of Thailand, the state owned forest is mainly managed and used by local villagers that catch fish and crabs with standing nets or traps. At low tide they also dig out crabs on the mudflat. To our knowledge wood is rarely harvested by cutting down single trees within the forest. In Pak Phanang *Rhizophora* seedlings are planted on the vast mudflats to promote this desired species rather than let *Avicennia* and *Sonneratia* naturally colonize. However Pak Phanag is rapidly filling up with sediments and the forest is pro-grading naturally in most places.
In Palian a boardwalk leads from the local village into the mangrove forest with the intention to promote local tourism, however it is partly destroyed and impassable now.

Figure 7.9 pictures of the ongoing cliff erosion at Tanjong Piai and the geotextile bags placed in front of the cliff.

7.4 Data and knowledge gaps

Within the SDWA-mangrove project, there is currently a scientific literature review being written, highlighting the most important knowledge and knowledge gaps from both a biological and physical perspective (Friess et al. in prep). Based on the SDWA-research proposal and the review by Friess et al. (in prep), we summarise the following important knowledge gaps which we see as critical from a BwN perspective (as explained in detail below):

1) To what extent does habitat fragmentation affect the healthy functioning of mangroves, what is the dispersal distance of propagules, and how is pollination affected by fragmentation?
    a) How does this depends on size of the remaining mangrove
    b) How does this depend on distance between the remaining mangroves?
    c) Is there an interaction between size and distance?

2) Which factors enables vs. hampers mangrove seedlings to establish
   a) tidal inundation
   b) sediment chemistry
   c) sediment stability
   d) hydrodynamic forcing
3) How do the vertical sediment dynamics of mangroves work at different time scales
   a) short-term sediment accretion dynamics
   b) seasonal sediment-erosion dynamics
   c) long-term net surface elevation change as the balance of sediment accretion minus subsidence and the consequences for their ability to follow sea-level rise
4) What is the time-scale of the horizontal sediment dynamics of mangroves, and how does this depend on hydrodynamic forcing
5) To which extent can mangroves help protecting coastal areas

Ad 1) If the distance between adjacent mangroves become too large to enable healthy mangrove functioning, it could be relevant to “create” (via BwN approaches) mangroves in between mangroves to restore connectivity by reducing the inter distance or increase the size of existing mangroves. We are however still a long way from understanding these relationships. This is a key research interest of the lab. of Prof Webb, the NUS PI in the SDWA-Mangrove project. Besides working on this question in the SDWA-mangrove project, Prof. Webb his research lab is currently also using molecular genetics to address this question. Within the SDWA-mangrove project we hope to make progress on this by requesting some modelling work to be done on large-scale propagule dispersal by BwN project SI 4.3 (supportive modelling).

Ad 2) The successful building of mangroves does require us to obtain a good understanding of these processes and their interactions. Without this knowledge, BwN activities are likely to fail. These are a main focus in the SDWA-mangrove project, and preliminary flume results presented on 19 November on the SDWA-workshop in Singapore show that the techniques we currently employ are promising in enhancing our insights.

Ad 3 & 4 & 5) Addressing these questions is one of the main objectives identified in the SDWA-mangrove project, which focuses on these 3 questions by a multidisciplinary research team consisting of biologists, physical geographers, and hydrodynamicists. In the SDWA-mangrove project, we will quantify how the short-term bio-physical interactions between flow and vegetation govern the long-term bio-geomorphologic development of mangrove ecosystems and vice versa. This question will be addressed by combining field studies, flume studies, mesocosm experiments and process-based hydrodynamic modelling. The results will be generic, in that the project will provide quantitative insight in how these interactions are affected by hydrodynamic forcing and ecosystem scale. The project will learn to which extent, and on which time scales, mangroves can i) act as buffering mechanism against anthropogenic sediment inputs, ii) clear coastal waters and iii) contributing to coastal protection. The modelling tools that will be developed in the project, enables scenario studies to predict the response of mangroves to ongoing global change processes and anthropogenic disturbances. Thus, the project will gain fundamental insights needed for mangrove restoration in the Singapore area and mangrove management in neighbouring countries.

8 Model Inventory

8.1 Introduction

A model inventory was performed to ascertain the various advances in numerical modelling of Singapore waters. The assessment was carried in two steps:

1 Internal review of non-confidential Deltares | Delft Hydraulics models for Singapore applications
2 External scan of peer-reviewed literature on numerical modelling studies in Singapore waters (via ScienceDirect and Google queries)

In section 8.2, the Deltares model programs are introduced which have been implemented in various Singapore studies, and a brief overview is given of the Singapore models that have been built (*only the non-confidential models*) for the individual applications prior to the Singapore-Delft Water Alliance (SDWA) and commencement of the Building with Nautre (BwN) project. The models developed in SDWA and BwN are purposefully excluded from this inventory because a large number of the models are currently under development, therefore a complete overview is not available. In section 8.3, an overview of the external models (non-Deltares | Delft Hydraulics models) which have been published on in peer-reviewed journals is given.

In Section 8.4 a discussion on modelling needs is given, focusing on hydrodynamic and sediment transport modelling in sensitive species habitats, such as coral reefs and mangroves. Finally, in section 8.5 a brief conclusion is provided.

8.2 Deltares Models

8.2.1 Modelling Programs

SOBEK

Below is a brief overview of the background and capabilities of SOBEK. For additional information please refer to Deltares | Delft Hydraulics (2009).

SOBEK 1D2D is an integrated software package which enables the construction of complex models by dynamically integrating 1D components from SOBEK-Rural, SOBEK-Urban and SOBEK-River and 2D components from SOBEK Overland Flow (formerly known as Delft-FLS).

SOBEK 1D (Rural, Urban and River) solves the Saint-Venant equations by means of a finite difference scheme. Breaches can be modelled by means of a complex “river weir” with time dependent properties. Breach growth can be described by time series for crest width and crest level. Breach flow is obtained from weir flow equations.

SOBEK 2D (Overland Flow) uses a rectangular grid and solves the shallow water equations by means of a finite difference scheme; identical to the one used by SOBEK 1D. SOBEK 2D is capable of handling flooding and drying, spatially varying surface roughness and wind friction. It also contains a “dam break” link, capable of describing breach growth by means of empirical breach growth equations ((Verheij-) vanderKnaap).

Delft3D – FLOW

Below is a brief overview of the background and capabilities of Delft3d-FLOW. For additional information please refer to WL | Delft Hydraulics (2007a).

WL | Delft Hydraulics has developed a unique, fully integrated computer software suite for a multi-disciplinary approach and 3D computations for coastal, river and estuarine areas. It can carry out simulations of flows, sediment transports, waves, water quality, morphological developments and ecology. It has been designed for experts and non-experts alike. The Delft3D suite is composed of several modules, grouped around a mutual interface, while being capable to interact with one another. Delft3D-FLOW, which this manual is about, is one of these modules.

Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid. In 3D simulations, the vertical grid is defined following the sigma co-ordinate approach.

Areas of application

- Tide and wind-driven flows (i.e. storm surges).
- Stratified and density driven flows.
- River flow simulations.
- Simulations in deep lakes and reservoirs.
- Simulation of Tsunamis, hydraulic jumps, bores and flood waves.
- Fresh-water river discharges in bays.
- Salt intrusion.
- Thermal stratification in lakes, seas and reservoirs.
- Cooling water intakes and waste water outlets.
- Transport of dissolved material and pollutants.
- Online sediment transport and morphology.
- Wave-driven currents.
- Non-hydrostatic flows.

Standard features

- Tidal forcing.
- The effect of the Earth’s rotation (Coriolis force).
- Density driven flows (pressure gradients terms in the momentum equations).
- Advection-diffusion solver included to compute density gradients with an optional facility to treat very sharp gradients in the vertical.
- Space and time varying wind and atmospheric pressure.
- Advanced turbulence models to account for the vertical turbulent viscosity and diffusivity based on the eddy viscosity concept. Four options are provided: k-□, k-L, algebraic and constant model.
- Time varying sources and sinks (e.g. river discharges).
- Simulation of the thermal discharge, effluent discharge and the intake of cooling water at any location and any depth.
- Drogue tracks.
- Robust simulation of drying and flooding of inter-tidal flats.

Special features

- Various options for the co-ordinate system (rectilinear, curvilinear or spherical).
- Built-in automatic switch converting 2D bottom-stress coefficient to 3D coefficient.
- Built-in anti-creep correction to suppress artificial vertical diffusion and artificial flow due to σ -grids.
- Built-in switch to run the model in either σ-grids or in Z-grids (Z-model)
- Various options to model the heat exchange through the free water surface.
- Wave induced stresses and mass fluxes.
- Influence of waves on the bed shear stress.
- Optional facility to calculate the intensity of the spiral motion phenomenon in the flow (e.g. in river bends) which is especially important in sedimentation and erosion studies (for depth averaged - 2D - computations only).
- Optional facility for tidal analysis of output parameters.
- Optional facility for special points such as 3D gates, Current Deflecting Wall (CDW) floating structures, bridges, culverts, porous plates and weirs.
- Optional facility to switch between a number of advection solvers.
- Optional facility for user-defined functions.
- Domain decomposition.

Coupling to other modules

The hydrodynamic conditions (velocities, water elevations, density, salinity, vertical eddy viscosity and vertical eddy diffusivity) calculated in the Delft3D-FLOW module are used as input to the other modules of Delft3D, which are:

- Delft3D-WAVE short wave propagation
- Delft3D-WAQ far-field water quality
- Delft3D-PART mid-field water quality and particle tracking

Delft3D –WAQ (and ECO)

Below is a brief overview of the background and capabilities of Delft3d-ECO and WAQ. For additional information please refer to WL | Delft Hydraulics (2007b).

Delft3D-ECO and WAQ are Delft Hydraulics' state-of-the-art Delft3D suites for the modelling of water quality of surface water systems. Delft3D contains separate modules for the simulation of water and sediment quality (ECO and WAQ; Delft Hydraulics, 2007b) and water flow (FLOW). This modelling suite is based on professional, thoroughly tested software, and is equipped with extensive facilities for graphical pre- and post processing. The modules have been developed, calibrated and validated for a vast number of applications for marine as well as fresh water systems. ECO simulates 3D water quality, with the focus on nutrients, phytoplankton, organic matter and dissolved oxygen. Both ECO and the general water quality model WAQ are based on the general "process library", that contains a comprehensive set of predefined process formulations for a large set of "substances" including various inorganic and organic nutrient components (N,P,Si), phytoplankton, organic matter (detritus in various fractions), dissolved oxygen, suspended sediments, transparency, salinity, feacal coli bacteria, heavy metals and organic micro pollutants. For the present applications ECO has been extended with faecal coli bacteria. Process formulations for other substances such as micro pollutants can be added to ECO in the future.

ECO's state-of-the-art and extensively validated BLOOM sub-model simulates phytoplankton species (up to 15 species or groups) subject to the limitation of primary production by nutrients (N,P,Si), light (energy), growth rate, grazing, settling and temperature. The light limitation is derived from a light extinction coefficient that is composed of contributions of water, various organic matter components including algal biomass, and suspended sediment. A recently developed new version of ECO has been applied, with which both water compartments and sediment layers are explicitly simulated. All water quality processes in the model are active in water compartments as well as sediment layers, but local chemical conditions determine the way processes turn out. This allows for optimal simulation of sediment-water interaction.

The Delft3D modules are used in a coupled way. The flow and temperature fields calculated with FLOW are off-line input to ECO. The development of the Delft3D FLOW models is described in Delft Hydraulics (2007a). The coupling of the modules also means that the computational grid (land contours, bathymetry, and horizontal and vertical grid structure) of the water quality model is derived from the grid for the hydrodynamic model FLOW. Since less spatial detail is required for the water quality simulations, the hydrodynamic grids have been spatially aggregated to reduce the computational burden of ECO. Using Delft3D's user interface, the coupling and aggregation is fully automated and mass conservative.

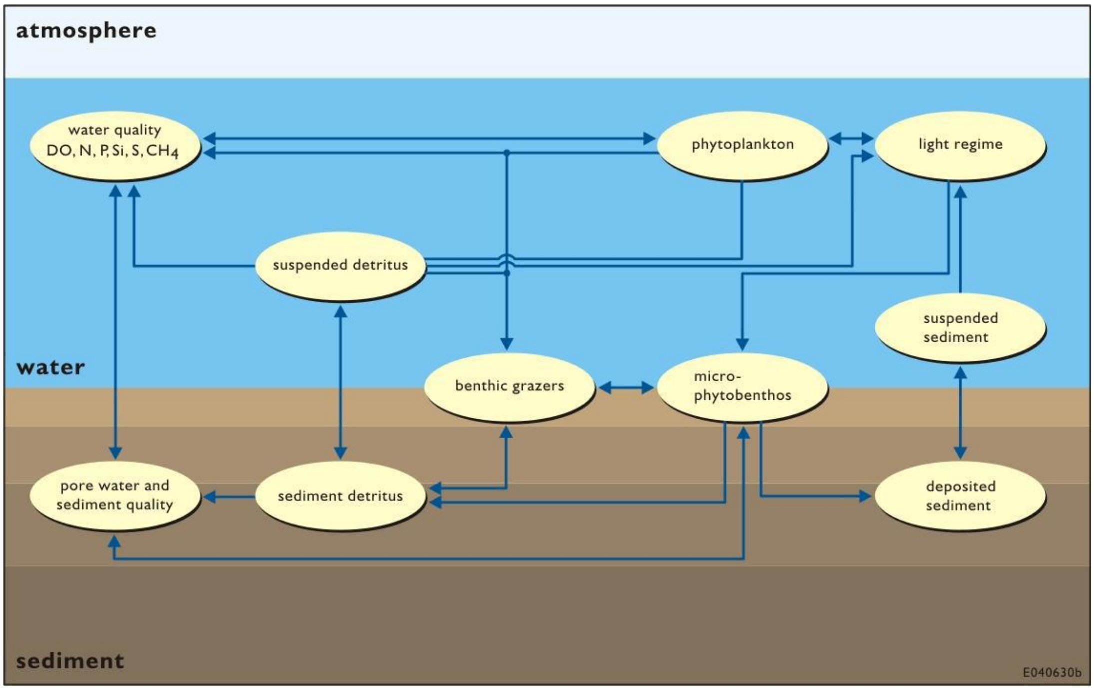


Figure 8.1 Schematic overview of the ecosystem components and interactions in ECO

8.2.2 1D Model Applications

Marina Reservoir Hydraulic Model

Marina Reservoir hydraulic SOBEK model was developed to feed water quality models for pollutant loading modelling. The model is an application of Deltares SOBEK modelling package. The hydrology is described in the rainfall-runoff module (SOBEK RR) and the hydraulics are described in a combined application of the Channel Flow and Sewer Flow modules (SOBEK CF/SF). The SOBEK schematisation is based on the Channel Flow schematisation derived from the converted CDM Mike-11 schematisation. This schematisation has been extended with artificial manholes (street-level connections to underground sewerage systems) used in the Rainfall-Runoff module, and pipes connecting the manholes to the Channel Flow system. Various adjustments to the schematisation have been made, as provided by PUB. Model preparation was executed in close collaboration with TMSI.

The catchment was divided into 196 sub-catchments for which a general schematization is applied (Figure 8.2). In each of these sub-catchments the rainfall-runoff process and the drainage to the main channels is described using the following two network elements in SOBEK:

Flow – Manhole with Runoff (called “Manhole” henceforth in this document)
Flow – Pipe (called “Pipe” henceforth in this document)

The Manhole stores the total runoff (or acts as a collection point for the runoff) and the Pipe conveys the stored runoff to the main channel.

Some of the adjustments of the SOBEK model included the following:
- Individual sub-models for Singapore River, Rochor-Kallang, and Geylang rivers were combined into one model.
- The outflows from the rivers into the Marina reservoir are connected at boundary nodes.
- One boundary node is representing the location where Rochor, Kallang and Geylang flow into the Bay, and another boundary node represents the location where Singapore River and Stamford flow into Marina Bay.
- Also a model in which Marina Bay is completely included has been made. Detailed tidal boundary conditions are taken from Delft-3D modelling results. This model also includes additional rainfall-runoff areas, directly discharging into the Bay. Additional cross-sections for the Bay are added (MC001 t/m MC009, MC101, MC_R, MC_L1 and MC_L2).
- A Sobek schematisation for the post-closure situation has been prepared. In this case, the barrage is represented by nine weirs and one pump (operating in six stages). Downstream of the weir a new boundary condition is added with a tidal boundary. This boundary condition will be derived from Delft3D modelling results later.

Additional adjustments were made to the rainfall-run off and channel flow modelling. These adjustments are detailed in Janssen et al. (2007).

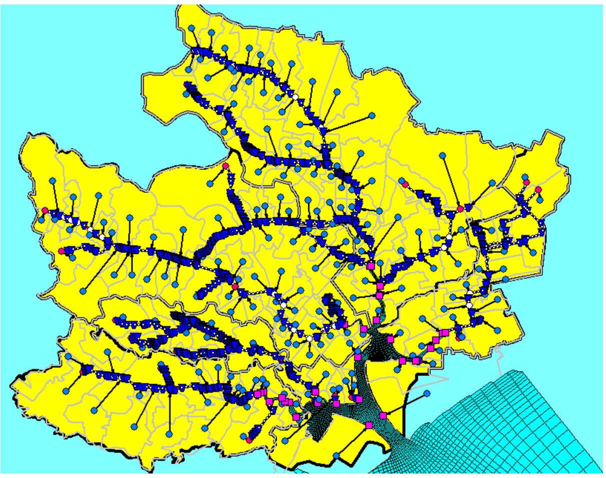


Figure 8.2 Marina Reservoir catchment model

8.2.3 2D Model Applications

Singapore Regional Model

The model in this section is described in Twigt (2007).

The Singapore Regional Model (SRM) covers large parts of the seas around Singapore (including Malacca Straits, Singapore Straits and parts of the Andaman Sea, the South China Sea and the Java Sea) to allow the computation of the residual currents in Singapore Strait in this model rather than prescribe these as boundary conditions. Another advantage of a large overall model set-up is that local changes in the centre of the model do not necessitate changes in model boundary conditions. The grid varies in size between 200 m and 300 m around Pulau Tekong, and over 15 km at the open boundaries of the model domain (Figure 8.3). The resolution is relatively high in Johor and Malacca Straits. The bathymetry in the model is based upon mostly Admirality chart data, in combination with soundings collected in 1999 around Pulau Tekong and Pulau Ubin.

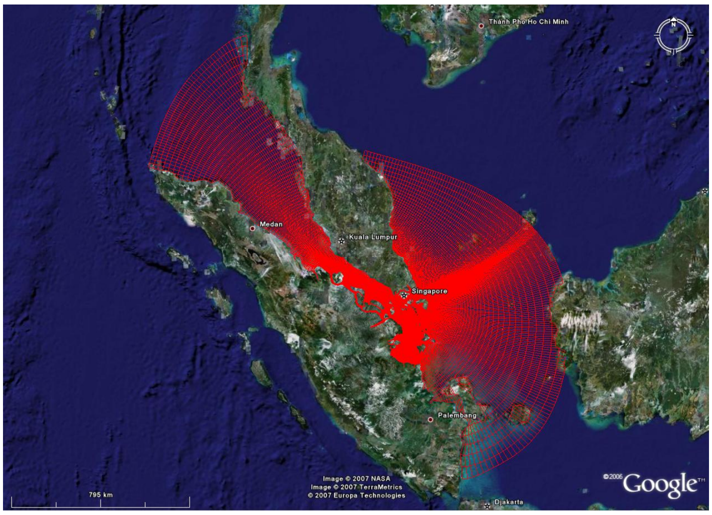


Figure 8.3 Singapore Regional Model grid

This tidal model has three open boundaries, located in three sea basins, with a total of 17 boundary support points (Figure 8.4). The SRM has previously been used to generate tidal boundaries for other smaller scale models in the Singapore region. The model includes the semi-diurnal tidal constituents (mainly M2 and S2, with 2 high and 2 low tides per day) mainly coming from the direction of the Andaman Sea, and the diurnal components (mainly K1 and O1, with one high and one low tide per day) coming from the direction of the South China Sea and a minor contribution from the Java Sea. The water level boundary condition consists of three components:

- Bathymetry
- MSL anomaly
- Tide

The bathymetry is constant in time and space, which is in contrast to the latter two components. The MSL anomaly and the tide vary in both time and space. The tidal forcing is prescribed by 8 tidal components: M2, S2, N2, K2, O1, K1, Q1 and the P1. Averaged winds are also applied in the model forcing. River discharge flows are also applied on the 9 freshwater discharge locations, though Sungai Johor is the most significant freshwater discharge.

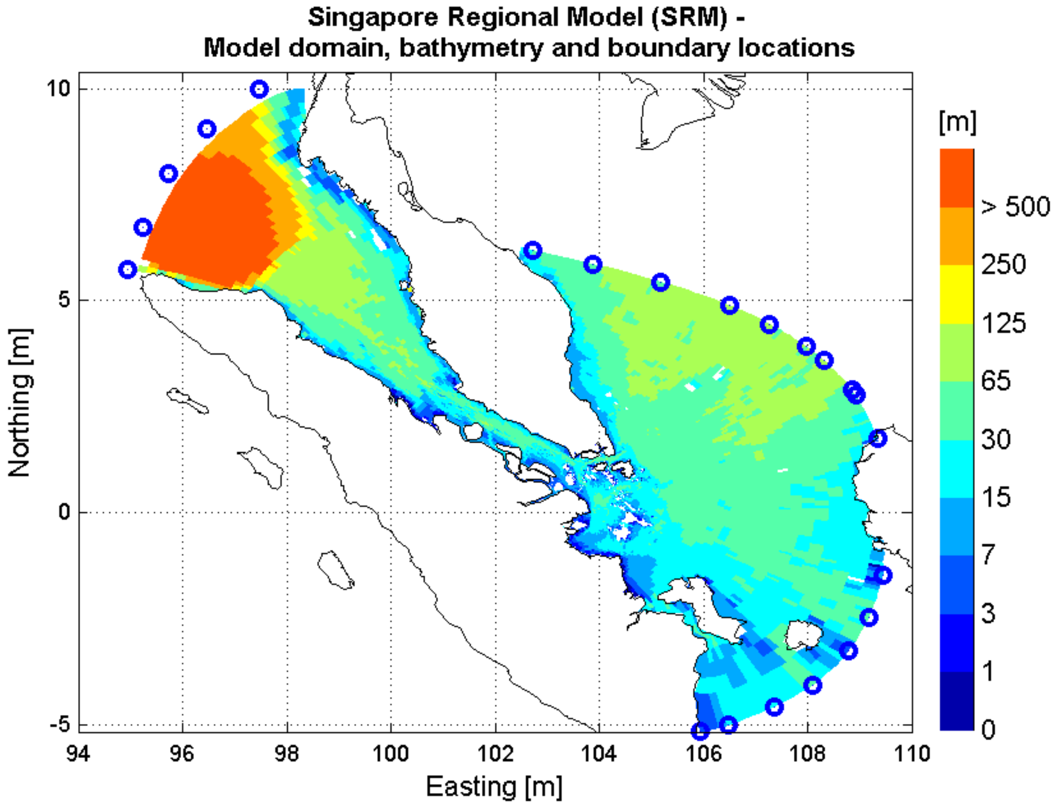


Figure 8.4 *The SRM has been utilized in a recent study to investigate data assimilation techniques based upon chaos theory and Kalman filter (Sun et al., 2009).*

Singapore Island Model (SIM)

The Singapore Island Model covers the waters around Singapore Island, including Singapore Strait and Johor Strait (Figure 8.5). The grid has a resolution that ranges between 50 m, in the East Johor Strait, and 1000 m, near the southwest boundary. The grid coordinates are in SVY'95.

The SIM was built to investigate effects of the land reclamations around Singapore and the Johor Strait. The SIM has been calibrated and validated extensively in terms of tidal water level elevation and velocities (WL | Delft Hydraulics, 2005).

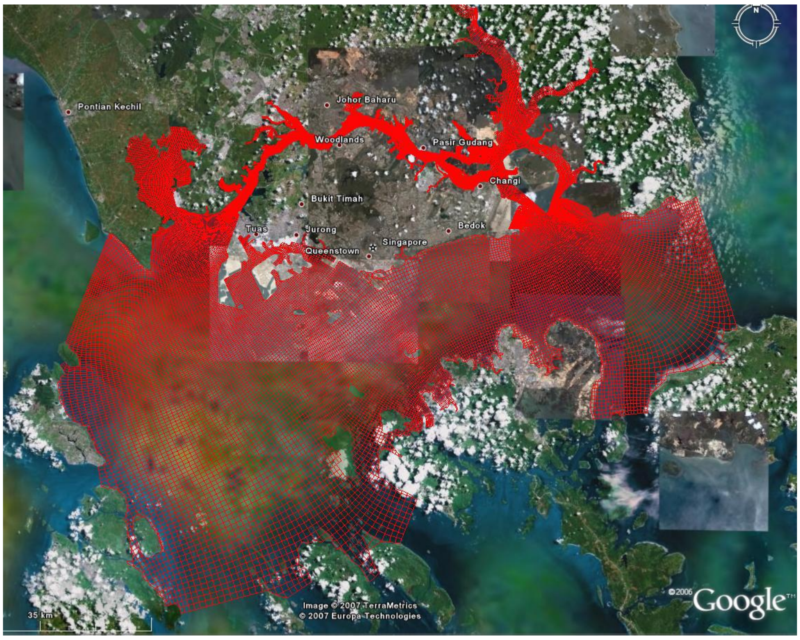


Figure 8.5 Singapore Island Model grid

8.2.4 3D Model Applications

East Singapore Local Model (ESLM)

The ESLM was developed to investigate the influences of land reclamations in the waters east of Singapore. The grid resolution is as refined as 25 m in the regions of navigation channels (Figure 8.6). The bathymetry in the model is based upon a mostly Admiralty chart data, in combination with soundings collected in 1999 around Pulau Tekong and Pulau Ubin.

The open boundaries are forced using the SRM. The fresh water and wind forcing applied in the ESLM is the same as applied in the SRM.

Box 8.1 SRM update as part of SDWA project

The SRM was recently updated (Autumn 2009) to increase the resolution around Pulau Tekong. This model was updated to make it applicable for modelling density driven flows (to model sediment transport effects) due to the freshwater influence of the Johor River. The grid was partially redrawn around Pulau Tekong to ensure the grid lines followed the bathymetry of the island, and the resolution was subsequently increased to roughly 100 m x 200 m in this region. The vertical resolution was increased to 10 σ-layers, each resolving 10% of the total water depth.

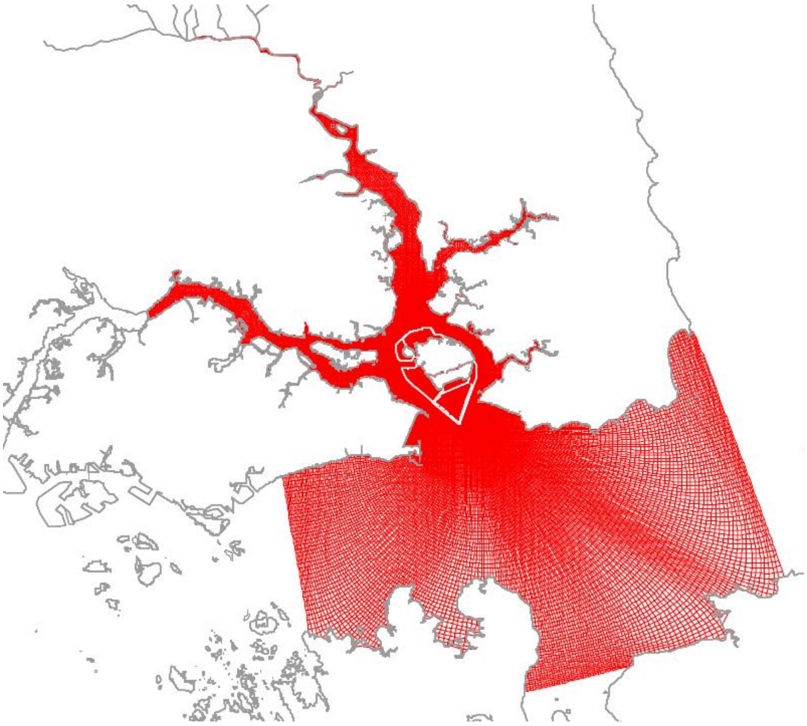


Figure 8.6 ESLM grid (red) and land boundary (grey).

Marina Bay Model

The model in this section is described in detail in Zijl and Twigt (2007).

The Marina Bay model was developed to simulate the impact of strategies and scenarios in terms of the expected water quantity and water quality in Marina Reservoir. The reference system used in the 3D Marina Bay model is SVY'95 (local coordinate system) with respect to geographical positioning and Mean Sea Level (MSL) with respect to elevation level (Datum). The areas of the Marina Bay basin, Kallang basin and Marina Channel have a typical grid size of 25 m by 25 m (Figure 8.7). The part of the grid covering Singapore Straits has grid sizes of 100 m up to 400 m in the most outer areas. In the 3D Marina Bay model 10 equidistant sigma layers (thus each with a thickness of 10% of the local water depth) are applied. The number of layers was decided after a number of sensitivity tests.

The Marina Bay model was nested in the SIM to get the offshore boundary conditions. To improve the representation of stratification, the anti-creeping option of Delft3D-FLOW is used. This built-in anti-creeping correction suppresses artificial (numerical) vertical diffusion and artificial flow due to the use of the σ-layer schematization at locations with steep bottom gradients.

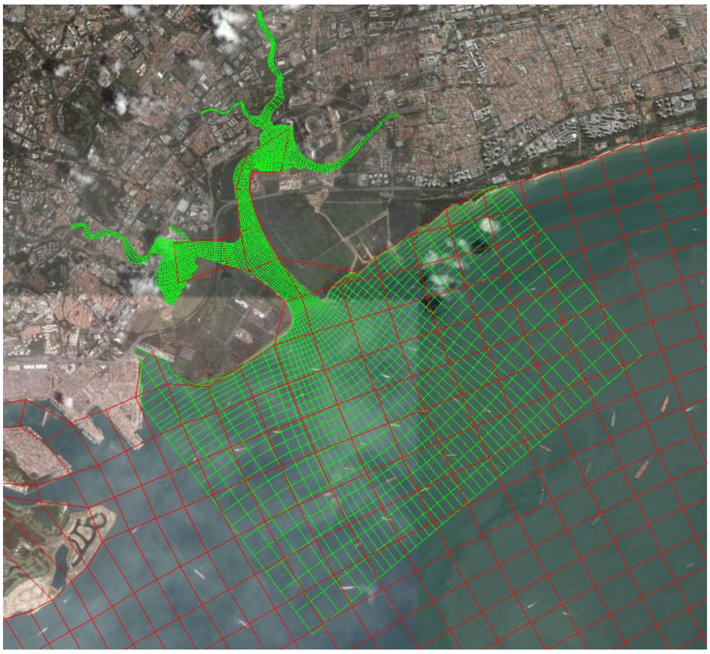


Figure 8.7 Marina Bay 3D model (green grid) and the SIM (red),on the south-central side of Singapore Island

Upper Peirce and Lower Peirce Models

The models in this section are described in detail in Zijl and Twigt (2007).

Delft3D mass balance and ECO water quality models for the existing Upper and Lower Peirce Reservoirs were developed to study both the planned water supply pumping of water from Marina Reservoir into Upper Peirce reservoir, and the impacts of the ABC (PUB Active, Beautiful and Clean) program supporting recirculation program. These reservoirs form a closed system (i.e., from a modelling point of view there are no open boundaries), so it is important to have a closed water balance taking into account all relevant in- and outflows. Evaporation, runoff and precipitation, wind, and aeration were all included in the hydrodynamic modelling. The reference system used in both the Upper and Lower Peirce Reservoir models is SVY'95 with respect to geographical positioning. With respect to elevation level (Datum), initially Mean Sea Level (MSL) was taken.

Altogether, the number of active grid cells in the Upper Peirce model grid is about 1500 in the horizontal plane, with a typical grid size of 50 m by 50 m (Figure 8.8). In the 3D Upper Peirce Reservoir model a maximum of 19 layers (in the deepest parts) is used. The layer thickness varies over the vertical. The thinnest layer can be found at the water surface, gradually increasing towards the bottom. Due to certain restrictions in Delft3D-FLOW, 36 m was been added to the reference water level of the Upper Peirce Reservoir model. Thus, the reference level used was MSL + 36 m. This corresponds roughly to Flood Control Level of the Upper Peirce Reservoir, which is 36.12 m above MSL. Bathymetry data for the Upper Peirce Reservoir has been digitized from drawing nr. RI/08.

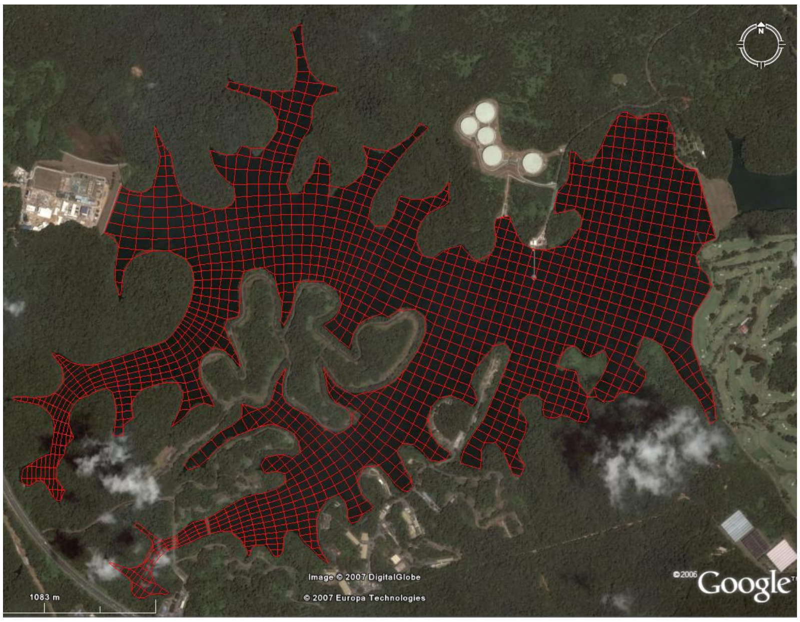


Figure 8.8 Upper Peirce Reservoir model grid

In the Lower Peirce model grid the number of active grid cells is about 1200, with a typical grid size of 25 m by 25 m (Figure 8.9). A Z-layer vertical schematization is employed. In the shallower 3D Lower Peirce Reservoir model, a maximum of 8 layers is used, with a uniform thickness of about 0.9 m (except for the upper-most layer in use, as the thickness there depends on the (time-varying) local water level). For the Lower Peirce Reservoir model, a reference level of MSL + 14 m was chosen. The Bathymetry data for the Lower Peirce Reservoir has been digitized from drawing nr. 93 269 / 1 to 5.

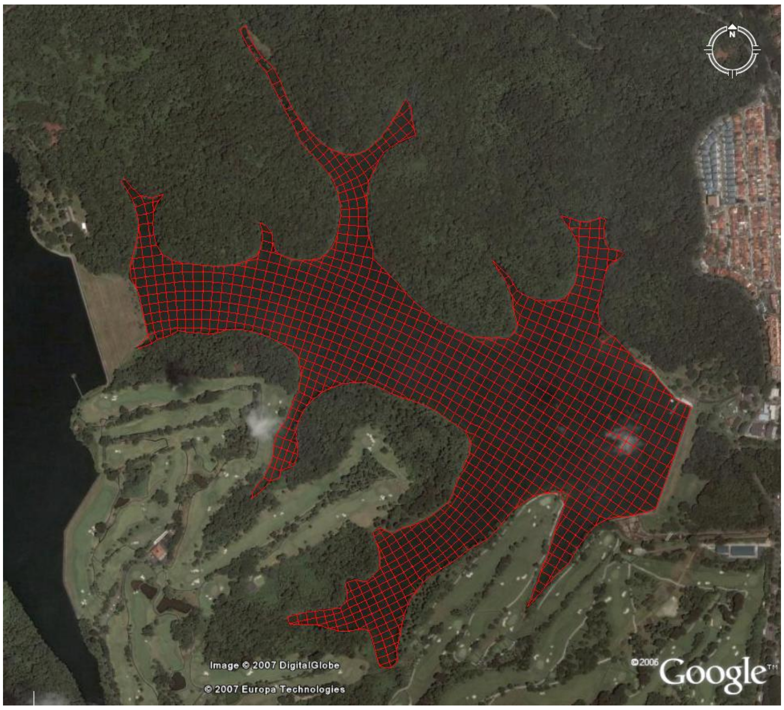


Figure 8.9 Lower Peirce Reservoir model grid

Marina Reservoir Model

The model in this section is described in detail in Zijl and Twigt (2007) and Smits et al. (2007).

The Marine Reservoir Model was built to investigate the effects, which will result from the closure of Marina Bay, of the Marina Barrage development. Once Marina Bay becomes closed it will become a reservoir, which will be cut off from tidal influence and salt water intrusion. Therefore, the reservoir will eventually become fresh water due to rainfall run-off.

The horizontal model grid of the 3D Marina Reservoir model is based on the model grid of the Marina Bay model, with the difference that the part covering Singapore Straits is cut off at the location of the Marina Barrage. The outline of the resulting grid is shown in Figure 8.10. As in the Marina Bay grid, this grid covers the Marina Bay basin, Kallang basin and Marina Channel. Furthermore it extends up to 2 km upstream into Kallang River, Rochor Channel, Geylang River, Singapore River and Stamford Canal.

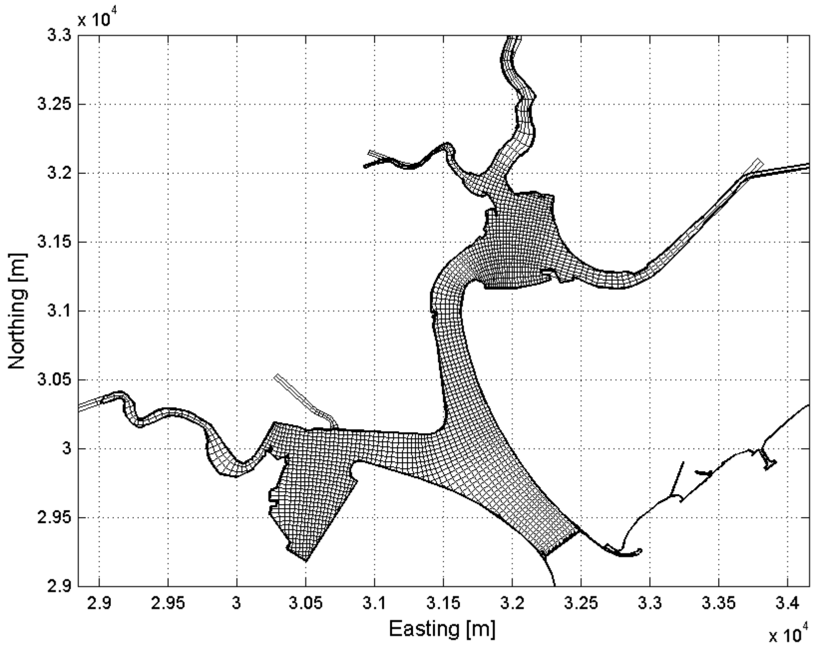


Figure 8.10 Marina Reservoir Model grid

Altogether, the number of active grid points in the Marina Reservoir model grid is about 2500 in the horizontal plane. The areas of the Marina Bay basin, Kallang basin and Marina Channel have a typical grid size of 25 m by 25 m. Further upstream larger grid cells have been used, with grid sizes (in the direction along the river) of more than 100 m.

In the 3D Marina Reservoir model a maximum of 12 computational layers (in the deepest parts) is used. The layer thickness varies over the vertical. The thinnest layer can be found at the water surface, gradually increasing towards the bottom. As in the Marina Bay model, the reference system used in the 3D Marina Bay model is SVY'95 with respect to geographical positioning and Mean Sea Level (MSL) with respect to elevation level (Datum).

The bathymetry of the Marina Reservoir model has been taken from the Marina Bay model. Near the barrage, the bathymetry has been slightly adapted. The grid cells immediately adjacent to the Marina Barrage have been given a depth of MSL -2.5 m to reflect the crest level of the gates. Some cells along the shore of Marina Channel, close to the western side of Marina Barrage have been given a depth of MSL -5.5 m to reflect the depth at which the pumps are operating.

The Marine Reservoir model is a closed system model (in terms of hydrodynamic modelling). This model was forced using input from the 1D SOBEK run-off model, as well as wind-forcing.

Marina Bay Water Quality Model

The Delft3D water quality model for Marina Bay is coupled to a SOBEK water quality model for the tributaries and drains, which in turn is coupled to an emission module. The water quality model for the tributaries only transports substances, by means of deactivation of the water quality processes. This simplified approach is justified by the very short residence times (hours) in the drains and tributaries during runoff. The emission module generates the upstream loads for all model substances from various sources in the Marina catchment.

The Marina Bay WQ model considers settling and re-suspension. The settling organic components are allocated to one sediment detritus components for C, N, P and Si each. These detritus components are decomposed according to first-order degradation with an average decomposition rate constant (0.0075 d^{-1} for C, 0.03 d^{-1} for N and P and 0.015 d^{-1} for Si at 20°C). Inorganic nutrients return to the water column.

The model includes three sediment fractions. IM1 represents the very fine fraction in sediment that is discharged from the Marina catchment, IM2 the remaining coarser fraction. IM3 represents the Marine sediment that enters Marina Bay from the Singapore Straits.

The grid for the water quality model is a 4x4 aggregated version of the hydrodynamic grid (Figure 8.11). The 10 layers of the hydrodynamic grid have been aggregated into 5 layers in the water quality model. The thickness of each layer is 20% of total depth. As depth varies over time with the tides, layer thickness varies from slightly less than 2 m to slightly over 1 m in the deepest part of Marina Bay.

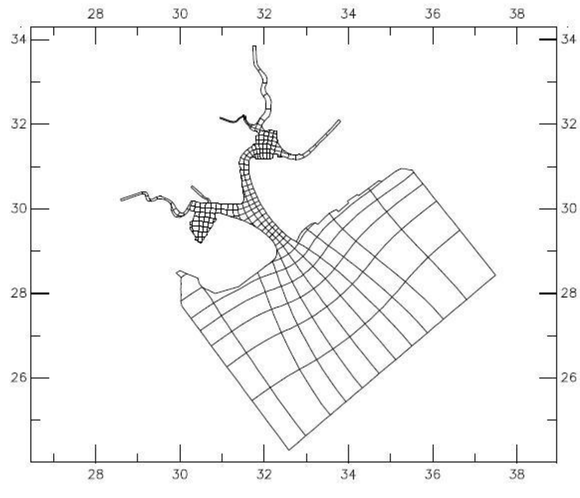


Figure 8.11 Marina Bay Delft3D-ECO model

Figure 8.2 shows the SOBEK schematization, with the sub catchments, the drains and the tributaries. In addition to the SOBEK run-off model forcing and Marina Bay hydrodynamic model forcing, water temperature, solar radiation and wind forcing are also applied.

8.3 External Models

8.3.1 2D model Applications

Cheong et al. (1992) implemented a 2DH hydrodynamic (tide only) model and built a sediment transport model, for south-eastern Singapore, to simulate the dispersal of a radioactive tracer. The tracers were released to obtain 'measurements' of transport rates. An increase in sediment accretion had been observed at the Tanjong Pagar Container Terminal (TPCT) since 1982. The source of this increased sediment load was thought to be from the silt slurry discharged near Bedok at Changi. The radioactive tracer experiment was performed to ascertain if the influx of sediment to TPCT was from the silt slurry and/or from the reclamation works at Marina City. The experiment showed that the radioactive tracers were transported to the TPCT, indicating the silt slurry released near Bedok is likely contributing to the increased sedimentation rates. The hydrodynamic model is based upon the work of Cheong et al. (1991), and employees a nested scheme, as described by Yang (1989). The coarse grid model has a grid size of 500 m x 500 m, whereas the fine grid has spacing of 100 m x 100 m. The hydrodynamic model utilized 12 tidal constituents at the open boundaries as model forcing. The overall model performed well at accurately predicting the tidal range and temporal oscillations. However, the model predictions had a phase lag in the tidal fluctuations compared to the tide table. The sediment transport model performed well at predicting the alongshore transport direction and alignment of the tracer plume dispersal; however, the model over-predicted the plume lateral spreading. The over-prediction is likely due to using the depth-averaged velocities, which are larger than the near-bed velocities, when the majority of the plume transport occurred near the seabed.

Riddle (1996) made tidal current predictions off the Southwest coast of Singapore Island. The study is centred on a sensitivity analysis of the model parameters. Riddle (1996) is focused on accurately predicting the turning of the tide, using drogues in both simple and complex tidal flows. He also employed particle tracking techniques to model the spreading and dilution of a dye patch. Two 2D hydrodynamic models were set-up, which were based upon a modified version of Leendertse (1967). The outer model covered a 100 km x 37.5 km area, and included the tidal station at Tanjung Piai, Sungai and Belungkor, and Horsburgh lighthouse, which provided boundary conditions and validation data for the model simulations. The outer model used grid cells that were 200 m x 200 m. The inner domain focuses on the southwest region of Singapore Island. This domain is 27 km x 18 km and used a grid cells that were 54 m x 54 m. The bathymetry was based upon admiralty chart data. The overall nested model was successfully able to predict the diurnal nature of the spring tidal currents, as well as the change of the tidal current structure to a semi-diurnal nature during the neap tides. This study focused on investigating the sensitivity of the water depth, bed friction, boundary conditions and the wind forcing. It was found that the prediction of the turning of the tide was most sensitive to the boundary conditions. A regression analysis was also performed in combination with a Monte Carlo simulation in order to determine the distribution of the model uncertainty in predicting the turning of the tide.

Recently, Huang et al. (2009) employed the COMCOT model (Wang and Liu, 2006) to investigate the potential effects of tsunami generated by a Manila trench earthquake on ports of operation in Singapore. A series of 4 nested grids were used to obtain sufficient resolution around eastern Singapore. The model grids used latitude and longitude coordinates and utilized bathymetry data from ETOP02 and local survey data in Singapore waters. The study predicted that significant affects would be experienced by the ports of operation around eastern Singapore due to the simulated tsunami generated from a 9.0 magnitude Manila trench earthquake.

Pang and Tkalich (2003) employed the Princeton Ocean Model (POM) in a 2DH simulation of the Singapore Strait. The focus of their study was to predict tidal and monsoon driven currents in the Singapore Strait. This study investigated the net flow for various regions within their domain, but no comparisons were made against data.

8.3.2 3D model Applications

Chao et al. (1999) developed a multi-level turbulence model based on the three-dimensional Navier–Stokes equations to compute tidal water levels and currents in the Singapore Straits. In the computational domain, the coastal waters are divided into five layers and the velocities are averaged along the layer depth. The horizontal and vertical diffusivity terms are all considered according to the Boussinesq Approximation (Falconer and Li, 1994), and the vertical coefficient of turbulent viscosity is given by the Prandtl mixing length method (Rodi, 1980). The model domain is 110 km x 70 km, with 1 km x 1 km grid resolution (Figure 8.12). The open boundaries are forced with 60 tidal constituents by means of harmonic analysis.

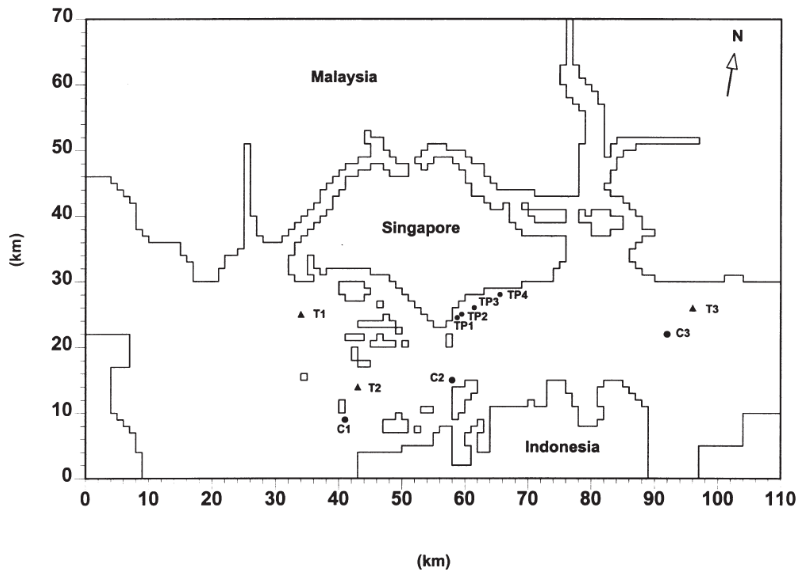


Figure 8.12 Computation domain of Singapore coastal waters (taken from Chao et al., 1999).

Chao et al. (1999) were able to predict the phase of the tidal oscillations and the amplitude of the diurnal tidal currents well for most stations; however they consistently over-predict the semi-diurnal tidal currents. The water level oscillations are predicted well for all stations.

Zhang and Gin (2000) develop a 3D-hydrodynamic finite-difference model to simulate the effect of tidal motions and winds on tidal currents. They perform a variety of theoretical tests prior to their field application of Singapore waters. The model performed well with the theoretical test cases. The grid developed for the Singapore test case is similar to that of Chao et al. (1999). It is also a 110 km x 75 km grid, with 1 km x 1km grid spacing. The study implemented 9 vertically-fixed layers in the model domain (same as z-layers in Delft3D), with only the top layer changing in thickness with time due to the water surface elevation oscillations. The model predictions were compared with water level and current measurements (Shankar et al., 1997). Again, similar to that of Chao et al. (1999), the semi-diurnal tidal currents are under-predicted. Zhang and Gin (2000) also found the current magnitude predictions to be sensitive to the internal friction coefficient and the bottom friction, but less sensitive to the horizontal eddy viscosity. These sensitivity studies were further elaborated upon in Zhang and Chan (2003), with similar conclusions made.

In Zhang (2006), model predictions are made using both the Princeton Ocean Model (POM) (Blumberg and Mellor, 1983) and MIKE 3 (DHI Water and Environment, 2003) of tidal water levels and currents, and compared again the same measurements discussed in Zhang and Gin (2000). The model grid is employed as in Zhang and Gin (2000) for both models; however POM uses σ-coordinates in the vertical, whereas MIKE 3 utilizes z-layers. In the POM model, 9 equi-distant vertical layers are used, whereas in the MIKE 3 model, 9 z-layers are used that are 6m thick. Both models perform well at predicting the observed water level oscillations at the various measurement stations. Similar to the previous model applications, both models consistently under-predict the semi-diurnal tidal currents, and MIKE 3 also under-predicts the peaks of the diurnal tidal velocities (also refer to section 2.1.1).

In Zhang et al. (2004), the effects of wave-current interaction on the hydrodynamics in coastal regions is investigated. The POM is again applied in this study, but a modified Grant-Madsen analytical model is incorporated to describe the wave-current interaction. The same grid is utilized in this study, as in the Chao et al. (1999) study; however 15 σ-layers were used in the vertical. The waves are predicted using a third generation wave model, WAM (The WAMDI group, 1998). Zhang et al. (2004) found that the inclusion of wave-current interaction within the bottom boundary layer reduced the predicted current velocities, resulting in velocities predictions near the seabed that compare better with observations.

Similarly to Zhang et al. (2004) and Zhang (2006), Chen et al. (2005) implemented a 3D POM model to investigate the large-scale hydrodynamic patterns in the Strait of Singapore. Chen et al. (2005) used a POM model covering the Strait of Singapore, with a grid resolution of 960 m x 960 m (Figure 8.13). They utilized 11 exponentially distributed vertical σ-layers.

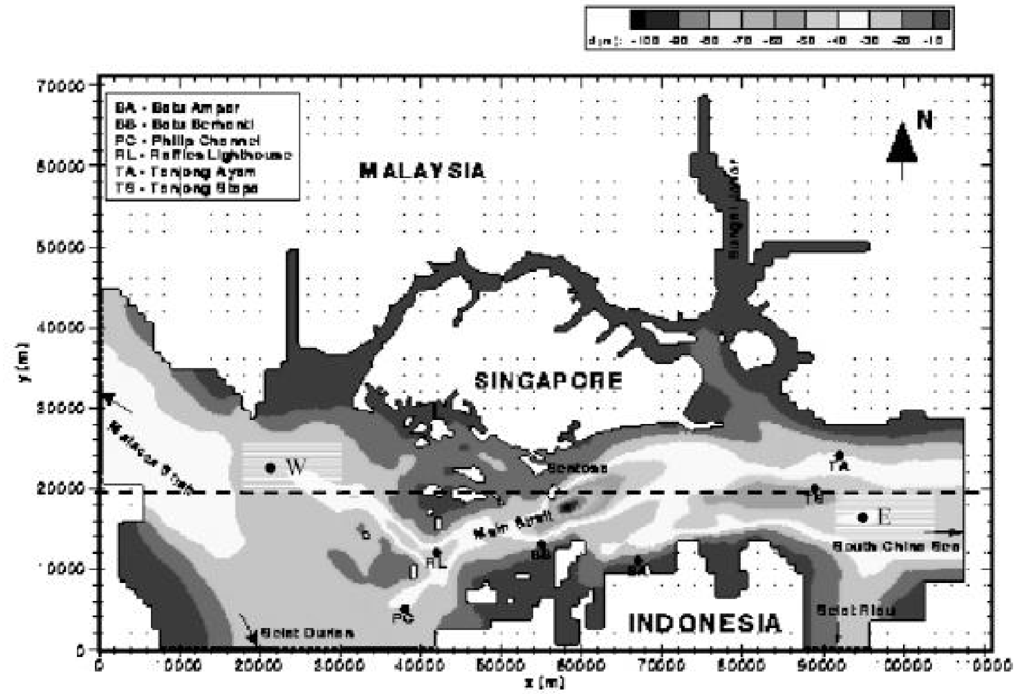


Figure 8.13 Strait of Singapore model domain (as shown in Chen et al., 2005).

The model was forced at the open boundaries using water surface elevation time series, and radiation conditions of Sommerfeld type are specified for the domain computations (Chen et al., 2005). The pressure gradients are included in the model forcing via the water surface elevation time series applied at the open boundaries. Wind forcing is applied uniformly across the domain using monthly mean values.

The model under-predicts the peak tidal flows, particularly when the semi-diurnal component of the tide is dominant. During this same time period, the current directions are also poorly predicted for a number of the measurement stations. For winter simulations, the model appears to perform well when predicting the current directions, but the current magnitude is slightly out of phase with the measurements. Chen et al. (2005) concluded by proposing more accurate modelling of the wind and pressure fields, over a domain covering the South China Sea, for this would likely improve the hydrodynamic model predictions.

8.4 Modelling Needs

8.4.1 Sediment transport modelling

In the last two decades, a number of researchers have made advances in modelling the complex hydrodynamics observed in Singapore waters. Based upon the hydrodynamic work, some water quality modelling studies and analyses have been made. In contrast, limited modelling work has been published on simulating waves and sediment transport around the Singapore coastal waters. Sediment transport predictions are quite important in order to predict the effect of the combination of continuous dredging and reclamation works along side an extremely active shipping ports and regional traffic on the marine ecosystem (Doorn-Groen, 2007)), such as a reduction in light attenuation which will affect the growth of photosynthetic organisms.

Sediment transport predictions are also quite important for the health of the flora and fauna in the surrounding marine environment. Particularly sensitive species, such as corals and eel grass have low tolerances to sedimentation and reduced solar radiation. No peer-reviewed publications could be found on modelling the sediment transport due to the current marine works (dredging, reclamation, port expansion, etc) to determine the effect upon the existing sensitive species populations in the surrounding waters. Hydrodynamic and sediment transport modelling studies are in general limited in coral and mangrove environments.

8.4.2 Coral Reefs

Numerical modelling of flow and transport processing in and around coral reefs is becoming more heavily investigated in recent years. Most studies have historically, and even recently, focused on collecting measurements in coral environments to determine the dominant physical processes. These types of studies have often stemmed from issues with fine sediments covering coastal reefs due to human-influences (Storlazzi et al., 2008).

Stanford University, University of Hawaii and the USGS Pacific Science Center appear to all be currently active in this field of research and making advances in the numerical modelling of these complicated hydrodynamic regimes: http://www.agu.org/meetings/os06/os06-sessions/os06_OS15L.html and http://www.soest.hawaii.edu/oceanography/hoeke/hanalei/.

8.4.3 Mangroves

In the Singapore-Delft Water Alliance (SDWA) Marine Research Programme quantification will be performed on how the short-term bio-physical interactions between flow and vegetation govern the long-term bio-geomorphologic development of mangrove ecosystems and vice versa (SDWA, 2008). This question will be addressed by combining field studies, flume studies, macrocosm experiments and process-based hydrodynamic modelling. The results will be generic, in that the project will provide quantitative insight in how these interactions are affected by hydrodynamic forcing and ecosystem scale.

Specific Research Objectives:

1. Quantify the bio-physical interactions that control the attenuation of hydrodynamic energy and local gross sediment transport fluxes in mangrove vegetations.
2. Develop a process-based hydrodynamic model that can be used to describe the attenuation of hydrodynamic energy by bio-physical interactions within mangrove vegetations.
3. Use the model to predict the potential use of mangroves for attenuating hydrodynamic energy.
4. Quantify the relation of the gross short-term sediment fluxes, and their seasonal variation, with the long-term net sediment dynamics (and thus sediment storage) in mangroves.
5. Identify growth rules for mangrove species in order to obtain a plant growth algorithm that can be used for modelling the long-term mangrove development under contrasting abiotic conditions.

6 Develop a coupled hydrodynamic, morphodynamic and plant-growth model that can be used to simulate the long-term bio-geomorphologic development of mangroves, under different scenarios of sediment loading, sea level rise and hydrodynamic forcing.

8.5 Conclusion

A variety of numerical modelling studies have been performed in recent years by Deltares | Delft Hydraulics and others. Through these studies, hydrodynamic and sediment transport models (particle tracking) have been developed to investigate various marine works, including land reclamations, dredging activities, and port expansions.

As discussed in section 8.3, the model applications thus far have performed well at predicting the observed water level fluctuations; however, these models have mostly over-predicted the semi-diurnal fluctuations of the tidal currents.

As discussed in section 8.4, numerical modelling studies are still needed to investigate the effects of marine works on sensitive species, such as coral reefs and mangrove forests. These studies are particularly relevant when trying to protect these species from sedimentation and increased turbidity due to dredging and reclamation activities.
It is important to continue improving the numerical models for the Singapore waters for the execution of themes 3 and 4 (Figure 1.1):

- Theme 3: Combining existing and new knowledge generated in Themes 1 & 2 into the practice of eco-dynamic design. This requires the development of:
  - measurable and predictable criteria and early warning indicators for turbidity, sedimentation and ecosystem response;
  - designs and pilots for bio-diverse coastal protection.
- Theme 4: Supporting monitoring, field measurements, field and laboratory experiments and mathematical modelling for the scientific and applied studies in the other themes.

Turbidity, sedimentation and ecosystem response are difficult parameters to measure in a useful manner, particularly on short time scales. It is possible to employ numerical modelling approaches in an efficient manner (physics-based, empirical, and logical) when investigating the effects on these processes due to human-impacts.

Validated numerical models can be implemented in the assessment of environmental acceptance criteria, as well as in the development of these criteria (such as early warning indicators) for determining ecosystem health. Numerical modelling can also provide an initial assessment of various marine works designs (both soft and hard) prior to defining and executing pilot studies. These model studies will help define the weaknesses in the physical and ecological system knowledge that can be investigated in measurement campaigns and pilot studies.

9 Summary of key points per topic

9.1 Physical System

- The tides in Singapore's coastal waters are mixed diurnal – semi-diurnal. Due to large spatial gradients in the semi-diurnal and diurnal tidal waves, the water levels around Singapore are dominantly semi-diurnal while currents are dominantly diurnal.
- The monsoonal winds result in a pronounced seasonal variation in residual flows. The residual flows in the Singapore Strait are dominantly in the westward direction but may change direction from May to August.
- The wind is from the south from May to October, and from the northeast from November to April, with velocities rarely exceeding 8 m/s. The resulting local wind-generated wave heights are low, typically less than 1 m. Swell generated in the Malacca Strait or South China Sea does not penetrate into Singapore Coastal waters.
- The main river system is the Johor River, with an estimated annually averaged discharge of 60 m3/s and a concentration around 100 mg/l. Numerous smaller rivers drain into the coastal waters, but these have a low but unknown discharge. The seasonal variation in discharge is moderate, with typically two times more rainfall in the wettest month (December) than the driest month (July).
- The grain size of the seabed is poorly known, but the available data suggests that the mud content varies from 0 to 40%.
- The land reclamations have probably severely influenced the sediment dynamics in the area, but the impact is poorly known. The most quantitative measure is the reduction in visibility around Singapore's coral reefs, which have decreased form up to 10 m on a clear day, to several m.

9.2 Water Quality

- In the coastal waters of Singapore, the main sources of nutrients and organic pollutants are land-based inputs such as rivers, urban runoff, and domestic and industrial sewage.
- The Selatar and Serangoon areas run the highest risk of eutrophication in the situation that the nitrogen inputs further increase. This is also where two of the three sewage confluence areas are for Singapore.
- Nitrogen and Phosphorous may both be limiting nutrients in the Singapore region.
- Chlorophyll-a concentrations have been found to decrease when going from the middle of the Johor strait towards Kuala Johor.
- In the Singapore Strait, low chlorophyll-a levels have been found to coincide with North-East monsoon, whereas higher concentrations have been found to coincide with the South-West monsoon.
- Link between high nutrient load discharges into the rivers and surrounding sea with harmful algal blooms.
- Cheong and Shanker (2001) observed that DO levels in the Johor Strait can drop below 4mg/l, thus to levels that detrimental to most marine species.

- Deltares found the highest DO concentrations in the Johor Strait to occur during the rainy season, whereas the lowest concentrations occurred at the end of the long rainy season (October).
- Deltares also found that DO levels never drop below 4 mg/l in the Singapore Strait.
- Due to the shipping activities around Singapore, the leachate from ship anti-fouling paints can be found along whole Singaporean coastline, as well as in offshore Singaporean waters.
- A wide variety of heavy metals have been found in both suspended sediments, as well as in the sediment beds of areas effects by dredging and reclamation.
- POPs are present in all compartments of Singapore's marine environment, including marine sediments, seawater and biota.
- Obbard et al. (2007) concluded that locally high levels of PAH's are present in the Singapore marine environment, and can be attributed to activities in shipping, industrial discharge and land reclamation.
- Obbard et al. (2007) have found that PCBs are migrating seaward from petrochemical plants via sediment dispersal.
- Most data from Singapore waters is derived from stand alone study, implying that a trend analysis on the presence of contaminates in coastal waters can not be performed.

9.3 Human Activities

- Six major seaports have been developed since the mid-1960's, with Pasir Panjang being the largest.
- Most sand mining is now an offshore activity, commonly in neighbouring foreign waters
- No concrete link between dredging activities and changes in water quality due to a lack of pre and post monitoring of dredge works.
- Much of the Singapore coastline, including the southern islands, has been significantly altered by the placement sea walls to contain the reclaimed areas.
- The recreation beaches on the mainland have been created in reclaimed areas, and subsequently have a steeper profile than the historical system.
- Despite there being no oil or gas reserves around Singapore, significant oil and gas refineries and distribution centres have developed in and around Singapore, particularly on Jurong Island.
- The maritime activities contribute to the transfer of anti-fouling contaminate to the coastal system, as well as are linked to increased ocean litter, pathogens, noise, and introduction of non-native species.
- Marine fisheries and land-based aquaculture do not play a large role in Singapore economics, but are socially-valued. The marine aquaculture is negatively affected by the marine pollution linked to the shipping industry; however, the fisheries themselves also exert pressure on the environment in the form of marine litter.
- Singapore Green Plan (released in 1992) covers the core areas of environmental management, infrastructure development and public health.
- Monitoring activities are needed in order to determine and quantify the anthropogenic impacts on the environment, particularly related to dredging and shipping.

9.4 Coral Reefs

- Singaporean reefs have shown a strong decline over the last 20 years.
- Land reclamation and sedimentation (leading to both smothering of reefs and high turbid waters) are generally considered the most important cause of this decline
- Despite high turbidity of marine waters Singaporean coral reefs still have relative high species richness.
- Reef life is virtually absent at a depth below 8m and most coral life is found at the reef crest
- Reefs have potential to attract the public given the fact that they are easily accessible. They are visible at low tide, such that diving equipment is not needed to get an impression of the rich diversity of the coral reefs.
- Singaporean reefs have many important ecosystem service functions such as coastal protection
- Protection of marine habitats (e.g. coral reefs) in Singapore is not organized by a single coordinating agency. Improvement by management through such a body is suggested in the Blue Plan.
- Information on the influence of marine pollution on reef diversity, species growth and abundance is scarce, as is information on more fundamental ecological issues such as life cycle (recruitment, growth, longevity) and community structure and stable states and recovery potential

9.5 Sea Grass Meadows

- Seagrass meadows in Singapore play a vital role in sustaining coastal fisheries, maintaining coastal water quality and clarity, supporting a diverse community of associated marine flora and fauna, and as food for green turtles and dugongs;
- 12 different seagrass species have been recorded from Singapore waters;
- There has been very little study on the seagrasses of Singapore to date;
- Past land reclamation schemes in Singapore appear to have resulted in widespread losses of seagrass habitat along coastal Singapore (based on study of historical herbarium material), such as at Kranji, West Johor Strait, Changi beach, Beting Bemban Besar, Terumbu Raya, Hantu West, Pulau Tekong, etc;
- At present, seagrasses occur at some 25 sites in Singapore, incl. 7 sites along the shores of Singapore’s ‘mainland’, some of which harbour dense meadows;
- The total areal extent (ha) of seagrass habitat in Singapore is not known;
- Since early 2006, 6 of the main seagrass sites of Singapore are being monitored (i.e. Cyrene Reef, Pulau Semakau, Chek Jawa, Sentosa, Labrador Beach and Tuas) under the global SeagrassWatch programme;
- Due to the relatively turbid waters, most seagrass growth in Singapore is intertidal, with only a few sparse subtidal meadows down to 8 m depth;
- There is no detailed historical data available on the former depth distribution of seagrasses in Singapore, but it appears likely that the maximum depth penetration of most subtidal seagrass growth has decreased over the past few decades due to the marked increase in turbidity;
- There are no specific laws in Singapore protecting seagrasses, but some form of protection is offered in three protected areas (at Sungai Buloh, Labrador and Sisters Islands), while all seagrass species are listed as threatened in the Singapore Red Data Book;
- No seagrass restoration efforts have been made in Singapore to date.

9.6 Mangroves

Range of important ecosystem services:
- Coastal protection
- Nursery function
- Biodiversity
- Flagship species attract tourism
- Carbon sequestration
- Water quality via sediment storage & nutrient removal

Status:
- Globally declining
- Also the case in SE-Asian countries like Singapore, Malaysia, Thailand and Indonesia

Most important threats:
- Lateral erosion
- Anthropogenic reclamation for harbour extension, shrimp farming, etc
- Risk of pollution
- Sea-level rise

Knowledge gaps relevant to BwN perspective:
- To what extent does habitat fragmentation affect the healthy functioning of mangroves, what is the dispersal distance of propagules, and how is pollination affected by fragmentation?
  - How does this depends on size of the remaining mangrove
  - How does this depend on distance between the remaining mangroves?
  - Is there an interaction between size and distance?
- which factors enables vs. hampers mangrove seedlings to establish
  - tidal inundation
  - sediment chemistry
  - sediment stability
  - hydrodynamic forcing
- how do the vertical sediment dynamics of mangroves work at different time scales
  - short-term sediment accretion dynamics
  - seasonal sediment-erosion dynamics
  - long-term net surface elevation change as the balance of sediment accretion minus subsidence and the consequences for their ability to follow sea-level rise
- what is the time-scale of the horizontal sediment dynamics of mangroves, and how does this depend on hydrodynamic forcing
- to which extent can mangroves help protecting coastal areas

9.7 Model Inventory

Deltares models (model-type):
- Marina Reservoir catchment model (1D and 2D SOBEK-RR and SOBEK CF/SF)
  - Forced by rainfall run-off input, tides (water level boundary conditions), and river discharge
- Singapore Regional model (2DH Delft3D-FLOW)
  - Forced by 8 tidal components, wind and river discharge boundary conditions
- Singapore Island model (2DH Delft3D-FLOW)
- East Singapore Local model (3D Delft3D-FLOW)
  - Forced providing tidal information, wind and river discharge boundary conditions

- Marina Bay model (3D Delft3D-FLOW and Delft3D-ECO)
  - Delft3D-FLOW forced providing tidal information, wind, and river discharge information
  - Delft3D-ECO forced through a coupling to a SOBEK water quality model, as well as tidal information, solar radiation effects and wind forcing. This model predicts the effects on various organic and inorganic substance/materials within Marina Bay.
- Upper Peirce and Lower Peirce models (3D Delft3D-FLOW)
  - Closed boundaries, but include evaporation, river runoff, precipitation, wind and aeration process modelling
- Marina Reservoir model (3D Delft3D-FLOW)
  - Closed boundaries, but have input from SOBEK river modelling and wind forcing

External models (model-type):

- South-eastern Singapore, focusing on Tanjong Pagar Container Terminal (2DH hydrodynamic and sediment tracer model) (Cheong et al., 1992)
  - Forced using 12 tidal constituents
- South-west Singapore coastal model (2DH and particle tracer model) (Riddle, 1996)
  - Forced with tidal information
- Singapore region model (2DH tidal model), with a nested Southwest Singapore coast model.
  - Focused on accurate predictions of the turning of the tide
  - Employed Monte Carlo simulations to determine model uncertainty
- COMCOT model, with 4 nested grids) to investigate Tsunami effects from a Manila trench earthquake (2DH tidal and tsunami model) (Huang et al., 2009)
- POM Singapore Strait model (2DH tidal model) (Pang Tkalich, 2003)
- 3D Singapore Strait modelling
  - Chao et al. (1999) – forced using 60 tidal constituents employing a harmonic analysis to predict the water level oscillations
  - Zhang and Gin (2000) – forced using tidal information and winds to predict the water level oscillations. Compare again water level and current measurements. Performed a variety of theoretical and sensitivity analyses.
  - Zhang (2006) compare POM and MIKE 3 predictions of water level and currents again Zhang and Gin (2000) data.
  - Zhang et al. (2004) employ POM to investigate wave-current interaction in coastal waters. WAM model used to predict waves.
  - Chen et al. (2005) also employs POM to investigate large scale hydrodynamics. Using wind, atmospheric pressure and tidal information to force with.

Modelling needs

- Sediment transport (dredge material, fines, morphological evolution) modelling
- Coral reef hydrodynamic, (sediment) transport, and habitat modelling
- Mangrove hydrodynamic and habitat modelling

Conclusions

- Validated numerical models can be implemented in the assessment of environmental acceptance criteria
- Validated numerical models can be utilized in the development of early warning criteria for determining ecosystem health.
- Numerical modelling can also provide an initial assessment of various marine works designs (both soft and hard) prior to defining and executing pilot studies.

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